BATTERY ENERGY STORAGE SYSTEMS (BESS)

OVERVIEW OF GUIDELINES FROM DENMARK, BELGIUM, SWEDEN, UK, USA AND OTHER SELECTED COUNTRIES

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Abbreviations

ABV - Fire Ventilation System

ACH - Air Changes per Hour

AHJ - Authorities Having Jurisdiction

AK - Application Categories according to SE1

BOS - Balance of System

BESS – Battery Energy Storage Systems

BMS - Battery Management System

CFA – The Country Fire Authority, Victoria, Australia

DBI - Dansk Brand- og sikringsteknisk Institut

DEMA – Danish Emergency Management Agency

DiBK - Directorate for Building Quality

DRBV - Drammen Region's fire service IKS Norway

DSB - Directorate for Social Security and Preparedness Norway

EOS - Energy Storage Systems

EPRI - Electric Power Research Institute

ERP – Emergency Response Plan

ESMS - Energy Storage Management System

FFI - Norwegian Defense Research Institute

LFL - Lower Flammability Limit

LFP - Lithium Iron Phosphate Batteries

LIB – Lithium-ion Batteries

LMT - Light Means of Transport

HAZOP - Hazards and Operability Study

HF - Hydrofluoric Acid

HMA - Hazard Mitigation Assessment

HVAC - Heating, Ventilation, and Air Conditioning

IDLH - Immediately Dangerous to Life or Health

IFC - International Fire Code

IM - Installation Manager

NFPA – The National Fire Protection Association

NMC - Lithium Nickel Manganese Cobalt Oxide batteries

SLI - Starting, Lighting and Ignition batteries

SOH – State of Health

SOC – State of Charge

SWIFT - Structured What-if Technique

TMS - Thermal Management System

TR – Thermal Runaway

UL – Underwriters Laboratory

VOC - Volatile Compounds

WUI - Wildland Urban Interface

Contents

Executive summary

This report focuses on the safety guidelines, regulations, and knowledge gaps surrounding Battery Energy Storage Systems (BESS) across various countries. The document provides a review of these guidelines, with a particular emphasis on Denmark's guideline, developed by the Danish Emergency Management Agency (DEMA). Aside from presenting a viable opportunity for energy storage or balancing electrical grids, BESS present significant fire and explosion risks, due to employment of Lithium-ion batteries (LIB), which are susceptible to thermal runaway (TR). These risks are heightened by the growing number of installations, and notable incidents have underscored the need for further development of validated safety measures.

However, Denmark's existing guidelines, particularly for fire and explosion safety, lack detailed provisions on several critical fronts, including risk assessment or wastewater management.

While identified as a key risk, the Danish guidelines do not provide detailed measures to mitigate thermal runaway, unlike other countries where Battery Management Systems (BMS) are recommended. Denmark also lacks specific protocols for Lithium-ion battery fire and explosion testing, e.g., UL 9540A, which is a benchmark test recommended in many other countries. Danish guidelines may furthermore provide more clarification on when and which suppression systems should be installed, depending on BESS design parameters. While Denmark emphasizes collaboration with fire services, there is a lack of clear tactics and water management strategies, a gap covered by countries like Sweden and Australia.

Some of the identified knowledge gaps include limited understanding of explosion prevention and fire suppression in large-scale BESS settings. Furthermore, practical fire risk assessment tools may improve the design process. Additionally, it is necessary to evaluate safety hazards in BESS installations built from 2-nd life LIB.

To improve the existing Danish guidelines, a more detailed description of the documentation circulation and liabilities may be introduced and the application of standard fire testing, already used in other countries, would further improve safety. The guidelines may also specify preventive measures against the mechanical impacts and the risk assessment and hazard mitigation analysis could be used in situations where the expected design is outside the scope of the guidelines. Other aspects to be incorporated are guidelines on handling extinguishing water, contaminated runoff, and post-incident management.

Several research directions are suggested in this report including, development of practical fire risk assessment tools and approaches for BESS systems as well as investigating the critical conditions for explosions and explosion risk mitigation measures. Determining heat release rates and the heat fluxes at different distances from LIB and BESS system at different scales may further allow for more optimal design.

1. Introduction

This report reviews the existing guidelines and standards for Lithium-ion Battery (LIB) Energy Storage Systems (BESS) available up to 2024 and compares them to the guidelines currently used in Denmark. The goal of this comparison is to identify and highlight the current gaps in the guidelines, with the focus on the Danish guideline, and establish research directions. Additionally, the document presents two case studies that illustrate the use of current guidelines in Denmark.

1.1 Battery Energy Storage Systems (BESS)

BESS are used for storing energy generated from a renewable energy sources (e.g., solar or wind power) and non-renewable sources. BESS technical solutions are envisioned to balance the electricity grid in real time, since the demand on the grid may fluctuate due to various reasons, e.g., weather, power station outages, geopolitical reasons.

Several environmental advantages of BESS can be mentioned, including the possibility to enable using more non-stable and renewable sources of energy and the increase of energy efficiency by storing excess energy during low-demand periods and releasing it during peak-demand periods.

There are a variety of different battery technologies, e.g., flow, lead-acid, sodium-ion, nickel-based and Lithium-ion batteries (LIB). Among the mentioned technologies, LIB are dominant in the market and account for most of the batteries implemented nowadays and in the future [1], therefore, the main focus of this study is on these types of batteries. A more extensive overview of various battery technologies and phenomenon related to BESS (e.g., LIB battery thermal runaway), is presented in [2]. BESS come in various sizes, designs, and capacities, with different rated power capacities (MW) and energy capacities (MWh). In general, BESS includes the energy storage in battery cells, their encasing, and the auxiliary systems e.g., electrical cables, power conversion, monitoring, and control systems. Monitoring and control systems comprise the basic functionalities of battery management system (BMS), which among other, controls the safety of BESS.

BESS are becoming an increasingly popular solution to the challenges posed by renewable energy integration. Despite the growth of use cases and applications, BESS still poses safety concerns related to fire and explosion hazards. In the event of a thermal runaway, LIB batteries within BESS can release flammable and toxic gases which can lead to fires or/and explosions. There are several factors that influence the fire and explosion hazards, such as the state of charge, cathode chemistry, electrolyte composition, cell form, cell capacity, along with the type of failure mode. Understanding the influence of all the mentioned parameters is paramount to ensure the safety of these systems. Comprehending the existing guidelines is important for safer and less cumbersome implementation of these technologies in the market.

Even if the fire and explosion safety of BESS is not yet well understood, there is a demand from the society to develop guidelines, best practices, or regulations for how to ensure safety. Safety aspects of BESS that are currently investigated in the research community and applied by specialists are the following: thermal runaway risks, off-gassing and explosion risks, active and passive fire protection strategies, safe distances to other buildings, placement location within building, firefighting strategies, treatment of extinguishing water, etc.

1.2 The objectives and limitations of this document

This document has the following **objectives**:

- Reviewing the BESS fire and explosion safety related guidelines, requirements and recommendations in Denmark, Sweden, Norway, Netherlands, UK, Belgium, Germany, Australia and USA.
- Identifying the gaps in the Danish guidelines and proposing recommendations for improvement.
- Identifying the overall knowledge gaps in the guidelines
- Propose topics for development of knowledge and data that could support the formulation of the new guideline requirements.

The main **limitations** of this study are:

- This work is limited to BESS (electrical vehicles or mobility devices are out of scope). The focus is directed to LIB.
- Guidelines/standards from only selected countries are reviewed.
- There are other regulations, standards and guidelines that must be followed when implementing BESS facilities e.g., national building regulations. However, these documents are not considered in this work.
- Surveying and evaluating the state-of-the-art scientific publications on the BESS fire safety is outside of the scope of this document. This document strictly focuses on the regulations and comparative safety levels between countries.
- The practical aspects for implementing the provided recommendations are not considered. The practical aspects may include, but not limited to, additional costs for battery testing, necessary education for performing risk assessments, etc.

1.3 BESS incidents

The rapid increase of BESS installations has led to a concurrent increase in BESS safety incidents according to [3]. Using public databases, news articles, and government issued documents from around the world, Underwriters Laboratories (UL) Solutions developed a database of LIB incidents (fires, explosions, etc.). According to this database, out of over 8000 LIB failure events identified, 141 were related to the energy storage system events, and 60 of these were residential BESS events. In terms of geographical distribution, most of the residential BESS events have happened in Europe and Asia. Concerning the residential BESS systems, the main causes that led to these events were related to issues with the BMS or manufacturing defects.

The Electric Power Research Institute (EPRI) BESS failure incident database [4] was initiated in 2021, and the insights from the database are presented in [5]. The root causes of the incidents are classified as: Design; Manufacturing; Integration, Assembly & Construction; and Operation. Cell/Module, Controls, and Balance of System (BOS) are considered the elements that failed. The identified failures were due to Integration, Assembly & Construction in 36 % of the cases, Operation in 29% of cases, Design in 21%

of cases, and Manufacturing in 14% of cases. Most of these incidents happened in the first years of the system (first 3 years). The controls and BOS account for most failed components. Integration was the most common root cause of BESS failures, and most of the incidents involved BOS components. Operation was the second most common root cause, and in all cases, the operation failure occurred in the control systems. Mitigations and recommendations are also discussed in the same document. The importance of complying with relevant codes and standards (UL, NFPA) is highlighted, since the latest revisions have incorporated lessons learned from past failures. However, when incidents related to BESS occur and are presented, the following aspects are usually not mentioned: the presence of fire and explosion safety strategies; guidelines that governed the design of these strategies and effectiveness of these strategies during the incidents. Without knowing these aspects, it is difficult to understand how efficient the recommendations in the current standards/guidelines are and how these could be improved.

One widely reported incident took place in Arizona and is described in [6]. The BESS consisted of a 2 MW facility containing Lithium Nickel Manganese Cobalt Oxide (NMC) batteries. The facility was equipped with an automatic clean agent suppression system (Novec 1230), which activated as designed. The following contributing factors are mentioned in the report:

- The training curricula for the responding firefighters did not (at the time of incident) cover basic BESS hazards, while extra-curricular BESS-specific training did not yet comprehensively cover BESS hazards.
- There were no sensors to provide information about the presence of flammable gases.
- The BESS communication system failed before the arrival of the firefighters at the incident location.
- The emergency response plan was not provided to the fire service prior to the incident (it was not required by codes at that time).
- The emergency plan provided to fire service on the scene, did not provide guidance for mitigating the thermal runaway, fire, and explosion hazards.
- Deflagration venting was not included in the design of BESS.
- The used suppression system was not designed to provide explosion protection.

The key recommendations from this incident were the following:

- Basic firefighter training should emphasize BESS safety.
- Full-scale testing research should be conducted for a better understanding of effective and safe tactics for the fire services. Until this is done, the fire service is recommended to define a conservative potential blast radius and remain outside of it.
- Online education tool with the base knowledge about BESS hazards and fire service tactical considerations was since then developed [7].
- Gas monitoring should be incorporated in BESS.
- Multi-scale testing should be conducted to evaluate the effectiveness and limitations of stationary gas monitoring systems.
- The communication systems within BESS should be robust.

- Owner and operators of BESS should develop operations plan with local fire services and authorities having jurisdiction (AHJ).
- Signage to identify the content of BESS should be placed on all BESS installations.
- Adequate explosion prevention protection should be incorporated.
- Full-scale testing should be conducted to determine the most effective fire suppression and explosion prevention systems for BESS.
- Research focused on best practices regarding emergency decommissioning and the role of fire service in an emergency should be performed.

Those recommendations and lessons serve as inspiration for developing guidelines and standards worldwide.

1.4 Regulatory landscape

In recent years, particularly in the middle of 2010's, codes and standards were developed in response to documented loss events, aiming to keep pace with the increased development and application of LIB. A summary of development of the codes is provided in [8].

One of the first requirements for the protection of LIB BESS was included in the International Fire Code (IFC) in 2006. In 2016, Underwriters Laboratories (UL) published the first edition of the UL9540 [9] which presented requirements for construction and design for BESS to gain UL 9540 certification. Later, in 2018, UL 9540A [10] followed, and since then, it has served as the industry' primary testing framework for large-scale fire and fault condition testing and evaluating the potential risks of thermal runaway and fire propagation within LIB BESS. Cells, modules, units and installations can be evaluated according to this standard and data such as temperature profiles, gas emissions, heat release rates (HRR) are collected, along with a pass-fail criterion for UL9540 certification.

In 2020, NFPA 855 [11] was introduced, where allowing for assessment of separation distances, suppression systems, explosion control systems based solely on UL 9540A unit-level testing.

The meta-analysis [8] concluded a large variability in propagation, fire, and gas data, indicating that the current standards may not consistently predict or mitigate real-world BESS fire hazards. Additionally, it pointed out a lack of requirements for evaluation of fire suppression and explosion control systems, posing a question of holistic approach and adequacy of the current testing standards. Moreover, the scalability of cell level heat release data used to predict full-scale behavior is not linear, thus posing challenges to fire hazard assessment methodologies.

1.5 EU Battery Regulation 2023/1542 Directive

1.5.1 Background

The "European Green Deal" announced by the Commission December 2019 outlines Europe's strategy for achieving a sustainable, prosperous society by 2050, with an economy that emits no net greenhouse gases and grows without overusing resources.

As a part of the European Green Deal, EU Regulation 2023/1542 [12] concerning batteries and waste batteries (amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC) aims to create a circular economy for the batteries sector by targeting all stages of the life cycle of batteries, from design to waste treatment. This initiative is of major importance, particularly in view of the massive development of electric mobility. The demand for batteries is expected to grow by more than tenfold by 2030.

Regulation 2023/1542 will apply to all batteries including all waste portable batteries, electric vehicle batteries, industrial batteries (BESS), starting, lighting and ignition (SLI) batteries (used mostly for vehicles and machinery) and batteries for light means of transport (LMT) (e.g. electric bikes, e-mopeds, e-scooters), regardless of their shape, volume, weight, design, material composition, chemistry, use or purpose. Regulation 2023/1542 entered into force on the 17th August 2023 and applied from 18th February 2024 in general, with some of the articles applying from later dates.

Regulation 2023/1542 sets a tangible threshold of 2 kWh capacity for batteries. For more than 2 kWh this regulation dictates additional requirements like carbon footprint, recycling, performance and durability, labelling and marking, and battery passport regulations.

1.5.2 Safety of stationary BESS

Chapter II of EU Battery Regulation describes the safety of stationary BESS. **Article 12** describes requirements for technical documentation that covers the safety requirements for stationary batteries under normal use. This includes tests for safety parameters as described in Annex V - Safety parameters and Annex VII - Parameters for determining the state of health and expected lifetime of batteries. The technical documentation (specified in Annex VIII Conformity assessment procedures) shall:

(a) demonstrate that the stationary BESS are safe during their normal operation and use, by including evidence that they have been successfully tested for the safety parameters, set out in Annex V, for which state-of-the-art testing methodologies shall be used:

- Thermal shock and cycling
- External short circuit protection
- Overcharge protection
- Over-discharge protection
- Over-temperature protection
- Thermal propagation protection
- Mechanical damage by external forces

- Internal short circuit
- Thermal abuse
- Fire test
- Emission of gases

The safety parameters shall only apply in so far as a corresponding hazard exists for the stationary battery energy storage system in question when it is used under the conditions envisaged by the manufacturer;

(b) include an assessment of possible safety hazards of the stationary BESS that are not addressed in Annex V;

(c) include evidence that the hazards referred to in point (b) have been successfully mitigated and tested; state-of-the-art testing methodologies shall be used for such testing;

(d) include mitigation instructions in case the identified hazards could occur, for example a fire or explosion.

The technical documentation shall be reviewed if a battery is prepared for re-use, prepared for repurposing, remanufactured or repurposed.

1.6 Regulatory situation in Denmark

Currently in Denmark, Beredskabsstyrelsen (the Danish Emergency Management Agency (DEMA)) offers guidance on fire protection of large storage of LIB and BESS [13] (referred later in this document as DK1). The guideline is applicable for the following cases: (i) stocks of factory new and unused batteries with a capacity larger than 2000 kWh; (ii) stocks of used batteries with a capacity larger than 1000 kWh; and (iii) BESS with a capacity larger than 2000 kWh. DK1 states that the local fire departments can use Beredskabsloven § 34. Stk.2 to demand extra safety measures for capacities above 2000 and 1000 kWh respectively. DK1 emphasizes that LIB in such applications as: electric cars/hybrid cars in buildings, smaller storages of new LIB's in buildings, smaller storages of end-of-life LIB's in buildings as well as lower capacities of BESS in buildings should fall under the fire regulations in the building legislation, which is under the Social and Building Agency in Denmark. Nevertheless, the authors are not aware of any efforts to include effects of LIBs in the building regulations from the Social and Building Agency in Denmark.

DK1 is based on the recommendations from Artelia Group, on behalf of Beredskabsstyrelsen, and referred later in this document as DK2 [14]. The recommendations rely on the location of the batteries (indoors or outdoors), the capacity of the batteries, the state of charge (SOC), the use of batteries (connected or not), or the history of batteries (new or used batteries). The requirements are detailed for capacities under 2400 kWh, depending on the above-mentioned parameters.

DK1 does not specify the requirements for BESS capacity above 2400 kWh; however, capacities of some BESS installations in Denmark are significantly larger than 2400 kWh. Chapter 4 describes two case studies, designed at Dansk Brand- og sikringsteknisk Institut (DBI), by highlighting gaps and uncertainties in the Danish regulations. These practical examples indicate that further work is needed to better understand the background of the existing guidelines and to address the gaps.

1.7 Reviewed BESS guidelines/standards

Several guidelines were analysed in this report and Table 1 present an overview of these guidelines.

Table 1. Overview of the considered guidelines/standards.

Country	Institution	Document title	Reference	Abbreviation
Denmark	Beredskabsstyrelsen	Vejledning om brandsikring af større oplag af litiumionbatterier samt BESS	[13]	DK1
	Artelia Group (previously MOE)	Forslag til brandtekniske krav til BESS og oplag af litium-ion batterier	[14]	DK2
Sweden	RISE	Guidelines for the fire protection of battery energy storage systems (including Appendix C)	[15]	SE1
Norway	DSB, FFI, DRBV, DiBK, Nelfo	BATTERISYSTEMER I BOLIGER. *Brann- og elsikkerhetsveileder*	[16]	NO1
Netherlands	Gevaarlijke Stoffen	Lithiumhoudende energiedragers: energieopslagsystemen (EOS). Richtlijn voor de veilige opslag van elektriciteit inenergieopslagsystemen	[17]	NL1
UK	Frazer-Nash Consultancy for Department for Energy Security and Net Zero	Health and Safety Guidance for Grid Scale Electrical Energy Storage Systems	[18]	UK1
	NFCC National Fire Chiefs Council	Grid Scale Battery Energy Storage System planning – Guidance for FRS	[19]	UK2
Belgium	ANPI (Inspection body for fire and theft prevention)	Dossier technique ANPI DTD 181: Les systemes de stockage d'energie sur batteries (BESS)	[20]	BE1
Germany	BVES (German Energy Storage Association)	Vorbeugender und abwehrender brandschutz bei lithium-ionen Großspeichersystemen hinweise und informationen für planer, bauherren, einsatzkräfte,	[21]	DE1

		versicherungen und genehmigende stellen		
Australia	CFA (The Country Fire Authority, Victoria, Australia)	Design Guidelines and Model Requirements. Renewable Energy Facilities v4	[22]	AU1
USA	NFPA	NFPA 855 – Standard for the Installation of Stationary Energy storage Systems	[11]	USA1
	FM Global	FM Global Property Loss Prevention Data Sheets 5-33: Lithium-ion Battery Energy Storage Systems	[23]	USA2

1.7.1 Denmark

DK1 [13] provides guidance depending on the three defined application categories: Storage of new and lightly used batteries, storage of expired and used batteries, and BESS above 2 MWh.

DK2 [14] provides recommendations on the three defined application categories: Storage of new and lightly used batteries, storage of expired and used batteries, and BESS under 600 kWh outdoor and under 50 kWh indoor.

1.7.2 Sweden

SE1 [15] provides guidance depending on the three defined application categories (AK): (1) AK1 for BESS in detached houses (private individuals); (2) AK2 for BESS in apartment buildings or commercial properties (group of individuals or companies); and (3) AK3 for BESS in large industrial plants or in large energy production facilities. All recommendations are made for the application categories without specifying battery capacities. This is due to the rapid advancements in batteries chemistry and technology, making it impractical to continuously update capacity values to which requirements would apply.

1.7.3 Norway

NO1 [16] addresses the batteries stored in detached houses, with very limited capacities, i.e., under 15 kWh.

1.7.4 Netherlands

The guideline in Netherlands, NL1 [17] is applicable to a specific subset of BESS, namely those consisting of lithium-containing rechargeable energy carriers that are electrically connected (in groups) with a total installed capacity larger than 20 kWh. It applies to new, used and discarded energy systems until they are decommissioned. Emissions to soil, water and air are addressed in a separate document.

While countries, such as Denmark, Sweden, and Norway, have available guidelines, the Netherlands takes a different approach. Several sections of [17] are normative and the proposed measures are based on risk assessment approach.

BESS are divided into six categories: (1) BESS in a container (outdoor); (2) BESS containers park (outdoor), (3) BESS park with inaccessible outdoor enclosures; (4) Mobile BESS (outdoor or indoor); (5) Indoor BESS with own space; and (6) Stationary indoor systems located in space which is primary intended for another function.

1.7.5 UK

The UK1 guideline [18] focuses on health and safety aspects of grid-scale battery applications that are rated at 1 MW and greater. The document applies to all phases from design to decommissioning, including the situations where battery collocate with other technologies. An overview of standards is presented, covering various stages such as battery design, system design and planning, transportation, installation and commissioning, operation and maintenance, decommissioning and end-of-life.

UK2 [19] specifically relates to grid-scale BESS (1 MW or larger) in open air environments. The document references AU1, USA1 and USA2.

1.7.6 Belgium

BE1 addresses the decision makers, manufacturers, prevention officers, facility managers, operators, technical managers, insurers, emergency services, authorities, and others, focusing on energy carriers containing lithium. The document does not cover emissions into the external environment, issues related to electric vehicles or battery storage, or wastewater treatment.

BE1's goal is to identify risk control measures for BESS. This is done by identifying the risk scenarios and setting prevention and protection objectives. The BE1 guide therefore does not provide concrete recommendations, but rather sets generic requirements of measures adequate for different levels of risk that may be present.

1.7.7 Germany

DE1 presents information on how to avoid fire and its effects, by describing structural, technical and organizational protective measures and prevention options. DE1 provides guidance for stationary systems of 50 kWh and larger.

1.7.8 Australia

AU1 [22] is applicable to batteries placed within 50 m from a dwelling or within an industrial or commercial building. Moreover, BESS are classified into: (1) large scale BESS, with capacities over 1 MWh; and (2) small scale BESS with capacities under 1 MWh.

The guideline aims to lead companies through all steps of the BESS development process, including pre-planning application, required documents before development can start, development phase, operation phase, decommissioning.

Given Australia's susceptibility to wildland fires, additional requirements are specified for BESS placement in the Wildland Urban Interface.

1.7.9 USA

USA1, i.e., NFPA 855, [11] is applicable to design, construction, installation, commissioning, operation, maintenance, decommissioning of stationary BESS (or mobile BESS installed as stationary for maximum of 90 days) and storage of Lithium-ion batteries (LIBs).

Unlike the other existing guidelines, in NFPA 855, a wide range of batteries are covered, such as lithium metal, Lithium-ion, capacitors, flywheels, and a more detailed classification is as follows:

1. BESS for one-two families, townhouse units (only chapter 15 applies to this case), with capacities equal and greater than 1 kWh (3.6 MJ).
2. Lead-acid, Ni-Cad, Ni-MH, Ni-Zn BESS, with capacities equal and greater than 70 kWh.
3. LIBs, with capacities equal and greater than 20 kWh.
4. Na-Ni-chloride, with capacities equal and greater than 20 kWh (70 kWh if follow UL9540A).
5. Capacitors, with capacities equal and greater than 3 kWh (note that not all capacitors are included).
6. Flywheel, with capacities of 0.5 kWh.
7. Other BESS, with capacities equal and greater than 70 kWh.

All the other investigated documents refer in one way or another to the NFPA 855.

USA2 [23] provides loss prevention recommendations for design, operation, protection, inspections, maintenance, and testing of BESS that use LIB. Other types of electrical energy storage are not covered by the document, nor the batteries, battery charges, and associated systems related to backup power in UPS systems or DC power for circuit breaker protection.

2. Evaluated parameters/aspects

The following groups of interest have been considered when reviewing all the investigated documents: documentation aspects, passive fire protection (including general distances), active fire and explosion protection, firefighting and water disposal, lifecycle procedures, repurposing and refurbishing. Table 2 presents the parameters that have been assigned to each group.

Table 2. Groups of interest with the associated parameters/aspects.

Group of interest	Parameters/aspects
Documentation aspects	• Involved parties, liability and documentation circulation • Hazard mitigation analysis or risk analysis • High voltage hazard • Thermal runaway control • Mechanical impact risk management • Safety (lightning) • Fire and explosion testing

Passive fire protection (including general distances)	• Outdoor installations • Indoor installations
Active fire and explosion protection	• Detection • Explosion prevention • Suppression and extinguishing systems
Firefighting and water disposal	• Emergency response • Extinguishing water management
Lifecycle procedures	• Inspection • Commissioning • Training • Operation • Maintenance procedures • Decommissioning procedures
Repurposing and refurnishing	• Repurposed and re-furbished batteries

The following section will provide a detailed focus on each group of interest.

3. Summary of the groups of interest in selected guidelines

3.1 Documentation aspects

3.1.1 Involved parties, liability and documentation circulation

DK1 prescribes fire protection measures which must be considered as a superstructure of the building regulations. The building regulations must be met, but sometimes supplemented with extra measures given in DK1. The strictest requirements given by different regulations must be followed. DK1 defines the documentation that the electricity company (in danish: virksomhed e.l.) must provide to the municipal emergency services. It also mentions that it may be relevant to develop a response action plan in cooperation with the emergency services. Such a plan would include information about contact persons from the company, who should assess the emergency services.

SE1 guidance assumes that the facility design complies with the existing laws and building regulations. Facility owner or holder (Anläggningsinnehavaren) is responsible for ensuring that electrical installations are safe. They must check if the person carrying out the electrical installation work is in Electrical Safety Authority’s register, continuously check the installations, determine routines and ongoing control, and act if deficiencies are discovered. The electrical installation company’s duty is to correctly execute the work.

NO1 document is a voluntary guideline that operated under "the Electricity Supervision Act". The installation should be reported to the local electricity grid company, municipality fire services and building authorities.

NL1 has safety regions (in dutch: veiligheidsregio), which is a public body that manages fires and disasters. Fire brigade is a part of the safety region and is responsible for preventing, limiting and combating fires and other accidents. It is the safety regions' responsibility to prepare for and organize responses and advise on environmental issues. To fulfill these tasks, they follow the NL1. It is the responsibility of the BESS installation manager (IM) to intervene remotely, initiate a shut down and call the fire brigade. It is the responsibility of IM to ensure access to the BESS site for the fire brigade and provide an updated emergency response plan. Contact details for IM, maintenance company, climate installation maintenance company and BESS manufacturer shall be provided in the emergency plan.

UK1 refers to ISO 45001 [24] for the framework of stakeholders, roles and responsibilities. It also shows illustrative relationship between different stakeholders and responsibilities for each lifecycle stage. The illustrative stakeholders include designer(s), installer(s), operator, asset owner, new investor / developer, regulator, assessor / insurer and fire services. Overall UK1 provides a detailed description of stakeholder relationships.

UK2 document, focusing on the conditions that the fire and rescue services are exposed to, requires certain information to be provided to the local fire and rescue services. The required information is listed, and includes but not limited to battery chemistry, battery cell form, site plan, evidence that site geography has been taken into consideration (e.g., prevailing wind conditions), details on fire resistance, fire suppression, and other systems, as well as site emergency plans. Site emergency plans include a risk management plan and emergency response plan.

BE1 is not very explicit on the responsibilities of parties involved. It only recommends that the BESS supplier and subsystem manufacturer provide operating and safety manuals to the owner, installer and operator.

DE1 states that the owner and builder is responsible that the project meets relevant building permit requirements and additional requirements that may arise from fire protection aspects that go beyond the building regulations. Involvement of relevant authorities and potentially also insurers is advised at the early stages of the project planning.

AU1 states that the CFA has statutory responsibilities for taking and enforcing all necessary steps for prevention and suppression of fires in country of Victoria, Australia. This included involvement of CFA during the stages of planning, design and operation of BESS system sites. The list of documentation that has to be provided to CFA includes (but not limited to): site address and plans, type and size of facility components, specification and data sheets of BESS. A planning permit application may be notified to CFA as a part of the application process, to give an opportunity to provide comments. Risk management, fire management and emergency plans are required. The document also specifies that minimum of 30 days before commissioning the BESS system, the Country Fire Authorities must be notified.

USA1 (NFPA 855) provides the most extensive description of liabilities and document circulation. The building owner has the liability for the safety. The main parties include building owner, Authority Having Jurisdiction (AHJ), Approved Testing Laboratory, system supplier and installer. Several documents must be provided to AHJ, including site location and layout diagram, details of fire resistance rated assemblies, quantities and types of BESS units etc. Fire and explosion tests shall be done by Approved Testing Laboratory and reported to AHJ. System supplier and installer shall provide operation and maintenance manuals, documentation of BESS size, contact information for a contracted service agency or responsible inhouse personnel, narrative of how BESS should be operated and service record log to the building owner.

Summary: Currently, the DK1 document provides very limited description of the involved parties, liabilities and the document circulation, primarily referencing to other documents, such as relevant building regulations and the Electrical Safety Act. It does define documentation that must be transferred from the owner to the municipal emergency services. Nevertheless, it does not specify how the owner should obtain the documentation (e.g., if there is any approval process for safety engineers, system suppliers, maintenance personnel, testing laboratories). The required information also does not include fire and explosion test data, hazard mitigation or risk analysis, commissioning and decommissioning plan, or a service record log. The most detailed description of relationships between the involved parties and document circulation is provided in UK and USA documentation.

3.2 Hazard mitigation

3.2.1 Risk analysis and management

DK1 and DK2 documents do not mention risk assessment.

SE1 requires risk assessment to be carried out, except for private buildings with BESS capacity under 600 kWh. The risk assessment should consider factors such as distance to other buildings, infrastructure, separate BESS units, thermal propagation, risk of explosion, emergency services' response time and capabilities, and extinguishment water management.

In NO1, a risk assessment is one of the documents included in the document package and it must be carried out before starting the work on the electrical installations.

In NL1, a risk approach is used in a systematic manner as the basis for documentation. Structured What-if Technique (SWIFT), a method that uses 'what if' questions to identify risks, and Hazards and Operability Study (HAZOP), a technique for identifying hazards and operability problems, are methods provided as examples. A qualitative approach is suggested, which divides the scenarios into low-, medium- and high-risk scenarios.

UK1 guideline suggests conducting risk assessment and analysis, and provides an example reference BS EN 62933 Part 5-2 [25]. Stakeholders should implement risk reduction measures if the risk is deemed intolerable. The guideline provides a list of hazards (including fire) and initiating events for risk assessment. The listed initiating events include (but not limited to): thermal runaway, overcharge, created buildup of internal pressure, external electrical short circuit, inadequate management or the operational environment, emergency service inability to respond effectively etc.

UK2 states that National Fire Chiefs Council in UK expects comprehensive risk management process, including identification of hazards and implantation, maintenance and review of risk controls. A risk management plan should be developed by the operator and Site-Specific Risk Information should be made available to the crews.

BE1 identifies the risk analysis as one of the tools for mitigating potential negative consequences. It gives both the relevant guidelines and the scenario examples (cause and effect). The nature of the risks is divided into electrical, chemical, thermal, explosive, mechanical and specific conditions that increase risk to the stakeholders (e.g., potential inability to recognize the presence of BESS system). However, the assessment of probability or frequency is not addressed for risk ranking.

DE1 relies heavily on risk analysis to minimize risks and define appropriate protection measures. Building regulations, occupational health and safety laws, environmental protection, and insurer and operator interests should be considered in this work. It provides a list of relevant standards and guidelines describing functional safety of different parts of BESS infrastructure. Nevertheless, it also mentions that the current standards describing risk analysis are not mandatory. A qualitative approach is suggested in the document by using a decision tree that includes the extent of the potential damage due to failure (S), frequency of failure mode (F) and possibility to avoid the hazard (P). Two grades are suggested for each of the above-mentioned parameters, e.g., S1 means low damage/severity and S2 means serious damage/severity. Combining these parameters in a decision tree results in five fire risk levels (very low, low, medium, high, very high).

According to AU1, BESS systems require risk assessment and risk management plan. It defines a fire risk management process, which includes risk identification, risk analysis, risk treatment/control, monitoring, reviewing, recording and reporting. Specific examples of hazards related to BESS systems are listed and include (but not limited to) electrical hazards (e.g., overcharging, lightning), chemical hazards (e.g. due to spills and leaks), explosion hazards and fire spread.

In USA1, Hazard Mitigation Assessment (HMA) is required (i) if technology is not covered by the standard UL9540; (ii) if more than one technology is present in one area with risk of fire; (iii) if the capacities are over the value stated in the document in non-dedicated buildings; (iv) if hazard is not addressed in NFPA855 etc. HMA should evaluate thermal runaway, mechanical failure risks, battery management system and protection system risks.

Summary: The Danish guideline does not require risk assessment or hazard mitigation analysis, unlike several other countries that have adopted this approach. The Danish guidance presents some pre-accepted solutions in which no further documentation is required. If these pre-accepted solutions are exceeded, then risk assessment or hazard mitigation analysis can be used . The most detailed descriptions are provided in guidelines of the Netherlands, Belgium and Germany. These guidelines primarily focus on establishing the scenarios and implementing preventive measures. Although general recommendations are provided, the quantification of risk and hazard mitigation analysis is a limiting *factor. Qualitative approaches are suggested at best. One of the main limitations is quantification of risk scenario frequencies or probabilities. Moreover, the guidelines do not advise on how to quantify the consequences of the selected scenarios when developing the risk analysis.*

3.2.2 Thermal runaway control

DK1 discusses the definition, causes and potential consequences of the thermal runaway. It mentions that more stable electrolytes are investigated to limit the potential hazards due to the thermal runaway. It recommends the use of toxic gas detectors for signaling cell venting. Nevertheless, it does not provide any specific recommendations at the module or system level. DK2 states that the connections and control systems should be done according to manufacturer's instructions and recommends that systems from different manufacturers are not interconnected.

According to SE1, verification of system design against thermal runway and fire can be tested according to different standards, such as IEC62619 or UL 9540A.

UK1 states the thermal runaway as the key failure mode for BESS systems that can result in fire, explosion and release of toxic gases. Some cause scenarios listed are physical damage, misuse, ageing, and inappropriate temperature conditions. It is stated that these hazards pose serious risks in the vicinity of the BESS and therefore the site location is an important aspect to consider during the design and planning stage. It is also stated that the lithium iron phosphate (LFP) batteries have a lower thermal runaway probability compared to the NMC batteries. BMS is proposed as a system to detect and therefore mitigate the thermal runaway related risks.

UK2 requires an effective method for early detection of faults, e.g. BMS or specific electrolyte vapor detection system. Early alert system for emergency services is required for the detection of thermal runaway conditions.

BE1 states the thermal runaway as one of the failure modes for BESS systems. The guideline provides examples of thermal runaway risk mitigation measures, e.g. controlling the climatic condition the BESS is exposed to, regulating the charging process, and equipping the BESS system with devices designed to prevent the propagation of thermal runaway. It also mentions that cooling the surrounding infrastructure may be the only viable response option if the system goes into thermal runaway. Additionally, after the incident, moving the damaged battery can trigger a new, delayed thermal runaway reaction.

DE1 states that the batteries should be designed in a way that thermal runaway does not lead to external flaming and also provides references to associated relevant safety guidelines and standards.

AU1 recommends that the BESS systems are equipped with BMS for monitoring the state of the batteries during the operation.

USA1 states that energy storage management system (ESMS) or BMS shall be provided for monitoring operating conditions and maintaining voltages, currents, and temperatures within the manufacturer's specifications, unless modified in accordance with Chapters 9 through 13. The ESMS or BMS shall electrically isolate the BESS or affected components of the BESS or place the system in a safe condition if potentially hazardous conditions are detected.

USA2 lists thermal runaway as one of the main hazards in BESS systems. The BMS system is required, and the manufacturer should verify the applicability of the system for the intended use. A list of specific safety functions is included in the document at cell level, rack level and supervisor level.

Summary: According to DK1 guideline, thermal runaway is recognized as one of the main risks associated with BESS. Nevertheless, it does not explicitly provide prevention or hazard mitigation measures apart from the requirement for toxic gas detectors. Most of the other reviewed documents stated the need to have BMS that is used to monitor potential faults and engage in case of failure as well as monitoring and controlling the operational limits.

3.2.3 Mechanical impact risk management

DK1 states that the batteries should be handled correctly to prevent dropping, crushing, or breaking, however it does not provide specific preventive measures or rules for avoiding mechanical impact hazards.

DK2 also recognizes physical and mechanical impact as a risk that can lead to thermal runaway. It recommends arranging the batteries to reduce the risk of mechanical impact by placing them away from areas with vehicles or people, although no strict rules are provided.

SE1 states that the risk of mechanical impact should be taken into consideration and an example of falling ice from wind turbine blades is given.

NO1 acknowledges the mechanical damage as one reason for a thermal event and recommends designing protective enclosure around the battery system.

In NL1, mechanical and physical impact to the batteries is recognized as one of the risks, and several mitigation measures are suggested: placement on a stable surface, regulated container stacking, limiting vehicle speed near BESS, constructing shields for collision protection, ensuring installed BESS is out of reach from cranes and other lifting equipment, or providing physical protection against falling objects.

UK1 mentioned mechanical damage as one of the initiating events of fire hazard. Accidental, intentional and natural phenomena creating damage should be considered. No further specification on the reduction of this risk is given.

BE1 recognizes mechanical impact and potential perforation of the cell as one of the failure modes and scenarios. It states that the BESS facilities must be designed to ensure impact protection and avoid any mechanical damage to the containers and enclosures. However, no specific design requirements are provided.

AU1 states that the BESS systems should be regularly inspected for any signs of mechanical damage. The neighborhood BESS should be provided with protection from potential mechanical damage.

USA1 states that BESS should be in areas protected from physical damage.

Summary: In general, mechanical impact is recognized as one of the risks associated with BESS systems. In Danish guidelines no specific preventive measures are mentioned. As the first step a checklist of *potential sources of mechanical impact could be provided, based on other guidelines. This could include collision from vehicles, fall due to the mishandling of the lifting equipment, falling ice, tress etc.).*

3.2.4 Fire and explosion testing

DK1 does not mention fire or explosion testing. DK2, however, includes recommendations stating that if it can be documented that a certain battery chemistry has low consequences in the event of fire, the potential battery capacity limits can be increased. No specific test standards are mentioned.

In SE1, the suggested test standards for thermal propagation and fire are IEC 62619 [26] and UL9540A.

NO1 recommends choosing batteries with good documentation of safety testing from a recognized supplier.

NL1 states that the housing of Energy Storage System must be made of fire class A building material, with few exceptions if the fire propagation test is passed according to NEN-EN-IEC 62933-5-2 [27] or UL9540A.

UK1 mentions UL9540A standard for relevant procedures to ensure the robustness of installation. However, it is also stated that the stakeholders should not fully rely on test compliance alone and must ensure that the specifically designed system matches the test conditions.

UK2 requires that any testing of the proposed system be detailed, with UL9540A provided as a reference.

BE1 does not explicitly mention fire and explosion testing, however, UL 9540A standard is included in the list of technical standards within the document.

AU1 states that in absence of specific Australian standards UL 9540A (along with NFPA 855, UL 9540 and FM Global property Loss Prevention Data Sheet 5-33) should be used.

USA1 refers to UL 9540A or equivalent test methods for battery testing. The testing should be conducted or witnessed and reported by an approved testing laboratory. The test will characterize gas composition and fire propagation between the units in representative end-use arrangements. If BESS cabinets are a part of the design, the tests will also evaluate deflagration mitigation measures. The test report will be supplemented by an additional interpretation report prepared by a registered design professional.

USA2 requires the use of equipment, materials and services that are approved by FM Global.

Summary: The Danish guidelines do not specify any fire or explosion tests that must be conducted on batteries as part of a BESS system. In contrast, some other countries have such requirements, with UL9540A frequently mentioned as the preferred testing standard.

3.3 Passive fire protection

3.3.1 Outdoor installations

Passive fire protection is often ensured by means of separation distances between a potential hazard (e.g., BESS) and areas of interest such as buildings, roads, ventilation intakes, evacuation paths etc., or between potential hazards (between BESS cabinets or containers). The separation distances are summarized next for all the reviewed documents.

According to DK1, if the batteries (new batteries and end of life batteries) are stored in containers, then a minimum separation distance of 5 m should be ensured to the neighborhood boundaries, roads, paths etc. When the end-of-life batteries are stored in quarantine areas, or in the case of BESS with capacities larger than 2000 kWh, then this separation distance increases to 10 m.

The separation distances mentioned in DK2 are dependent on the capacity of the batteries, SOC, and type of storage (in a container or not). The longest mentioned separation distance is 5 m, nevertheless, this can be reduced to 0 m in certain cases. Usually, the following factors influence the values of the separation distance, such as fire resistance and the surface classification of the building's façade, the existence of ventilation intakes from buildings, the possibility of intervention, and the division of batteries units and the separation distance between them within the system.

The recommendations in SE1 specify that the separation distances should be established based on risk analysis, especially due to explosion risks. However, if no risk analysis is performed, a minimum separation distance of 8 m is specified for the AK2 (BESS in apartment buildings or commercial properties) and AK3 (BESS in industrial and energy production facilities) categories, in accordance with Swedish building regulations. Only those systems that are tested and approved for use in Swedish climate, are allowed to be placed outdoors.

In NL1, the separation distances depend on the type of the categories (6 categories are defined in section *1.7.3.*), accessibility of the emergency services, the fire resistance of the encapsulation or surrounding structures, flammable objects, boundary of certain locations, separation distance to sideways and ventilation intakes. These separation distances can vary, but the maximum mentioned separation distance is 10 m. The separation distance referred to the sum of clusters on the vertical and horizontal direction is also mentioned for some situations.

The separation distances for outdoor installations mentioned in UK1 are mainly referred to those presented in USA1 and USA2. More specifically, the required standard separation distance presented in USA1 is minimum 3 m, nevertheless, this can be reduced to 1 m if a large-scale fire test and the use of non-combustible walls or containers with 2-hour fire resistance are fulfilled, according to the mentioned standards. According to USA2, the separation distance is differentiated depending on the battery chemistry, i.e., a minimum separation distance of 1.5 m or 4 m (2.4 m if the containers have a min 1-hour rating) to sides that contain access panels. Additionally, doors or deflagration vents are recommended for

LFP and NMC battery chemistries, respectively. In UK1 it is mentioned that the guidance on appropriate separation distances between BESS containers is provided in UK2.

In UK2, a minimum spacing of 6 m between BESS units is suggested, though reduced distances are allowed if supported by documentation. For the distance from BESS units to occupied buildings and site boundaries, a minimum distance of 25 m is proposed prior to any mitigation measures, such as blast walls, are implemented (reduction of distances is possible in areas of lower-risk, such as rural settings). Additionally, areas within 10 m of BESS units should be cleared of combustible vegetation or any other vegetation.

BE1 has a section that describes the appropriate locations of BESS. In general, separation distances between BESS and other enclosures, delimitation of the site, other buildings on the site, vegetation, should be equal or larger to the distance to which the thermal radiation from BESS cannot ignite other elements of the site. The fire separation distance should be at least 10 m, and the fire barriers must be constructed with non-combustible materials.

A separation distance of 5 to 10 m from other objects is specified to be safe in DE1. Other values must be determined on a case-by-case basis.

In AU1, the Country Fire Authority, CFA expects a Fire Safety Study (i.e., risk assessment) to be performed by a specialist for BESS where guidelines requirements are proposed to be reduced. A Fire Safety Study is also required when BESS is to be placed in residential areas within 50 m to a building. When a BESS is located in an industrial area, it is recommended to place containers, enclosures, or cabinets outdoors. The separation distance from outdoor BESS units in an industrial setting should be at least 10 meters, or sufficient to prevent radiant heat from a fully involved battery container in a fire from igniting a building, and vice versa.

In the USA1, the placement of the BESS is dependent on the location of the installation (i.e., remote locations, locations near exposures, specific outdoor locations such as rooftops, open car parks, or mobile BESS installations), existence of fire barriers, the fire resistance of the walls or compartment, the existence of the lot lines, public ways, buildings, stored combustible materials, hazardous materials, electric grid hazards, the existence of the combustible vegetation, or the fire and explosion testing. Therefore, these separation distances vary between 0.9 m and 3 m. The recommended maximum stored energy is 600 kWh for locations near exposures, garages, rooftops, and for mobile BESS. The limit for the exterior wall is 20 kWh. It is recommended that the groups of 50 kWh should be spaced with distance of 0.9 m between each other.

According to USA2, the space separation between BESS enclosures and adjacent buildings or critical site utilities or equipment are stated in the FM Global Data Sheet 1-20 [28]. This separation distance depends on factors such as the wall fire rating, hazard category, building occupancy (exposure heights), and whether the wall is combustible or not. These separation distances can vary between 1.5 m and 40

m. The separation distance between adjacent BESS enclosures is recommended to be 6 m if the walls are noncombustible. For non-combustible walls, these distances should be established according to Data Sheet 1-20. If separation distance between BESS enclosures is less than 6 m, a thermal barrier rated of minimum 1h is required on the inside and outside of the enclosure.

Summary: In Denmark, the separation distances (from BESS to buildings, roads etc.) vary between 0 to 10 m. The separation distances proposed in DK2 are one of the most detailed ones. The separation distances proposed in the other evaluated countries are mainly governed by the national regulations, resulting in various proposals. There are certain similarities between the countries, but it is not always easy to compare them or understand the reason behind these choices. Additionally, requirements for passive protection of the surroundings also depend on the national regulations.

3.3.2 Indoor installations

According to DK1, only capacities up to 2000 kWh are to be placed in buildings. A separation distance of a minimum of 2.5 m to neighboring boundaries, roads, paths is mentioned.

In DK2, the fire resistance of the compartment and the one of the facades, the separation distance to combustible materials, and the placement of the BESS vary depending on the stored capacities, the SOC, and whether the batteries are new or already connected. The minimum recommended fire resistance of the compartment (i.e., (R)EI) is 60 min, while the maximum is 120 min. The recommended reaction to fire of materials is A2-s1,d0, according to EN 13501-1 [9]. The placement of the BESS is recommended to be on the ground level or in a basement with ramp access. It is recommended to clear all combustible materials in distances to at least 5 m around the batteries. The batteries should be divided in groups of 50 kWh with 1 m between each other (similar to USA1 recommendations).

SE1 recommendations are dependent on the application category (AK) and are more general, lacking precise specifications. Nevertheless, depending on the AK, factors such as the presence of sleeping people, the presence of free and loose combustible materials in its vicinity, the designated separate fire cells, placement near the escape routes, and risk analysis are recommended to be considered. Similar to DK2, it is advised to place the installations on the ground floor for easier access.

NO1 is only applicable to installations with capacities under 15 kWh. The placement of such installations is recommended to be in a separate building (e.g., garage, storage), with no sleeping spaces/rooms and free of loose combustible materials in the vicinity. A 30 min fire resistance of the compartment is recommended. The parameters such as: the placement of the escape routes or sleeping people areas, non-combustible support for the installation, existence of flammable materials between the batteries and the roof, mechanical damage, opening of ventilations, protection against shorth circuit, possibility to carry maintenance, service and supervision, should all be considered when deciding the location of the installation.

NL1 gives recommendations based on the type of installations (6 types defined), including cause and consequence scenarios, goals and measures for each type of installation. Therefore, the fire resistance of the compartments can vary from 30 to 120 min. The fire class of the building materials can be A, or B.

The penetration seals should also be fire resistant. For a specific scenario, a maximum capacity of 100 MWh is recommended in buildings, divided into units of 600 kWh with separation of 1 m between each other. Regarding the separation distances from escape routes and façade opening, values of 3 m or 10 m are specified, depending on the location and capacity of the BESS.

No recommendations regarding the indoor installations are given in UK1, UK2 and BE1.

According to DE1, if a BESS is located inside a building, the requirements depend on whether the room or enclosure is classified as a "room with explosion or increased fire risk". If it is, then fire resistant partition walls in solid construction with fire-retardant, tight and self-closing enclosures are required as a minimum. Otherwise, the partition walls should have the fire resistance of the load-bearing and stiffening components of the floor. It is also mentioned, without specific details, that for capacities of and above 1000 kWh, special construction requirements may be required. If BESS are to be installed in garages, they must be separated from the rest of the garage space in a fireproof manner. These recommendations are very general and lack specific details.

AU1 recommends using a separated fire compartment, according to the National Construction Code. No other items should be placed in the room, and batteries should be located away from the electrical installations.

The recommendations from USA1 are given for the following placements of the BESS: dedicated use buildings, non-dedicated use buildings, and open parking garages. If BESS is placed in dedicated buildings, then 2 h fire barriers are required, but no requirements for the maximum stored energy. And if approved by the authorities and building is 30.5 m away from other buildings, lot lines, public ways, stored combustible materials, hazardous materials, and other exposure hazards associated with electrical grid infrastructure, then the requirements about fire control and suppression, size and separation can be omitted. When stored in non-dedicated buildings, the maximum allowed stored energy is 600 kWh. Higher capacities are allowed only if authorities approve it, and a fire and explosion test is performed. BESS should be housed in a non-combustible space and should not be installed in sleeping rooms or spaces opening directly into sleeping rooms and living areas. In general, no combustible materials should be stored in the vicinity of BESS. The combustible materials related to BESS should be stored within 0.9 m from BESS equipment. When placed in open parking garages, various values for separation distances to be kept are mentioned, depending on the location of the inlet for buildings HVAC systems, exits, outdoor enclosure fence of BESS, and separation distances to other important places (e.g., buildings, lot lines, hazardous materials, etc.). These separation distances can vary between 0.9 m to 15.3 m. USA1 has a separate chapter on BESS installed in one- and two-family dwellings and townhouse units. The requirements apply for batteries with a minimum capacity of 1 kWh and maximum of 40 or 80 kWh, depending on the placement (e.g., basement, attached or detached garages, outdoor wall mounted, outdoor ground mounted). BESS should not be installed in sleeping rooms, or in closets or spaces opening directly into sleeping rooms. When installed outdoors on exterior walls or on the ground, the location of the BESS should be at a minimum of 1 m from doors and windows directly entering the dwelling unit. Individual BESS units shall be separated from each other by a minimum distance of 1 m.

According to USA2, any prefabricated container or enclosure that is larger than 46.5 m^2 should be treated as a building. The dedicated BESS building should be made of noncombustible materials and the minimum separation between dedicated BESS buildings and other facility buildings, or critical site utilities or equipment should be established according to Data Sheet 1-20 using hazard category 3. The damage-limiting construction should be established according to Data Sheet 1-44 [30], using propane as representative gas. For BESS cutoff rooms, where multiple racks are installed in a single row or back-to-back, solid, noncombustible fire barriers between adjacent racks should be installed. The fire barriers should extend 0.3 m from the face of the rack and the separation distance between them will depend on how many racks can be protected by the available water supply. For back-to-back racks, a solid metal partition should be installed. The cutoff rooms should have a minimum 1 h fire rated floor, walls and ceiling, and the fire doors, fire barriers for all floors, ceiling and wall penetrations should be FM approved. A minimum separation distance of 1.8 m should be provided from noncombustible materials, construction elements, between aisle faces of adjacent racks, or 2.7 m for combustible construction elements respectively.

Summary: The most common similarity between the recommendations in the various countries is the maximum stored capacity of 600 kWh, the division into groups of 50 kWh with 1 m distance between them. Similarly to section 3.3.1, the national standards have an influence on the requirements presented in this section.

According to DK2, NO1 and USA1, there are clear requirements for lower capacities (e.g., under 15 kWh in NO1). For example, in DK1, a 60 min fire resistant compartment is required for batteries with capacities under 50 kWh, while a 30 min fire resistance compartment for batteries with capacities under 15 kWh is required according to NO1. Therefore, there might be a need to communicate these requirements more clearly to the public.

Although the separation distances are based on the national regulations, it is unclear whether these are sufficient when explosions are likely to occur. Therefore, more work is needed to properly establish the safe distances.

3.4 Active fire and explosion protection

Active fire and explosion protection BESS guidelines vary widely across different countries but share the fundamental goal of ensuring safety. This chapter explores these variations for detection, explosion prevention and suppression.

3.4.1 Detection

DK1 guideline does not provide information on when detection should be installed, recommending making decisions based on the size of a storage room and quantities of batteries stored. The recommendation is to use automatic fire alarm for large storage of different types of new batteries. For large storage of used batteries, especially if charging is ongoing, detection should also be installed. DK1 is based on DK2 and it therefore gives recommendation to base detection on CO, NO_2 and HCl sensors, the gases that first reach Immediately Dangerous to Life or Health (IDLH) values according to [31]. Detection at the floor level is recommended. If it is not possible to detect the above-mentioned gases, an optical detector should be used. Detection shall be designed to trigger ventilation and send signals to first responders and service providers.

DK2 recommends optical smoke detectors placed below and at the ceiling level due to smoke stratification. Automatic fire alarm connected to the fire department and triggering ventilation is recommended for BESS in containers outdoors with capacities under 600 kWh and for storage of batteries in containers outdoors for capacities under 1.200 kWh SOC 100 % or under 2.400 kWh SOC 30 %. For used batteries fire alarm is recommended for non-damaged batteries in total capacity over 600 kWh in buildings in containers outdoors. When it comes to damaged batteries in quarantine container the fire alarm is recommended if quantities exceed 200 kWh.

SE1 recommends combining smoke detection, gas detection, and temperature monitoring. Flame detection as the sole measure is not recommended. Gas detection shall be done using H_2, CO and/or CO_2 sensors for early detection of thermal runaway gas. A gas detector shall be connected to ventilation system and triggered at 25% lower flammability limit (LFL) [11]. For AK1, interconnected fire alarm is recommended as the best practice, whereas, for AK2, having a fire alarm in and around BESS space is a guideline to ensure safe evacuation and alarm firefighters and control room. As best practice, fire detection and evacuation alarm are recommended.

NO1 recommends the use of Norwegian technical building regulation requirements for smoke detection and alarm, connected in series with other detectors in the building. In addition to the smoke alarm, a CO detector is recommended. An alarm should send a signal to the owner's telephone, alarm company, fire department or service of the facility. NO1 mentions BMS, but no recommendation is made to use it for detection purposes.

For BESS with capacities over 100 kWh, NL1 recommends using CO sensor (in range of 0-200 ppm) that is cross-sensitive to H_2. The installed detector shall follow the manufacturers' guidelines for the number of detectors to be installed and their location. For redundancy, the number of detectors may need to be doubled. Other detectors can be used if they show themselves to be effective in early detection of thermal runaway. If required, continuous monitoring of system alarms, signals of overcharging or deep discharge, temperature levels, gas release during fire can be performed.

For 1 MW BESS and larger, UK1 recommends using Battery Management System (BMS) to detect fire, thermal runaway, cell venting or leakage early on. In addition, separate smoke detectors, heat sensors and off-gas detection are recommended. A separate more detailed guideline requires immediate battery disconnection upon detection [19] and fire services to be alerted. Detection systems should respond to other possible fires (e.g., electric) that can occur in the compartment. The recommendation is to monitor H_2, CO, volatile organic compounds (VOC) continuously and upon detection of flammable gas shut down BESS and switch on ventilation system.

UK 2 mentions the use of an effective BMS and/or specific electrolyte vapor detection system. If thermal runaway is detected, then there should be the facility for the early alerting of the emergency services. If the fire is caused by other means than thermal runaway (e.g., electrical wiring), a detection system should be in place for alerting the fire. Continuous combustible gas monitoring within units should be provided and the location should depend on the type of detected gas (e.g., H_2, CO, VOC). Gas detectors should alarm at the presence of flammable gas, shut down the BESS, and cause the switchover to full exhaust of the ventilation system.

BE1 does not give any details on what detection system can be used in BESS, besides mentioning that BESS should have an integrated detection and extinguishing system. And if such a system is missing, then details on detection must be given in the risk management plan.

DE1 guideline recommends two detection options: local automatic fire alarm or an automatic alarm to a remote location where people are permanently present. DE1 acknowledges that fires in electrical system are amongst the most common fire causes. If a fire is caused by an internal battery fault, the plastic housing is heated and smoke is released, which is hard to detect in presence of air conditioning system. Therefore, the recommendations for actions upon fire detection in DE1 include system emergency shut down and activation of automatic extinguishing system. DE1 shows that detection system choice depends on many parameters (e.g., air flow, openings, type of battery and gas released etc.), thus proof of suitability of detection system must be provided for each separate project.

Outdoor BESS according to AU1, shall be equipped with systems to detect smoke, heat, fire, and toxic off-gassing within battery containers. These detection systems shall be designed to trigger from a single event and shall be capable of detecting both lighter and heavier than air gases, providing early warnings via BMS. Indoor BESS units shall be in rooms with a detector linked to the fire indicator panel. If feasible, detection alarms shall be directly monitored by the fire brigade to ensure an immediate response.

According to USA1, BESS are required to have smoke or radiant energy sensing systems compliant with NFPA 72 [32], along with backup power. Storage facilities need a fire alarm system triggered by an advanced smoke detection system with an occupant alert, installed according to NFPA 72 guideline. Additionally, a BMS is needed for monitoring operational conditions.

USA2 suggests using either cell temperature or off-gas detection (VOCs) of gases that precede thermal runaway. Such sensors can be installed for each rack and for the room/enclosure with at least one reference detector in an open area to prevent false alarms. The early detection shall be controlled by BMS to electrically insulate a failed cell upon detection, which is only effective in case of electrical abuse. The guideline warns that this strategy won’t be effective in case of thermal or mechanical abuse.

A summary of the recommendations regarding detection provided in the reviewed documents is presented in Table 3.

Table 3. Summary of the recommendations regarding detection provided in the reviewed guidelines.

Regulation	Recommendation regarding detection
DK1	CO, NO_2 and HCl
DK2	Optical smoke detector (high/low) CO, NO_2 and HCl Thresholds given
SE1	smoke detection, gas detection (H_2, CO and/or CO_2), and temperature.

	25% LEL triggering ventilation
NO1	Smoke detection with CO sensor
UK1	BMS H_2, CO and VOC. Connect and trigger ventilation
BE1	No details
DE1	No details
AU1	BMS Detecting all: smoke, heat and toxic gas high/low No details
USA1	Smoke or radiating heat Smoke detection NFPA 72 BMS
USA2	BMS Temperature and VOC

Summary: There is no agreement on the type of sensors for early detection. Although DK1, DK2, SE1, NO1 and UK1, all mention CO as a gas of choice, other suggested detection gases vary and include NO_2, HCL, H_2, CO_2, VOC. Six of the reviewed guidelines do not provide specific recommendations for gas sensors. Most countries (DK2, SE1, NO1, AU1, USA1) agree on the need to use a smoke detector. Several guidelines mention that gas detection needs to be done both at high and low levels due to the smoke behavior during a battery fire. Utilizing the existing BMS system to detect thermal runaway and support automated responses is a clear advantage, as several countries (UK1, AU1, USA1, USA2) have already noted.

3.4.2 Explosion prevention

Ventilation is one of the explosion prevention measures typically triggered by detection. A review in section 3.4.1 showed that SE1 and UK1 explicitly mention the need to ventilate the battery off-gas once detected.

DK1 suggests basing the decision for ventilation depending on the size of the battery storage area, volume of stored batteries, and if the location of the building or room allows for venting towards outside. If new batteries are stored together with other combustible materials, guidelines such as the DEMA's Guideline No. 17 [27] on natural fire ventilation and smoke venting in buildings should be consulted. Additionally, DK1 guideline suggests that managing explosion risk for larger BESS should involve placing them outdoors. Organizations applying for permissions to install BESS are tasked with evaluating explosion risks and determining whether ventilation or other measures are necessary. Aimed primarily at first responders, this guideline also details procedures for safely handling BESS containers, including ventilation and gas venting.

DK2 is the only document that provides detailed capacity thresholds for ventilation installation. For indoor BESS installations over 600 kWh, DK2 recommends installing ventilation. Ventilation is advised as well for outdoor BESS in containers. When it comes to battery storage, ventilation is recommended if the storage capacity is over 1200 kWh at 100% SOC or over 2400 kWh at 50% SOC. When storing batteries in containers, outdoors ventilation is required for capacities under 1200 kWh at 100% SOC or under 2400 kWh at 30% SOC. Ventilation is recommended for used batteries storage as well, the requirements for which depend on their capacity, volume or weight, and their location.

Fire gas ventilation is recommended for SE1 categories AK2 and AK3. The ventilation shall allow the venting of fire gas without the need to enter the compartment. The best practice is to ensure the possibility to activate gas ventilation from a safe distance. SE1 distinguishes between a guideline and a best practice, the latter being a recommendation for further reduction of explosion risk. As a best practice for AK1, ventilation can be used to reduce explosion risk, and the battery off-gas should be vented outside. For AK2 types of BESS, explosion preventive ventilation and negative pressure in the battery compartment are included in the guideline. As a best practice, a spark-resistant fan and an explosion relief system are recommended. AK3 spaces are recommended to be well-ventilated by design and equipped with pressure relief panels.

NO1 recommends good ventilation connected to the outside considering battery venting opening direction, which should respond to temperature changes in BESS. It is recommended that air intake be at the floor level and outflow at the ceiling. NO1 provides concrete recommendations on ACH (air changes per hour) based on floor area and battery capacity.

As a minimum explosion safety requirement in NL1 for BESS, pressure relief is necessary. In the event of gas detection, the ventilation must be capable of providing a high exhaust rate. If the suppression system is activated, the ventilation system must shut down. The fire department must have access to control the emergency ventilation.

In UK1 and UK2 BESS must be equipped with venting and explosion protection, activated at 25% LEL. The vented flames and materials should be discharged to a safe location to avoid being the cause of fire spread. If emergency ventilation is used, the firefighters should be informed to make sure the function is not de-energized during the fire event.

BE1 states that adequate ventilation shall be provided with no further details given.

DE1 states that pressure relief devices are needed to sustain the integrity of a room and that openings should lead directly outside.

In AU1, BESS must be equipped with explosion prevention through sensing and venting, or explosion mitigation via deflagration panels. Additionally, measures must be taken to prevent embers from wildfires penetrating battery containers or enclosures. Explosion ventilation should be designed according to battery manufacturer instructions or relevant standards.

According to USA1, a hazard analysis performed by a registered safety design professional must be submitted to the AHJ, assessing the risk explosion. According to USA1, if such a risk exists, explosion protection must be installed.

USA2 recommends an alarm triggered by detection of hydrogen at 10% LEL that would trigger electric insulation of BESS and start emergency exhaust ventilation. The suction should be located at or near the ceiling and exhaust should lead directly outdoors, away from doors, inlets or other openings. The emergency ventilation shall increase the rate to 0.75 $m^3/min/m^2$. The ductwork for ventilation shall be made from non-combustible materials. USA2 recommends installment of access panels, doors or deflagration panels, although mentioning two most common chemistries (LFP, NMC) and distinguishing them with different separation distances.

Summary: Ventilation is suggested as a main explosion prevention measure when activated early or as means to ventilate the fire gas and prevent deflagration, flashover or flashfire when opening a fire compartment. Most reviewed guidelines do not provide specific recommendations on when ventilation must be considered. DK1 is the only guide that provides the BESS capacity limits on when ventilation shall be installed. On the other hand, when it comes to safe fire gas ventilation, this is considered only in SE1. It is therefore of high importance to understand the background of DK1 recommendations and whether these shall become a guideline. As for other explosion mitigation measures, such as deflagration panels, there is a lack of guidance in the Danish guidelines when this measure is to be considered, and which standard shall be followed to design the panels.

3.4.3 Suppression

DK1 guideline considers possibilities of other materials stored near batteries and recommends suitable manual suppression measures to be provided to deal with initial fire. Further on, it distinguishes between suppression systems for new and used batteries in buildings and containers. When it comes to batteries placed in containers, no suppression system is needed if containers are following safe distances between each other and other buildings. If due to the size of the BESS, suppression is needed, it can be solved by water hose connection DS 752 to the container at height of 0.5-1 m that can be activated from safe distance.

DK2 underlines the importance of early activation of suppression system to control the spread of the fire and reduce the consequences. The recommendation is to install a sprinkler system for BESS in buildings and battery storage in buildings for total capacities of 50 kWh and higher.

SE1 acknowledges the importance of design and testing of suppression systems with BESS installations and provides extensive review of other guidelines on suppression systems use for BESS. In AK2 risk assessment is recommended for decision on any system installation, nevertheless if applicable water management can be used as best practice. On AK3 level the system can be equipped with fire hose connection or dry pipe system, taking into consideration the damage that it can do to the untouched cells and the need for water management.

NO1 and BE1 do not cover suppression measures.

In NL1 it is recommended to equip BESS with a water hose connection in capacity of 1000 l/min at 0.5-1 m height and connection meeting fire brigade requirements. If such a water hose connection is supplied, the container shall be able to withstand the max hydrostatic pressure that can act upon it. NL1 allows an alternative fire suppression system to prevent propagation of fire, designed and tested by manufacturers.

UK1 considers suppression at both module and site level, with approaches depending on other mitigation measures (passive fire protection) and firefighting strategy. There is a number of possible solutions suggested, including water or aerosol-based systems using a separate guidance [19]. Water-based systems, according to UK1 are recommended over gaseous systems. If no suppression system is installed, this should be supported by risk analysis and Emergency Response Plan (ERP). Lack of water supply shall not be a base for suppression system choice.

UK2 mentions that the water-based suppression systems are more effective based on the current research, whilst gaseous suppression systems have been proposed previously. If in some cases the suppression system is not required by design, the choice should be supported by evidence. The choice of a suppression system and the calculations for the water supply should be made based on the identified risk, depending on the duration of its required activation and it should be evidence based. Water run-off and potential impact on the environment, along with mitigation measures, should be considered and detailed in the Emergency Response Plan.

According to DE1 high-pressure water mist or gas extinguishing system triggered by automatic smoke detectors are voluntary solutions. The choice of the system will depend on a fire scenario. DE1 identifies 4 scenarios that need to be considered when designing suppression systems or considering similar measures: fire from a battery cell, fire nearby battery cell, fire from secondary electronics and fire from outside the BESS. For example, if a fire starts from within a battery cell, the system must meet standard requirements of preventing the fire spread from the system by intrinsic design measures. Overall, DE1 underlines that burning battery cells cannot be extinguished, but the fire spread can be effectively prevented by suitable extinguishing system and quickly extinguish a fire from outside. If the battery contains an oxide cathode, the use of an aerosol extinguishing system is not allowed. To prove the effectiveness of the suppression system fire tests may be required, using scenarios from standards.

In AUS1 both fire suppression systems and firefighter water supply are mentioned as a part of risk management consideration. For firefighters, water supply detailed recommendations are made on identification of water points, water tank design, water tank refill, its location etc. No details are given about when suppression system is recommended to be used.

According to USA1, sprinkler systems are mandatory, with specific parameters: a minimum of 12 mm/min for units under 50 kWh covering 230 m^2, and for units over 50 kWh, densities based on fire testing per UL 9540A [10]. Alternative fire control and suppression systems are allowed but must comply with other NFPA standards. BESS in enclosed spaces or non-open rooftop or parking structures require automatic systems. Suppression can be omitted if tests confirm no risk to nearby vehicles or egress safety, upon AHJ approval, based on fire and explosion test results.

USA2 provides clear guidance on installment of automatic sprinklers (12 mm/min) with an additional allowance of 946 L/min for hose streams, designed for the room area, ensuring there is enough water supply for the design duration. The design will depend on the number of racks in a BESS space. If the water supply duration needed is greater than the available supply, it is recommended to install non-combustible partitions and solid metal barriers to prevent the fire spread. Gaseous suppression systems are not recommended.

Summary: Suppression system is used in BESS for the purpose of limiting fire spread, both from the battery system to surroundings and vice versa. Water may damage batteries that are still intact, therefore a clear guideline is needed for the use of suppression systems in BESS. Use of inert suppression systems in air-tight compartments does not provide cooling and in the past has led to severe consequences as it may lead to explosion hazard instead of a fire hazard [11].

DK2 lacks clear criteria for when firefighters should demand suppression systems. It's crucial to establish well-defined conditions for these demands to standardize safety measures and ensure consistency. One way to proceed could be to develop detailed criteria that guide the implementation of suppression systems based on risk assessment outcomes, the types of batteries (new vs. used), their capacities, and the materials stored nearby. The future guidance shall consider mandating standardized testing that systems need to undergo to ensure effectiveness for BESS settings. Additionally, guidance on inert gas and foam suppression systems use is needed.

3.5 Firefighting and water disposal

From a firefighting perspective, managing fires in BESS is a complex task. Recent incidents [33], [34] underscore the potential for injuries despite extensive precautions. Therefore, ensuring that facilities are readily accessible from public roads, having proper water connections, and detailed action plans are fundamental.

3.5.1 Emergency response

Under the DK1 guideline, facilities storing Lithium-ion batteries must ensure direct access from public roads and maintain unobstructed fire routes, including access roads and clear areas for emergency vehicle maneuvers. It is imperative that these routes remain free from obstructions, such as snow and ice. Safety signage must be displayed at entry points to areas containing battery storage. Battery storage should be on the ground floor, adjacent to an external wall to facilitate direct external access, enhancing firefighting efforts and emergency responses. Additionally, collaboration with emergency services is required to develop a detailed action plan that includes contact details and specific information about the battery storage and associated safety measures.

DK2 guideline gives no specific firefighting and emergency response measures. Upon arrival, it is critical that first responders are promptly informed when the fire involves Lithium-ion batteries, allowing them to adjust their response strategies accordingly.

In the SE1 guideline, the emergency response plan for facilities containing BESS should include critical information about the supply and handling of extinguishing water. Emergency action cards are an important component of fire safety measures for facilities with BESS. These cards must contain detailed information, including the location, size, cell chemistry, and emergency shutdown mechanisms of the BESS, as well as details on fire protection installations like fire gas ventilation and water sprinklers. It is also noted that these cards should be accessible at crucial points, such as next to the fire control panel or in a cabinet that can be unlocked with a fire brigade key. For enhanced fire response efficacy, these facilities should provide connections for fire hoses, preferably to a dry system that evenly distributes water over the battery storage to cool gases and prevent fire spread. Additionally, the room should be capable of withstanding high-water pressures and be watertight to contain firefighting efforts effectively.

NO1 guideline specifies essential measures for fire service facilitation in facilities housing BESS and solar panels. NO1 mandates clear and visible marking of buildings where batteries are stored. Critical signage includes warnings for batteries with voltages above 60 V DC as 'Dangerous voltage' and identification of all disconnect switches, as well as marking of distribution and connection cabinets receiving power from dual sources. Additionally, there should be explicit markings if solar cells are directly connected to the battery system. The full set of firefighting considerations is described in a separate comprehensive guideline on how to respond to battery fires in 'Risikovurdering og håndtering av brann i Litium-ion batterier,' [35], which provides in-depth risk evaluation and management strategies for firefighters addressing Lithium-ion battery fires, including the fires in BESS.

The NL1 guideline sets forth security and operational protocols for BESS facilities. The guide requires an emergency plan, detailing access routes for emergency services, contact information of relevant parties. Regular updates and tests of these emergency plans are obligatory every three years to ensure ongoing relevance and effectiveness. Safety signage indicating electrocution hazards and battery charging operations must be clearly visible, and any hybrid BESS systems must be distinctly labeled to show separate electrical and fuel or electrolyte compartments.

In UK1 Fire and Rescue Service shall be consulted at design and planning stage of BESS to understand the requirements and firefighting tactics. ERP should be provided by site operators to local fire services for approval including tactics, management of potential chemical release (smoke, water), access routes, cyber security. Additionally, risk management plan developed by the operator shall provide assessment of potential risks to emergency response team. UK1 includes electric shock in the list of hazards for risk assessment.

UK2 requires the owners to develop a robust emergency response plan. It should be based on the site-specific hazards and risks identified during the risk analysis. Emergency plans should also consider the potential impact of the water run-off to the environment; likely path of any vented gases or discharged materials; explosion/deflagration strategies; notification on the emergency ventilation power supply. Design for the site access should be developed together with fire and rescues services

Early on, when developing infrastructure on site, BE1 suggests considering safety of emergency responders. Meaning the location of BESS should be in vicinity of vehicle access and entrance to the site should not be aligned with prevailing wind direction. Water supply and firefighting water infrastructure shall be designed to allow adequate response to risks present in BESS. Firefighters may require water to cool the surrounding infrastructure to prevent the fire spread. Additionally, based on risk assessment outcome and local regulations, safety signage shall be provided. BE1 explicitly states electrical risks as BESS system specific risk. It should be considered as a permanent risk, including emergency and intervention for fire services. Related risks include electrocution, arc-flash and electromagnetic waves that can disrupt nearby electronic equipment. Residual voltage can be maintained inside the BESS system and pose a risk to firefighters.

DE1 underlines the importance of secure access to BESS for firefighting operations. The distances to firefighters' water connection points should be maintained according to German regulations. Proper signage on the wall near the entrance door shall be used to alarm firefighters of large-scale BESS and photovoltaic system. During a fire in BESS, flammable gas shall be vented as fast as possible to outside. The gas that is released should be quenched with water. The critical temperature of battery housing is 80 °C after which cooling may be required. Full-protective clothing with breathing apparatus is required when fighting the fire with thermal risk being higher than chemical. After the fire, the procedure should be followed as for hazard group GG II C. DE1 states that it can be assumed that hydrofluoric acid (HF) has chemically reacted with walls, concrete etc., thus acute HF risk is unlikely.

The AUS1 guideline emphasizes rigorous safety and emergency preparedness measures. These include displaying mandatory warning signs for electrical and high voltage hazards, which govern the grid connection of energy systems and electrical installations, respectively. Facilities must also provide contact details for the owners and specialist response personnel available 24/7 to support emergency responders. An extensive risk management plan is required, outlining access for firefighters, water supply provisions including the requirement for a 45000 L static water tank within 120 meters of each battery container if no hydrant is available. Additionally, the water tanks should be positioned away from prevailing wind directions.

USA1 requires clear signage at all entry points to identify the BESS type, associated hazards, and emergency contacts. BESS should be protected from physical impacts and installed considering local firefighting capabilities, with specific requirements for placement and height. Access roads and egress routes must meet local codes, ensuring safe separation distances. The guideline also specifies detailed emergency operation procedures, including system shutdown, regular inspections, and emergency responses, alongside required drills to maintain readiness. This ensures both facility safety and effective emergency responder coordination. Additionally, USA1 provides the information that firefighters should be aware of when responding to battery fires.

USA2 prescribes an ERP for safe BESS entry and emergency response. ERP includes guidance on how to manually disconnect the BESS, provides access routes, manual fire protection methods, manual smoke ventilation, and battery safety data sheets. The post-incident plan shall include removal and how potential re-ignition should be handled, and the equipment needed.

Summary: Most guidelines reviewed require accessible emergency routes, sufficient water supply, clear and informative signage, and detailed emergency planning. One of the important points raised in UK1 and BE1 guideline is involving firefighters in the development of emergency response plans at an early stage of a BESS project.

3.5.2 Extinguishing water management

DK1 does not mention extinguishing water management.

According to DK2, firefighting Lithium-ion battery fires demand substantial quantities of water. This extensive use of water can lead to contamination with HF, requiring that the water be treated as hazardous waste. To support effective and safe firefighting efforts, facilities must ensure an adequate water supply. Ideally, facilities should also be designed with recessed areas or containment basins where submerged batteries can safely complete combustion, minimizing environmental risk and facilitating controlled disposal of the contaminated water.

SE1 recommends considering handling of extinguishing water from fires involving BESS during the design and installation phases to prevent adverse environmental impacts. This consideration is crucial even for BESS facilities that do not employ a water-based extinguishing system, as emergency services are likely to use water in response to any fire incident. To make informed decisions, facilities must evaluate the environmental consequences of using water versus allowing the BESS to burn out, this should be a part of risk assessment process. The best practices for AK2 category are to plan collection and disposal of extinguishment water. For category AK3 handling of extinguishing water and nearby water protection is a minimum requirement.

NO1 guideline does not cover water management.

NL1 emergency plan shall include, amongst others, procedures for handling accidents, including electrolyte leaks and fire extinguishing water clean-up. No further details are given.

In UK1, water management is a part of ERP and requires not only a plan of contaminated run-off water management, but also assessment of smoke plume impact from a fire and drainage water management. The system for containing and managing water run-off should account for both suppression systems and firefighting activities. If BESS is in a flood zone, the proper protection and mitigation measures are required.

In UK2 the description of extinguishing water (water run-off) is that it could impact the environment and with mitigation measures, should be considered and detailed in the Emergency Response Plan.

BE1 recommends a fire water flow management system or a retention basin, including dikes, catch basins and/or purpose-built impermeable retention facilities. No further details are given in the guide.

DE1 acknowledges the need to manage large quantities of contaminated water after firefighting activities. Such measures shall be designed case-by-case according to the local water protection legislation and is a duty of BESS owner, installer and operator to collect the water and make sure the ground water is clean. Guideline DE1 provides a decision tree to assist water management design.

According to AU1 recommendation, the BESS shall be designed to contain and manage contaminated fire water. The Country Fire Authority (CFA) advises that such facilities install robust infrastructure, such as bunding, sumps, or specially designed, impervious retention facilities, to contain and manage potentially contaminated fire water. The recommended capacity for these containment systems should match that of the on-site fire protection system to ensure comprehensive management of all run-off water. Compliance with local legislation which addresses the storage and handling of class 9 dangerous goods is mandatory.

USA1 and USA2 do not cover water management.

Summary: The DK1 and DK2 currently lack concrete guidelines for management of extinguishing water from BESS fires. Guidelines like SE1, DE1, UK1 and AUS1 provide more details on how to prevent *environmental contamination through effective water management strategies. Several countries (SE1, DE1) mention that decisions on water management strategies should be taken based on risk assessment and such measures should be designed case-by-case. Only a few studies of run-off water contamination have been made so far, according to SE1. Therefore, there is a need for further studies and clear guidelines on handling of firefighting water associated with BESS fires.*

3.6 Lifecycle procedures

3.6.1 Commissioning

Neither DK1, DK2 nor SE1 address the commissioning procedures for BESS systems.

NO1 requires that the date of commissioning should be included in the information which is available near the BESS installation. Nevertheless, no detailed list of commissioning procedures is provided in the document.

NL1 documentation requires commissioning inspections prior starting to use the BESS system. During the commissioning inspection the correct functioning of all systems and protection measures should be assessed and confirmed. After installation of the mobile BESS, it must be checked for mechanical damage, and it should be made sure that the electrical connections are correctly set.

UK1 refers to the work by Sandia National Laboratories for the list of commissioning activities. This includes, but is not limited to, items, such as factory acceptance testing, site acceptance testing and robustness testing. The testing should be done by qualified personnel, and the importance of record keeping is stressed.

BE1 mentions that commissioning tests are operation during which risks may arise.

AU1 states the opportunity to request site visits from CFA's specialists to provide advice on risk management.

USA1 requires system commissioning before performing the final inspection and approval. A written commissioning plan should be prepared and a list of specific information to include in the plan is provided in paragraph 6.1.3 in the NFPA 855.

USA2 requires commissioning, which includes inspection of the battery system for indications of overheating, abnormal vibration and noise, or malfunction and infrared scanning.

Summary: Depending on the scope of the specific guidance, only some of the reviewed guidelines mention commissioning as a part of BESS lifecycle. Guidelines in Denmark is one of the examples where the commissioning is not addressed. Even those documents that mention commissioning often do not provide a checklist of specific activities required for the commissioning, not even a minimum program. Moreover, documents in general do not state the purpose of commissioning. UK guideline, with reference to work by Sandia National Laboratories, and USA1 are the better references that mention commissioning procedures.

3.6.2 Operation and training

According to DK1 an operation plan is one of the documents that should be provided by the system owner to the municipal emergency services. No further details or principles of operation are given.

NO1 states that the system's owner is entitled to documentation, which also includes operation and maintenance manuals. Operation and maintenance manuals should be hung up near the battery system.

NL1 requires that personnel have a sufficient expertise and have completed electrical engineering training and qualified as Professional (in dutch: Vakbekwaam Persoon VP). It provides references to additional regulations regarding the operation (e.g., NEN 4288:2020 [27]).

UK1 states the good practices which would ensure safe operation. This includes using personnel with expertise and using the system within its operational limits. Continuous monitoring of the system equipment and site security is advised. For safety reasons it is recommended to limit access to the site and to ensure cybersecurity provisions.

BE1 recommends that the BESS supplier and subsystem manufacturer provide operating and safety manuals to the owner, installer and operator. Manufacturers should also provide information on what expertise and qualifications are required for the personnel responsible for the safety systems. Periodic staff training is recommended and should include safety skills and training, including evacuation procedures and firefighting systems.

DE1 specifies the need to maintain certain environmental and temperature conditions, specified by the manufacturer during the operation of the BESS system. Operator or subcontractor is responsible for the safe operations on site, and it must be carried out in accordance with occupational health and safety regulations, operating instructions and the manufacturers documentation. Risk assessment is prepared to ensure safe operations. The preparation of risk assessment includes involvement from employees, safety officers, safety specialists, the company doctor and the works council.

AU1 used the fire management plan, developed by the facility owner in consultation with CFA, as a basis for the facility operation. The importance of vegetation management is highlighted as one of the priorities throughout the document to prevent the risks associated with bush and grass fires. During the operation, any short circuits, faults, temperature increases above normal, equipment failures with potential for ignition, off-gassing, smoke or fire must be immediately notified to the main emergency service number in Australia. Employers must provide training to their employees according to the Occupational health and Safety Act 2004 in Australia. A list of recommended information that must be provided to the employees is given in the document.

USA1 state that all BESS systems should be operated according to instructions and plans issued by the system manufacturer. System testing may be required occasionally, and it should be made possible to electronically access the testing records. It is also required to develop the operation and maintenance documentation with specific required information given in the NFPA 855. Regular training (at least once a year) of the personnel responsible for operation, maintenance, repair etc. activities is required.

USA2 provides specific parameters to monitor during the BESS operation. This includes room temperature, charging and discharging voltage and current, internal ohmic (resistance), capacity, SOC, state of health (SOH), alarm or fault log. The online conditioning monitoring system should also be able to transmit, analyze and make a summary of the data, generate alarms, have security and self-diagnostic capabilities. The personnel should receive training from the supplier/manufacturer of the BESS and additional training in accordance to specified data sheet (Data Sheet 10-8, Operators [36]). It is not permitted to store combustible materials in BESS enclosures, buildings, or cutoff rooms.

Summary: Most of the reviewed guidelines (including Danish guidelines) only state that the operation of the system is required following the manufacturer's instructions or manuals. Personnel operating the system should have specific qualifications or expertise and periodic training is required according to many of the reviewed guidelines. Some guidelines also list specific parameters that must be monitored during the operation and requirement for an immediate notification of failures with a potential for leading to fire are required in Australia. Compared to the Danish guidelines, some other countries are more specific about the periodicity of personnel training.

3.6.3 Regular inspections and maintenance

DK1 states that the municipal emergency services must carry out fire inspections in case of larger storages of Lithium-ion BESS. It refers to the Emergency Management Agency's documentation and requirements for the fire inspections. Furthermore, it is stated that BESS must be inspected also according to the suppliers' guidelines and done so by qualified person with knowledge in BESS. Self-monitoring of the fire safety measures must be carried out on a regular basis by the owner. DK1 includes the maintenance plan in the list of minimum documents that needs to be submitted by the system owner to the municipal emergency services, in case of BESS with total capacity above 2000 kWh. It also included maintenance of fire safety installations. DK2 document, on the other hand, address neither inspection nor maintenance.

SE1 defines that the facility owner is responsible for ensuring the safety of the systems. It also includes regular checks of the system and defining ongoing control procedures. Electrical installation company duty is to follow up with the owners self-monitoring program. In addition, SE1 explicitly mentions regular tests of the communicating smoke alarms to make sure they work according to the function. Facilities owners' self-monitoring program is required to make sure that the fixed electrical installations are safe.

NO1 states that the maintenance can only be performed by professionals. Instructions describing maintenance procedures, frequency and equipment must be written. System manufacturer documentation should specify what is required from the system owner. The system owner is responsible for maintaining the system and ensuring the availability of documentation which also includes operation and maintenance manuals.

NL1 includes inspection during the operation as one of the security level measures. Inspections should be carried out by a certified inspection body. Inspections should be done periodically, at least annually, and include energy carriers, containers, and associated systems (e.g., filters, pressure relief devices), climate and heating systems, fire extinguishing systems, inverters, and transformers. Both visual and operational checks are required, and it should be done by a competent person. The inspection body needs to reevaluate the UPD (which is a document basis for the design, implementation, management, and inspection of the fire management system) every 5 years. Seals and penetrations are checked at least annually and repaired if necessary. It is also required to annually inspect the related systems (e.g., solar power installations) that may cause risks to the BESS.

UK1 recommends expertise of personnel responsible for the operation and maintenance. The system conditions should be maintained within its operational limits. UK1 also mentions considerations related to possible system changes, unplanned modifications and ongoing improvements, for which the principles of design and operation should remain the same as for new systems.

UK2 requires maintaining the site in a way to reduce risks of fire propagation, which includes that combustibles are not stored adjacent to units and the access is clear. Any combustible vegetation should be cleared in areas closer than 10 m from the BESS. Other vegetation should be maintained in a way to limit the potential fire spread. Wildfire risks should be considered.

BE1 states that good maintenance of the premises and installations is one of the most important measures for fire prevention.

AU1 requires developing inspection and maintenance procedures that include schedule and personnel accountabilities. Routine testing and servicing are required for BESS, BMS and other safety and fire protection systems according to the manufacturer's instructions. The inspection included regular monthly checks for mechanical damage and accumulation of combustibles. Maintenance activities should be completed before the Fire Danger Period, related to periodical increase in the wildfire risks. The BESS systems are regularly inspected for mechanical damage and accumulation of combustible materials in and within 10 m of BESS system infrastructure. Neighborhood batteries are inspected regularly, testing and servicing as required by regulation and the manufacturers guidelines. Inspection should also follow significant weather events.

According to USA1, BESS is required to be maintained according to the system manufacturer's instructions. It is also required to conduct system testing following the manufacturers provided operation documentation. Regular training (at least once a year) of the personnel responsible for operation, maintenance, repair etc. activities is required.

USA2 requires developing the maintenance program. Specific activities for maintenance of BMS are listed in the document that include periodic system self-test, pack switch maintenance, heating, ventilation, and air conditioning (HVAC) maintenance, periodic check of spare battery modules and periodic tracking of state of health (SOH). Moreover, the document provides a list of specific activities to include in the established battery replacement program.

Summary: Periodic inspections are required by most of the investigated standards. The responsibility of the maintenance falls on the system owner and it should be done following the system manufacturers instructions and/or national guidelines. At least annual inspections are required according to some guidelines e.g., in Netherlands. A self-monitoring program is also required in several countries. Danish *guidelines address the inspections and the need for a maintenance plan, although more specific details could be provided (minimum periodicity and minimum list of inspection items).*

3.6.4 Decommissioning procedures and disposal

DK1 does not mention decommissioning and disposal procedures. It does, nevertheless, provide guidance for the storage of end-of-life Lithium-ion batteries, including preventive measures for fire risks. It is acknowledged that the end-of-life batteries pose higher risks compared to new batteries.

SE1 only mentioned that risk analysis is recommended for managing any damaged batteries after the fire. No detailed instructions are provided.

In NO1, the risk analysis is required for the dismantling process. Certified personnel are required for dismantling the system and local recycling companies are advised to be contacted. NO1 also provides a short discussion on operational time for the batteries. Damaged batteries require following separate guidelines for transportation and treatment.

NL1 states that system manufacturer or supplier must provide instructions on dealing with potentially damaged batteries, including storage and safe disposal. NL1 also states that the modules that have undergone thermal runaway should be removed in less than 24 hours after it has reached stability. Decommissioning and disposal require a plan, which is established together with relevant authorities. BESS should be disposed of as quickly as possible.

UK1 mentions considerations during the decommissioning, which includes risks associated with the removal from the grid and possible lifetime extension through replacement of outdated system parts. Regarding the disposal UK1 refers to The Waste Batteries and Accumulators Regulations 2009 according to which the Lithium-ion cells must be transported for recycling by an approved operator. The Lithium-ion cell distributors should be contacted before the disposal to assess their procedures for taking back and recycling the used battery cells – this should be done free of charge when requested by the end user.

AU1 requires providing a decommissioning plan if BESS becomes inoperable or unsafe before its end of life.

USA 1 requires system owners to prepare a written decommissioning plan, which shall be submitted to the AHJ. The USA1 document also lists specific information to be included in the decommissioning plan, including means and methods, responsibilities, detailed descriptions of activities etc. The system owner is responsible for the decommissioning, notifying the AHJ prior to the beginning of the work. The owner shall also prepare the decommissioning report.

Summary: Danish guidelines lack decommissioning procedures but provide storage guidance for end-of-life Lithium-ion batteries. In general, other guidelines emphasize the need for detailed decommissioning plans, risk analysis for managing damaged batteries, certified personnel for dismantling, and coordination with local recycling companies and authorities. USA guidelines are especially detailed about decommissioning.

3.7 Repurposing and refurnishing

3.7.1 Repurposed and refurbished batteries

DK1 limits the scope of the guidelines to large quantities of new, expired and second life batteries as well as BESS systems. Hence, it does not limit the guidelines to new batteries only, although repurposing is not explicitly mentioned in the document.

SE1 explicitly states that special requirements for second life batteries is outside the scope of the guideline.

NL1 addresses the reused energy carriers if the risks are comparable to new energy carriers. It discusses legal aspects of transfer of producer's responsibility - either the original manufacturer keeps the responsibility, or the responsibility is transferred to government recognized recycling company. The technical aspects include using the batteries within the parameters set by the original manufacturer and using the BMS system compared to the original BMS.

UK1 mentions considerations related to possible system changes, unplanned modifications and ongoing improvements, for which the principles of design and operation should remain the same as for new systems.

DE1 states that second life batteries should be considered in the risk assessment as they have a greater probability of being damaged compared to new batteries.

USA1 specifies that repurposed and refurbished batteries should fulfill technology specific safety compliance requirements. To repurpose the batteries previously used in another application, the system must be repurposed by a company that comply with UL 1974 [37].

USA2 recommends not to use refurbished or previously used BESS components.

Summary: Repurposing and re-furbishing of the battery cells for BESS application is seldom explicitly discussed in the reviewed guidelines. German guidelines explicitly state that there are additional associated risks with repurposed batteries compared to new ones. Some guidelines require achieving the same safety level compared to new batteries. The challenge on the legal aspects and liability is important to consider and is mentioned in guidelines of the Netherlands.

4. Case study

In this section two case studies where the department for fire consultancy at DBI provided consultancy on BESS design are presented. The first case study consisted of a BESS located in and old harbour, and the second case study consisted of a renovated BESS designed in a generator room of a decommissioned powerplant. Table 4 summarizes these two example projects for BESS system design.

The two presented case studies are outside the recommended limits by DK1, therefore these examples illustrate how these situations could be solved. Nevertheless, these solutions need to be approved and accepted by the local fire brigade, which can lead to a high variability in design and fire safety solutions. Table 4 also provides the closest recommendation that is given by the Danish guidelines.

In Table 4, the marked “Practical solution” corresponds to a solution developed by the DBI consultancy fire specialists. This solution provides a viable design based on the client´s specific needs. The “Guideline solution” (as marked in the table), corresponds to a solution that follows the DK1 Danish Guideline.

The table summarizes the location of the BESS system, the capacity of the system, the way the system was constructed, the firefighting strategies, the fire protection strategy, the detection and ventilation strategy, the purpose of the system, the authorities in charge and involved in the project, guidelines used for the project, and questions that were not properly answered by the current existing guidelines.

In situations when it is not possible to fit the guideline requirements with the client’s needs, the consultants may implement additional safety measures following the requirements of the fire brigade. The requirements of the fire brigade can vary depending on the region, thus it is important to develop guidelines for future, so the practice is more uniform across the country. An example of such situation is given in Table 4 for the case “Powerplant”. When it comes to the indoor placement of BESS, the current DK1 gives recommendations only for capacities under 2 MWh. Since the presented indoor example exceeds this limit, there were no clear recommendations for this case and the final design is agreed with the fire brigade.

Table 4. BESS projects designed by DBI fire consultancy and generic solutions.

Case studies	**Old harbor and industry**		**Powerplant**	
Project	**Practical solution**	**DK1 solution**	**Practical solution**	**DK1 solution**
Location	Outdoor	Outdoor	Indoor	Outdoor/Indoor
Capacity	15.736 MWh (client’s desired capacity)	< 2 MWh/container (1.9 MWh x 5 containers)	13 MWh (client’s desired capacity)	< 2 MWh/container
Chemistry	NMC and LFP	All type	LFP	All type
Placement	7 x 20f container • 1 container – 2.2 MWh NMC • 6 containers – 2.256 MWh LFP Placed at least 5 m away between each other or separated by EI 60 / A2, s1-d0 Inside the container, the batteries are placed one next to each other, with no separation distances (e.g., 1 m distance between 50 kWh) The closest building is situated at 21 m distance. No public roads are nearby	5 x 20f container Outdoor distances to another BESS ≤ 20 m and 10 m to property line or public road. Otherwise separated by EI 60 / A2, s1-d0	30 cabinets placed in one room 380 kWh for each cabinet For most of the cabinets there are no separation distances	5 x 20f container Outdoor distances to another building ≤ 10 m

Firefighting strategy	The fire fighters will not intervene, they will just make sure that the fire is contained within the grounds of the BESS.	The fire fighters will use their normal fire extinguishing strategy.	It is not clear, so far, they can use water.	The fire fighters will use their normal fire extinguishing strategy or demand a specific action plan for the system.
Fire protection strategy	NMC cabinet – there is a flooding system LFP cabinets – aerosol STAT X 60 E cartridges	No extra demand for any system/strategy other than the system required in the building code.	Sprinklers and ventilation in the room Individual cabinet is designed by the supplier (each cabinet has its own fire strategy – e.g., detection, ventilation, aerosol STAT X 60 E)	The fire brigade **can** demand other fire protection strategy.
Detection	NMC cabinet – CO sensor, smoke and temperature detection LFP cabinets – CO sensor, smoke and temperature detection Container – CO_2 sensor, smoke and heat detection.	None, besides the requirement from the building code.	Inside the building - Smoke and heat detector Each cabinet – heat and smoke detection.	The fire brigade **can** demand other detection types.
Ventilation	NMC cabinet – ventilation and cooling LFP cabinets - no ventilation (no intake or outtake of air), only internal cooling.	Smoke ventilation by the fire department, 0.5 % opening areal pr. m^2 by section areal. In building according to the building design (Industry, ABV).	Fire or smoke ventilation is considered (generic guidelines for all buildings are used, no specific info about batteries). No explosion ventilation.	Smoke ventilation by the fire department, 0.5 % opening areal pr. m^2 by section areal. The fire brigade **can** demand other types of ventilation.
Purpose	Connected to the 10 kV grid to stabilize the power grid	Irrelevant	Power supply for the island as a backup facility and stabilizer of the grid	Irrelevant
Authorities in charge and involved in the project	Owners (Electricity company) Field owners Commune Fire Brigades	Building/landowner	Owners (Electricity suppliers) Field owners Commune Fire Brigades	Building/landowner
Guidelines used for design	DEMA guidelines BR18 Kap 5. Kapitel 5 – Redningsberedskabets indsatsmuligheder [36]	Outside placement: DEMA guidelines Both: BR18 Kap 5. Kapitel 5 – Redningsberedskabets indsatsmuligheder	DEMA guidelines BR18 Kap 5. Kapitel 5 – Redningsberedskabets indsatsmuligheder	DEMA guidelines BR18 Kap 5. Kapitel 5 – Redningsberedskabets indsatsmuligheder Guidlines for specific installation.
Aspect during the project that the current guidelines could not answer:	Guidance on the layout of the field surrounding the container (e.g., parking for the fire brigade) Guidance on designing the ventilation strategy for different battery chemistry	Guidance on the fire class of the construction Guidance on what guidelines are to be used in the design	Guidance on safe distances between ventilation exhaust and the evacuation routes Guidance on the evacuation strategy of the nearby people Guidance on the fire extinguishing and ventilation	Guidance on the effect of the indoor placement of BESS, on the existing fire class of the building

	Guidance on the use of aerosols as an extinguishing tactic Guidance about the firefighting tactics Guidance on the water supply to the fire brigade (e.g., flow, location)			

Figure 1 and Figure 2 illustrate the difference in design according to practical solution and DK1 guideline solution, for the old harbor industry case.

Several differences between the practical solution and DK1 solution can be observed:

- The individual BESS container capacities used in the practical solution are slightly higher than the ones according to the DK1 guideline (2.256 kWh compared to 1.9 kWh).
- The distances between two containers in the practical solution are much smaller than the one required by the DK1 guideline solution (5 m most of the time, compared to 20 m).
- The distance from the BESS containers to the road in the practical solution is much smaller than the one recommended by the DK1 guideline (5.6 m compared to 10 m).
- The distance from the BESS containers and the property boundary is kept 10 m, as recommended in the DK1 solution.
- In the practical solution, a fence is considered, and several fire rated (both fire resistance and reaction to fire) separating elements are used in between the containers, which made it possible to reduce the recommended distances in the DK1 guideline. The fire stops are extended at least 0.5 m from the edges of the containers.

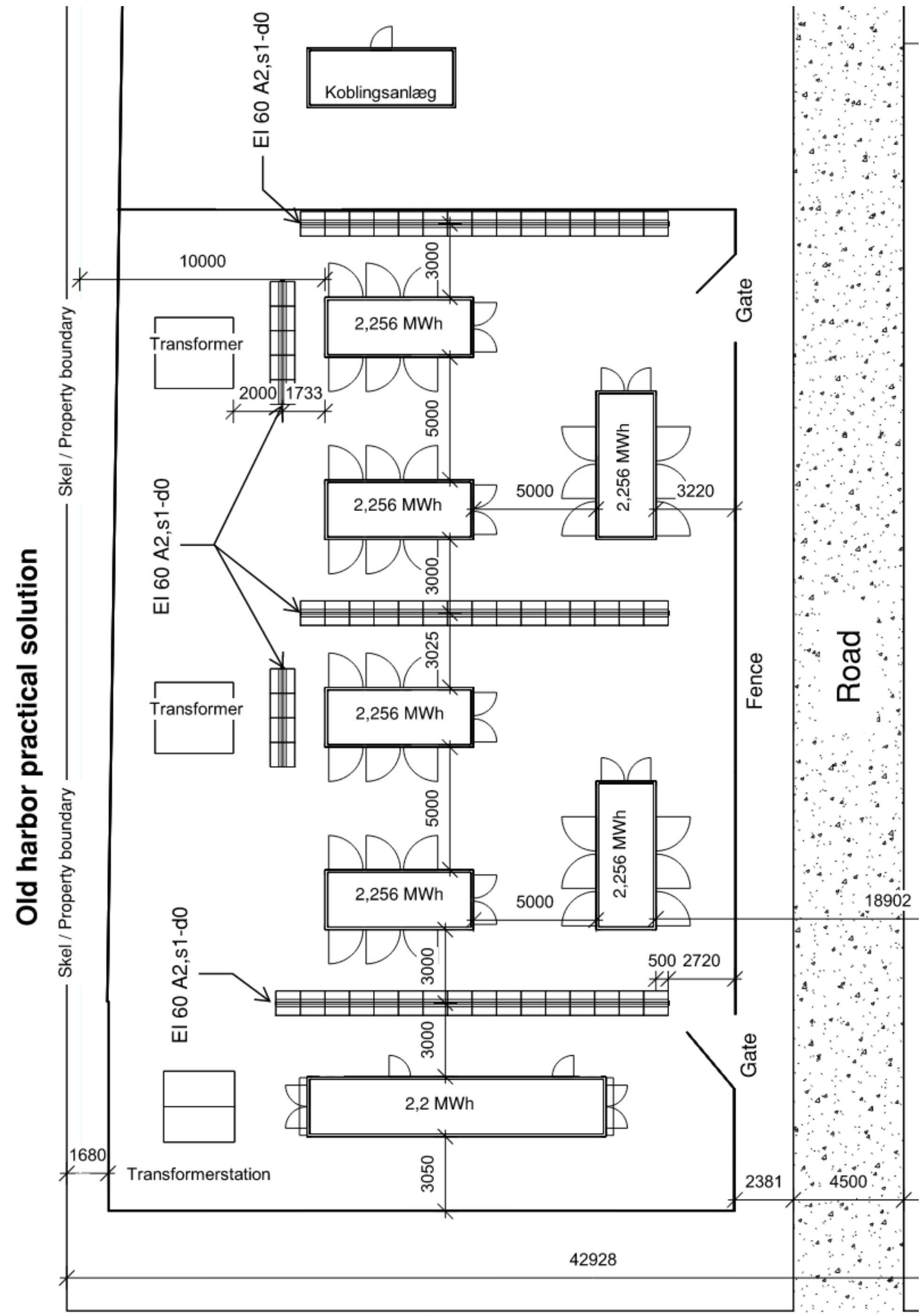

Figure 1. Illustration of the 'practical solution' for the old harbour case designed by DBI's fire consultancy following client requests and approved by the fire brigade.

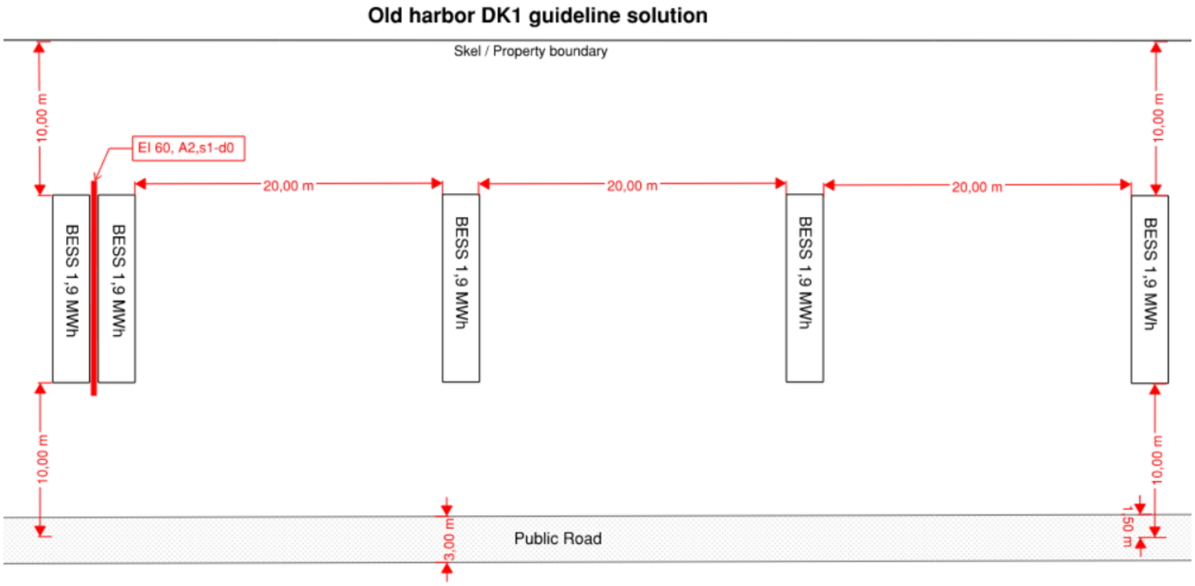

Figure 2. Illustration of the solution for the old harbour according to 'DK1 solution'.

The exact practical solution for the "powerplant" case cannot be shared due to confidentiality reasons. Nevertheless, Figure 3 illustrates a similar enough practical solution of the powerplant case. No solution according to the DK1 guideline is shown, since it is not recommended to place BESS with capacities over 2 MWh indoors.

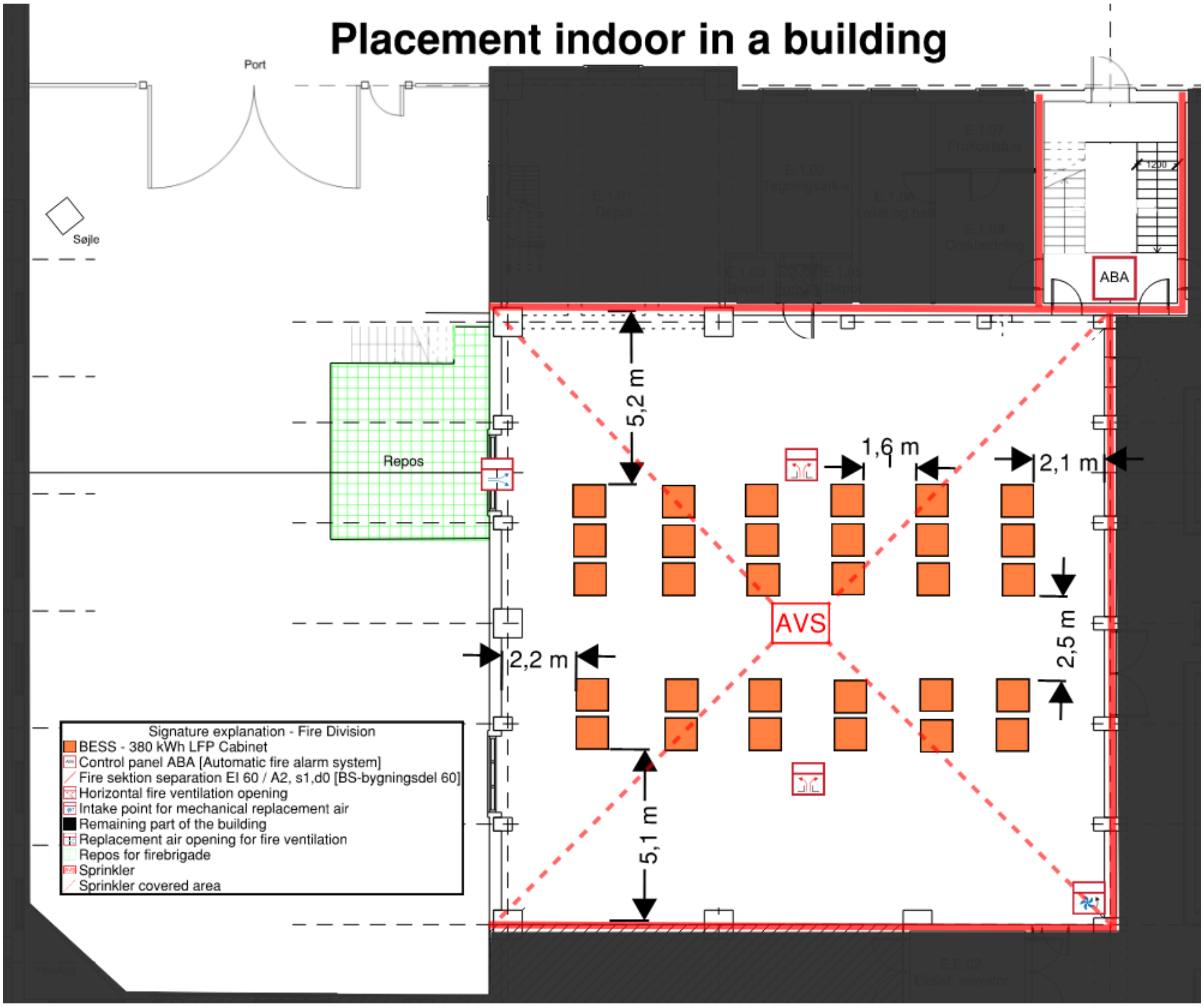

Figure 3. Illustration of the 'practical solution' for the powerplant case designed by DBI's fire consultancy following client requests and approved by the fire brigade.

5. Conclusions and recommendations

This report provides a review of the existing guidelines and recommendations for BESS for Denmark, Sweden, Norway, Netherlands, UK, Belgium, Germany, Australia and USA (Section 1.7 for the details).

One of the objectives of this document is to compare the guideline requirements when designing BESS systems in different countries. A specific focus here is placed on providing recommendations for updates of Danish guidelines. In parts, this review can also reveal some future research directions for supporting creation of future guideline requirements or easier implementation of already existing recommendations of the reviewed guidelines.

The **objectives** are summarized as follows, and addressed below in this section:

1. Summarizing the BESS fire and explosion safety related guidelines, requirements and recommendations in Denmark, Sweden, Norway, Netherlands, UK, Belgium, Germany, Australia and USA.
2. Identifying the gaps in the Danish guidelines and proposing recommendations for improvement.
3. Identifying research directions for validation or review of the recommendations.

5.1 Summary

Most of the reviewed documents in the European countries are guidelines (e.g., Denmark, Sweden, Norway). One exception is NL1 from Netherlands, where several sections are normative.

Table 5Table 5 provides an overview of the different fire safety aspects that have been covered in selected guidelines. The table presents a color-coded classification: green indicates the most explicit description of safety measures, yellow signifies partial mention of safety-related aspects, and red denotes that the aspect is not addressed in the guideline. The decided rank is based on the subjective interpretation of the guidelines by the authors of this report.

While the passive and active fire protection is described in most of the reviewed guidelines, the design and system documentation, the lifecycle procedures, repurposing and refurbishing aspects are mentioned only in some of the documents. Some hazard mitigation related aspects could also be improved in most of the revied documents, especially DK1, DK2, DE1 and BE1.

Table 5. Overview of addressed fire/explosion safety parameters/aspects in reviewed guidelines.

Group of interest	Parameters/aspects	DK1	DK2	SE1	NO1	NL1	UK1	UK2	BE1	DE1	AU1	USA1	USA2
Documentation aspects	Involved parties, liability and documentation circulation												
Hazzard mitigation	Risk analysis and management												
	Thermal runaway control												
	Mechanical impact risk management												
	Fire and explosion testing												
Passive fire protection	Outdoor installations												
	Indoor installations												
Active fire and explosion protection	Detection												
	Explosion prevention												
	Suppression												
Firefighting and water disposal	Emergency response												
	Extinguishing water management												
Lifecycle procedures	Commissioning												
	Operation and training												
	Regular inspections and maintenance												
	Decommissioning procedures and disposal												
Repurposing and refurbishing	Repurposed and re-furbishing batteries												

The general conclusions from the summary provided and this report and Table 5 are given below.

Hazard mitigation

- The most explicit descriptions of the risk assessment or hazard mitigation analysis are provided in the documents of Netherlands, Belgium and Germany. Although general recommendations are provided, qualitative approaches are suggested at best. This indicates a potential lack of data and methods for quantification of risk scenario frequencies, as well as methods for quantification of consequences.
- UL9540A stands out as the most often referred fire and explosion testing standard in the area of LIB and BESS.

Passive fire protection

- The national regulations are mainly defining required separation distances, passive fire protection along with the requirements regarding the fire resistance of the building's separating elements.
- In countries prone to wildland fires, such as Australia, additional requirements regarding placement in wildland urban interface (WUI) are defined.

Active fire protection

- There is no common agreement between the reviewed guidelines on what type of sensors should be used for early detection. Most countries agree that smoke detection, assisted by an additional gas detector, is needed. Several guidelines mention that gas detection needs to be done both at high and low levels due to the smoke behavior during a battery fire.
- Ventilation is suggested as the main explosion mitigation measure. However, most reviewed guidelines do not provide specific recommendations on the situation when ventilation should be installed.
- Most of the guidelines recommend the use of a water suppression system. Other types are also mentioned, though their efficiency should be tested.

Firefighting and water disposal

- Most of the documents mention the importance of detailed emergency planning and accessible and emergency routes, equipped with informative signage.
- SE1 is the document that describes the extinguishing water management the best.

Lifecycle procedures:

- Commissioning and decommissioning procedures are seldom mentioned in the guidelines reviewed.

Repurposing and refurbishing:

- This topic is only addressed by several of the guidelines, with more detailed descriptions in NL1, UK1 and USA1.

5.2 Gaps and recommendations in the Danish context

The reviewed Danish guidelines (DK1 and DK2) are either developed by or made as a supportive document to the Danish Emergency Management Agency (DEMA). It must be considered that these guidelines are created from the perspective and with those issues in mind that are in the direct jurisdiction of DEMA. Some of the reviewed aspects discussed in this document are not in the direct jurisdiction of DEMA and therefore are provided in the Danish guidelines to a lesser extent.

The identified gaps and the suggested recommendations in the Danish context are presented in Table 6. The recommendations given are based on the other guidelines reviewed in this report.

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Table 6. Summary of the identified gaps and proposed recommendations in the Danish context.

Parameters/aspects	DK1 & DK2	Recommendation
Documentation aspects – Involved parties, liability and documentation circulation	Danish guideline provides limited information on involved parties, liabilities, and documentation circulation, primarily referencing to other documents, such as Building Regulation and Electrical Safety Act. It lacks details on the documentation that needs to be circulated and the responsibilities of preparation of this documentation.	A clearer description of the BESS system documentation process is recommended, including approval process for safety engineers, system suppliers, maintenance personnel and testing laboratories. Responsibilities and interactions between different parties (owner, municipality, fire brigade, system supplier etc.) should be defined for each stage of the BESS life cycle.
Risk analysis and management	Unlike most of the other countries, the Danish guidelines does not require risk assessment or hazard mitigation analysis, which would allow more site-specific risk evaluation.	Risk assessment and hazard mitigation analysis could be used in situations where the expected design is outside the scope of the guidelines. Clear guidance on how to do the risk assessment should be provided.
Thermal runaway control	DK1 guideline recognizes thermal runaway as one of the main risks associated with BESS, without explicitly providing prevention or hazard mitigation measures, apart from the requirement for toxic gas detectors.	More details on provision of prevention or hazard mitigation measures for thermal runaway (apart from the requirement for toxic gas detectors) should be included.
Mechanical impact risk management	Mechanical impact is recognized as a risk in BESS systems, but Danish guideline does not mention specific preventive measures.	Specify preventive measures against the mechanical impact should be mentioned. As a first step, a minimum checklist of potential sources of mechanical impact should be provided, which may include collision from vehicles, fall due to the mishandling of the lifting equipment, falling ice etc. Recommendations to avoid the mechanical impact should also be presented.
Fire and explosion testing	The Danish guidelines do not specify fire or explosion tests for batteries in BESS systems. In contrast, other countries have such requirements, with UL 9540A often mentioned as the preferred testing standard. No standard method for BESS explosion testing was found.	It is recommended to refer to fire test standards used by other countries for approving the BESS systems in Denmark. References to relevant standards or methods on how to perform fire or explosion tests on batteries integrated in BESS are needed.
Passive fire protection in outdoor installations	Separation distances (from BESS to buildings, roads, etc.) in different guidelines ranges from 0 to 50 m and are determined based on risk assessment, fire resistance of nearby building elements, battery capacities, whether batteries are new, damaged or second life etc. Denmark has one of the most detailed guidance on separation distances, which can vary between 0 to 10 m.	Large variation in separation distances in different guidelines suggest lack of clarity in this area. It may especially be true in the context of potential explosions. Therefore, it is recommended to investigate the separation distances in the future, as suggested in Section 5.3.
Passive fire protection in indoor installations	Several reviewed guidelines include 600 kWh maximum capacity divided into 50 kWh groups with approx. 1 m separation, and	Large variation in separation distances and fire resistance of the surroundings in different guidelines suggest lack of clarity in this area.

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	specific fire resistance requirements. Overall, guidelines do not account for explosion hazard when estimating the distances for indoor BESS. Denmark has one of the most detailed guidance on separation distances.	It may especially be true in the context of potential explosions. Therefore, it is recommended to investigate the separation distances in the future, as suggested in Section 5.3.
Detection	DK1 guideline does not provide clear guidance on when detection should be installed, recommending making decisions based on the size of a storage room and quantities of batteries stored. DK1 is based on DK2 and it therefore gives recommendation to base detection on CO, NO_2 and HCl sensors. Detection at the floor level is recommended. Optical detector should also be used.	The current recommendations regarding the detection of fires need to be revisited and clarified to ensure they are applicable to BESS.
Explosion prevention	While ventilation is commonly recommended for explosion prevention, most guidelines lack specific recommendations on when to implement it. However, Danish guideline provides clear BESS capacity limits for ventilation. However, more guides on explosion prevention are given in Swedish and USA guidelines, including ventilation rates, safe ventilation for firefighting etc.	Guidance of when to design the mitigation measures or reference to relevant standards, such as deflagration panels, should be included.
Suppression	DK1 guideline recommends suitable manual suppression measures to be provided to deal with initial fire. No suppression system is needed if containers follow safe distances between each other and other buildings. If due to the size of the BESS, suppression is needed, it can be solved by water hose connection DS 752 to the container at height of 0.5-1 m that can be activated from safe distance. DK2 recommendation is to install a sprinkler system for BESS in buildings and battery storage in buildings for total capacities of 50 kWh and higher.	More clear guidance is needed regarding the suppression systems to be used, as well as protocols for assessing, handling, and disposing or recycling of batteries after an incident involving activated suppression systems. This should include details on water supply requirements for the fire brigade, such as needed flow, volume, location, collection, and treatment. It is recommended to develop detailed criteria that guide the implementation of suppression systems based on risk assessment outcomes, the types of batteries (new vs. used), their capacities, and the materials stored nearby. The future guidance shall consider mandating standardized testing that systems need to undergo to ensure effectiveness for BESS settings. Additionally, guidance on inert gas and foam suppression systems use is needed.
Emergency response	Most guidelines, including DK1, require accessible emergency routes, specific placement of BESS units (i.e. ground floor, specific proximity to external walls), sufficient water supply, clear signage. DK1 also requires developing a clear action plan	A new theme booklet [38] (released in December 2024) was published and targets the emergency response tactics. Note that this document was not reviewed in this work.

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	that includes specific details about the BESS system and emergency contacts.	
Extinguishing water management	DK1 does not discuss extinguishing water management, whereas its supportive DK2 recommends water containment basins. Nevertheless, it lacks concrete design parameters for managing extinguishing water.	Guidance on extinguishing water management as well as mitigation of other potential environmental contamination routes is needed.
Commissioning	Danish guidelines do not address BESS commissioning, while UK and USA1 guidelines, referencing Sandia National Laboratories, provide better commissioning procedures. Arguably there is still a lack of clearly stated commissioning purposes and strictly stated minimum checklist of specific activities required during the commissioning.	Guidance on the commissioning of the BESS is needed. The purpose of the commissioning should be clearly stated, and a checklist of specific activities required for the commissioning, including also a minimum program should be provided.
Operation and training	Most guidelines, including Danish ones, state only that BESS operation must follow the manufacturer's instructions, with personnel requiring qualifications and periodic training.	Regarding the operation and training, minimum requirements, should be provided by the Danish guidelines, of the system's parameters to be monitored during the operation as well as minimum periodicity and scope of training, which may further reduce risks associated with BESS systems during the operation.
Regular inspections and maintenance	Periodic inspection is required in most reviewed guidelines. Danish guidelines mention the need for inspections and a maintenance plan, but they do not provide specific details (on periodicity or minimum scope).	More specific details regarding the inspection and maintenance plan are needed, especially regarding the minimum periodicity and minimum list of inspection procedures. Self-monitoring program may be required.
Decommissioning procedures and disposal	Danish guidelines lack description of decommissioning procedures. Nevertheless, it does provide storage guidance for end-of-life LIBs. USA guidelines are especially detailed about decommissioning.	Guidance regarding the decommissioning procedures is needed, and these can emphasize the need for detailed decommissioning plans, risk analysis for managing damaged batteries, certified personnel for dismantling, and coordination with local recycling companies and authorities.
Repurposed and refurbishing batteries	Repurposing and refurbishing are out of scope of the Danish guidelines. Overall, there are very few guidelines on the use of repurposed and refurbished batteries in BESS. The Netherlands and USA are the only countries that discuss the topic. Germany underlines the need of risk assessment due to a higher failure probability.	Guidance on use of repurposed and refurbished batteries should be provided.

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5.3 Research directions

This section describes topics relevant to practical application in guidelines that were identified as needing future investigations.

Hazard mitigation

- Development of practical risk assessment tools and examples for fire and explosion hazards. This may require quantification of frequencies and validated tools for consequence analysis of selected scenarios.
- Development of modelling approaches and testing protocols to validate the design of the BESS system against thermal runaway propagation.
- Improving understanding of explosion conditions and hazards. This could include development of a repeatable and reproducible protocol for explosion testing. These protocols should prescribe the conditions in which the batteries are tested, the type and location of measurements that need to be done, along with the performance criteria.
- Studies of personal safety during the fire and explosion testing, taking into account different toxicological exposures coming from the battery fires compared to more traditional fires.

Passive fire protection

- Need to investigate the basis for the separation distances given in the guidelines and include considerations of explosion hazards.
- A determination of heat release rate from batteries and heat fluxes at various distances from batteries, with different chemistries and on various scales (cell, module, panel) is needed. This activity would provide additional basis for requirements for safety distances and fire resistance requirements of separating elements. It would also be important to include study hazards related to potential jet flames or flares.
- Understand the conditions in the case of external fires (e.g., heat flux, space configuration) around the BESS that could trigger the ignition of the battery casing the initiation of the thermal runaway.
- Fire hazards and explosion hazards can require conflicting passive mitigation measures. When a combination of both is required, a design strategy for these cases should be investigated.

Active fire and explosion protection

- More knowledge is needed regarding the type of sensors (e.g., gas sensors, smoke detectors, etc.) and placement of these sensors for early detection.
- The explosion mitigation measures should be further studied, to help select the optimal methods based on the BESS design.
- Fire hazards and explosion hazards can require conflicting active mitigation measures. When a combination of both is required, a design strategy for these cases should be investigated.

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- More studies are needed to understand the effects and the effectiveness of the existing suppression and extinguishing systems in real case scenarios. It should be also explored if different chemistries require different extinguishing and suppression methods.

Firefighting and water disposal

- More research is needed regarding the fire extinguishing and the ventilation strategies, especially when there is an explosion risk, with different battery chemistries, and placement near the evacuation routes.
- Research regarding the evacuation and emergency response of occupants in case of battery incident is needed.
- Determination of the environmental and human toxicity of battery fire effluents for assessing state of infrastructure after fire and safety of occupants and firefighters during operations is needed.

Repurposing and refurbishing

- Evaluation of hazards from second life LIB and proposing testing protocols for when used in BESS installations are needed, to be used as input for design or validation of fire safety strategy.

Disclaimer

This work was entirely performed by DBI - The Danish Institute of Fire and Security Technology, without inputs from other parties.

This work has considered selected guidelines and standards. However, a review of similar work described in scientific journals falls outside the scope of this project.

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