Case study of ventilation solutions and strategies for Li-ion battery rooms

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Abstract. Integrating renewable energy sources (RES) is crucial to achieve a carbon-neutral society. Using new or second-life Li-ion batteries (LIB) as energy storage is recognized as the most realistic solution to drive wider adoption and effective utilization of RES. However, the use of battery energy storage systems (BESS) inside buildings may bring significant potential risks, particularly in the case of fire. LIB fires develop differently than fires caused by other sources as they can undergo rapid thermal runaway releasing explosive and toxic gases and fumes. Furthermore, there is a lack of regulations and guidelines describing the requirements for establishing a battery room within or outside buildings. In this paper, results from an initial mapping of ventilation solutions and strategies for smoke extraction in battery rooms for BESS located in different buildings categories in Norway are presented. A case study involving six existing battery rooms has been performed to investigate design vulnerabilities and identify knowledge gaps with respect to ventilation and other active fire protection measures. Results from the mapping indicate large differences in the design of ventilation systems and strategies implemented in existing battery rooms.

1 Introduction

The construction sector, and buildings in particular, is recognized as a sector with large potential regarding energy efficiency [1]. To further enhance the energy performance of buildings and reduce emissions, integrating renewable energy sources (RES) close to and inside buildings is crucial [2]. Photovoltaic installation on buildings is one strategy to produce electricity locally. In Norway, the Green Transition in the construction sector and rapidly growing electricity prices has led to an increase in photovoltaic installations from almost 0 MW in 2017 to 170 MW in 2023 [3]. The building applied and integrated solar power production has led to a market demand for solutions for local storage of the produced electricity.

Using new or second-life Li-ion batteries (LIB) as energy storage in buildings is recognized as a solution to drive wider adoption and effective utilization of RES [4]. However, in Norway there are no specific requirements in the building code on the design of battery rooms, neither for related technical systems such as ventilation [5]. The building code includes a general performance-based requirement for technical systems that is also valid for Battery Energy Storage Systems (BESS). The requirement states that “the installation shall have no negative impact on the fire safety nor explosion safety of the building.”

Uniform national and international standards on battery room design and risk assessments for fire safety are also lacking [6–9]. One example is that the normative standard NFPA 855 [10] does not require mechanical ventilation of all types of battery rooms, such as required in the NEK 400 [6]. The NFPA standard requires mechanical ventilation if the BESS storage capacity exceeds 600 kWh [10].

The requirement for ventilation of battery rooms in normal operation is due to gases being released from the battery cells during charging and discharging [6,11,12].

Lithium-ion battery (LIB) fires differ from other fires due to their potential for thermal runaway, releasing explosive and toxic gases. Consequently, specific ventilation requirements are essential for battery rooms during overheating or fire [13–15].

Internal short circuits, chemical malfunctions, or Battery Management System (BMS) failures can ignite LIBs. The risk of internal fire initiation in virgin battery cells is approximately one in 10 million [16,17]. External factors like mechanical damage, overcharging, and fire exposure can also trigger LIB fires [16,17]. In the context of ventilation, indoor air quality, and energy use, understanding fire exposure is crucial for designing systems that can withstand or mitigate the effects of fire on indoor environments.

Despite the low fire risk, the consequences can be severe [11,17–19]. During charging and thermal reactions, gases form within battery cells. The hydrocarbon-based electrolyte is flammable. Gas buildup inside the cell/battery cabinet or infiltration into the room can occur [20,21]. Ignition resembles a hydrocarbon fire with rapid growth and jet flames. LIB fires exhibit thermal runaway, becoming self-sustaining at around 200°C. Toxic gaseous products include Hydrofluoric Acid, Carbon Dioxide, Carbon Monoxide,

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Hydrogen, methane, ethane, benzene, and other inert and toxic gases [20,21].Venting gases is crucial to prevent ignition, while ensuring occupant safety and minimizing fire effects indoors [22,23].

Active fire suppression systems will cool down the battery, but as battery cells are encapsulated, water may not reach the fire source [9,11,18].

Several fire incidents with casualties due to ignition of released gases from LIB fires are documented [24–26]. The risks related to toxicity and explosion hazards have been the basis for Norwegian guidelines for firefighters dealing with LIB fires [27]. These guidelines specify recommendations for control of smoke and fumes, safe evacuation of people, and gas measurements in closed battery rooms before entering. DNV's [9] experimental and numerical study of explosion risks related NMC (Nickel Manganese Cobalt) and LFP (Lithium Iron Phosphate) batteries is relevant for building integrated BESS. The experiments showed substantial amounts of explosive gasses also present before the onset of thermal runaway. A key finding in the study is the need for exhaust ventilation of explosive gasses. The ventilation rates should be set based on the BESS's storage capacity and the room size.

This study explores ventilation system design practices for LIB BESS installations in Norway. It maps the design and fire safety measures of six battery storage rooms in the country.

2 Methods

Case study methodology was selected due to insufficient fire and incident statistics in battery rooms. It enables in-depth analysis of specific buildings through design documents, interviews, and site inspections. Given the absence of Norwegian regulations for fire safety in battery rooms, investigating case buildings and design documents is a suitable approach to assess the need for clearer requirements.

2.1 Site inspections of case buildings

Experts in building technology and fire safety, along with the building owner's representatives, conducted site visits for six Norwegian BESS-installed buildings. Inspections systematically recorded fire protection measures, materials, ventilation systems, detection, and extinguishing in battery rooms. Details like battery capacity (MWh) and chemistry, location, and floor count were documented. Pictures were also used as documentation.

2.2 Design survey

A survey was performed in each building and involved reviewing building documentation, emphasizing fire safety measures, risk assessments and interdisciplinary interfaces. Interviews with building representatives assessed their familiarity with active and passive fire safety measures. The survey information, site inspections, and interviews were compared with scientific literature, standards, and recommendations.

2.3 Layout and description of technical installations in the battery rooms

An overview of the different active fire safety measures present in the case buildings is given in Table 2 at the end of this section. A design survey was used to review the technical specifications and fire safety measures installed in the battery rooms.

Surveyed buildings were: two schools, a portable container, a kindergarten, an office building, and a public building, all with BESS installations from 2019-2023. Details on storage capacity, chemistry, location, and floors are provided in Table 1. Table 2 outlines active fire safety measures in the buildings. Recordings of the technical installations included:

- Ventilation solutions (dedicated or common)
- Ventilation strategies (Shut-off or exhaust)
- Extraction location (floor, mid-, or ceiling level)
- Explosion mitigation measures (pressure relief panels or deflagration vents)
- ATEX-certified electrical equipment present
- Detection and alarm systems
- Fire suppression system

Table *1*. Key information from mapping of case buildings.

Case building	**Storage capacity [kWh]**	**Battery chemistry**	**Battery room location**	**No. floors**
School 1	150	2nd life (LMO)[1)]	Separate building	1
Public building	109	2nd life (LMO)[1)]	Base-ment level	3
School 2	450	2nd life (LMO)[1)]	Base-ment level	4
Container (portable)	378	New (NMC)[2)]	Separate container	1
Office building	150	2nd life (LMO)[1)]	Base-ment level	7
Kinder-garten	41	New (NMC)[2)]	First floor	2

[1)] LMO = Lithium Manganese Oxide
[2)] NMC = Nickel Manganese Cobalt

2.3.1 School 1

The battery room is constructed as a separate building and situated on the parking lot outside the school building. The building has walls and roof of concrete, measuring approximately 10 m^2 in floor area, with a room height of approximately 2.4 meters at the highest point (mono-pitch sloped roof). The room has mechanical ventilation with extraction ducts in the ceiling. In addition, it is equipped with deflagration venting as shown in Fig 1. The deflagration vent is located at the upper part of the facade, above the heating/cooling pump.

Fig.1. Right: Deflagration vent, inside battery room., Left: Deflagration vent, outside view, shown with red arrow.

2.3.2 *Public building*

The battery room is located on the basement level of the building beneath and on the side of public areas. The room is a refurbished uninterrupted power supply (UPS) room with concrete construction and steel-sheeted roof. The floor area is approximately 6 m^2, with an average room height of approximately 2.4 meters (sloped roof design). The room and ventilation extraction ducts are shown in Fig 2.

The ventilation ducts from the battery room are located on the side wall and connected to the main return air of the central ventilation (balanced mechanical ventilation) covering the basement area of the building, see Fig 3.

Fig. 2. Ventilation system, inside view. Air supply and extraction ducts shown with red circle.

Fig. 3. Ventilation ducts, outside battery room, connected to main ventilation system. Air supply and extraction ducts from battery room marked with red arrow.

2.3.3 School 2

The building was renovated in 2022 and the battery room was established in a technical room in the basement. The construction consists of concrete roof and floor, and partly concrete and gypsum walls. Floor area measuring approximately 10 m^2, with a room height of approximately 2.4 meter. A mechanical ventilation system is installed. The supply air is shared with the rest of the building, but the extraction duct is separate. One extraction duct is located at floor level and two extraction ducts at ceiling height, see Figure 4. Fire dampers installed indicate that the ventilation strategy during fire is « shut down », which implies that the ventilation system will be shut off and fire dampers seal off the battery room. Other active fire safety measures installed are sprinkler system, and fire and smoke detectors located at ceiling level.

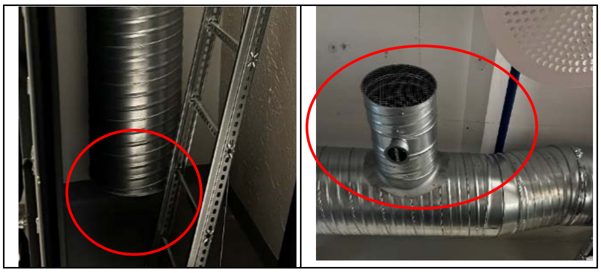

Fig. 4. Right: Extraction duct with intake at floor level, shown with red circle. Left: Extraction duct with intake at ceiling level, shown with red circle.

2.3.4 Container (construction site)

This case is a portable container currently situated at a construction site. The container has an insulated steel construction with approximately 8 m^2 floor area, and a room height of approximately 2.1 meters. The container is equipped with sensors detecting hydrocarbon gases (methane, ethane, propane, and hydrogen). Upon detection of gases, an alarm will be triggered and give signal to the control panel under surveillance by a technician at the container suppliers head office. Additionally, red warning lights will flash on the outside of the container. A fan will start up to ensure continuously ventilation of the gases to maintain gas levels below LFL (Lower Flammability Limit), see Figure 5 and 6. The container is also equipped with a smoke and temperature detector located at ceiling level. If this detector is triggered, fire dampers will close the ventilation system to seal the container. There is no extinguishing system installed but the container is equipped with fire hose connections for flooding the container in case of fire.

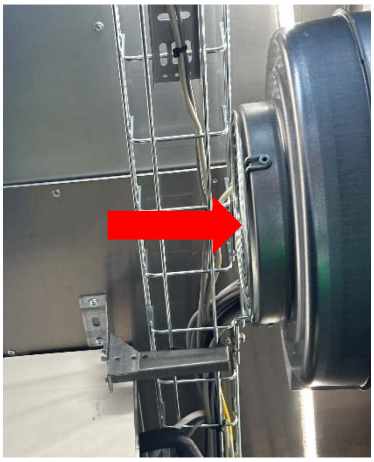

Fig. 5. Exhaust fan marked with a red arrow, seen from inside the container.

Fig. 6. Exhaust fan, seen from outside the container.

2.3.5 Office building

The battery room is located in the basement of the building, adjacent to the parking garage. The office building was built in 2018 but the decision on installing a battery room was made after the design phase was completed. Hence, the battery room has been established by dividing a technical room into two rooms. The construction consists of concrete roof and floor, and the walls are partly concrete and gypsum. Internal floor area of the room is approximately 11 m^2, with a room height of approximately 2.4 meters. The battery room has a separate ventilation system, see Figure 7, Figure 8, and Figure 9. During normal operation, ventilation fans draw air from the ventilated parking garage to ensure sufficient air exchange in the battery compartment for cooling purpose. The fans are equipped with fire dampers connected to the fire alarm system. The fire dampers will close when the alarm is triggered, and the ventilation shuts down completely. No explosion mitigation measures are installed.

Fig. 7. Ventilation extract inside the battery room.

Fig. 8. Ventilation supply at floor level inside the battery room.

Fig. 9. Ventilation supply and extract at ceiling and floor level, seen from outside the battery room.

2.3.6 Kindergarten

The battery room is located on the first floor of the building, towards an external wall and adjacent to a technical room. The construction consists of gypsum walls. Internal floor area is approximately 3 m^2 with a room height of approximately 2.5 meters. The compartment is equipped with an EX-proof exhaust fan, See Figure 10, and an air intake located on the external wall. According to the technical manager at the site, there is no ventilation during normal operation. The room is also equipped with a smoke detector. The exhaust fan is connected to the BMS and will start if the internal alarm is triggered.

Fig. 10. Exhaust fan at ceiling level.

Table *2.* Overview of active fire safety measures.

Case Building	**Ventilation solutions (separate or common)**	**Ventilation strategy upon fire detection**	**Extraction location**	**Explosion mitigation measures**	**Detection and alarm system (Fire and smoke detectors/gas detectors)**	**Suppression system**
School 1	Separate. Ventilation in operational mode is a closed A/C.	Shut down	Ceiling level	Deflagration vent	Yes/No	No
Public building	Shared. Supply and extract ducts connected to the main ventilation system	Extraction	Wall, mid-level	No pressure relief or deflagration vent	Yes/No	No
School 2	Shared supply air with the main ventilation, separate extract	Shut down	Two at ceiling level and one at floor level	No pressure relief or deflagration vent	Yes/No	Yes, sprinkler system
Container	Ventilation in operational mode is a closed A/C	Extraction	Ceiling level	No pressure relief panels	Yes/Yes (CO$^{1)}$ and HC$^{2)}$)	No. Hose connections for flooding
Office building	Separate system	Shut down	Ceiling level	No pressure relief panels	Yes/No	Yes, sprinkler system
Kinder-garten	Separate system	Extraction	Ceiling level	No pressure relief panels	Yes/No	Yes, sprinkler system

$^{1)}$ CO = Carbon monoxide

$^{2)}$ HC = Hydrocarbon

2.4 Review of risk assessments and design documents

Rooms containing Li-ion batteries are regulated by *The Norwegian Labour Inspection Authority* and the regulations concerning health and safety in potentially explosive atmospheres [28]. These regulations require an overall risk assessment considering probabilities regarding formation and duration of explosive atmospheres, probability of ignition sources present, and the presence of chemicals and associated hazards.

According to the standard NEK EN IEC 62485-2 [29], batteries must be placed in a “protected” environment. However, the specified implications are not outlined. Establishing a protected environment should be evaluated on a case-by-case basis, considering the unique circumstances of each situation. A hazard mitigation analysis and a fire risk assessment based on project-specific inputs is also recommended in NFPA 855[10].

Information on the conduction of risk analysis were assessed for the case studies. Only two of the six case buildings, school 1 and the kindergarten, had a risk assessment included in the design documents. The safety of the rescue service was not considered, and none of the design documents reviewed contained fire and explosion data for the specific ESS system installed, no calculations or modelling data on ventilation strategy chosen and no hazard mitigation analysis.

2.5 Detection systems

Detection systems like smoke, fire and gas detection are important measures to ensure early warning and trigger the ventilation system for gas removal or sealing of the fire compartment. Depending on the ventilation strategy for the individual battery room, triggering of alarm will start the ventilation exhaust system or shut down fire dampers to close the fire compartment completely. Early detection of toxic gases is critical to ensure early warning and prevent exposure to occupants in the building.

According to NFPA 855 [10], gas detection should be installed at floor and ceiling level to ensure detection of early off-gases that are heavier than air. The guideline also recommends installing ASD (Aspirating Smoke Detection) to provide very early smoke detection. Standard smoke detectors are not suitable for detecting smoke produced by thermal runaway (TR) in a battery cell. TR can propagate to include several battery cells before the smoke is detected [30].

The case buildings included in this study all had fire and smoke detectors as required in the Norwegian building regulations. However, only one the container case had additional gas detection as recommended in international guidelines and literature. This may indicate design vulnerabilities regarding early gas detection in the battery rooms surveyed and that the decision on type of detection system is based on compliance with the building regulations, not on the actual hazards and risks associated with Li-ion battery storage.

2.6 Suppression systems

An automatic sprinkler system is designed to detect a fire and extinguish it with water at an early stage, or to keep the fire under control so that the extinguishing can be completed by other methods. As there are no requirements in the Norwegian regulations for installing suppressions systems in battery rooms, the presence of a sprinkler system is usually decided by other factors, for example the number of floors and occupancy type in the building. Research performed on sprinkler protection of Li-ion batteries indicate that the system may prevent the fire from spreading from one battery rack to another, but this depends on the design and encapsulation of the battery pack [10]. It was also reported that the sprinkler system may have the capacity to absorb and cool flammable gases, hence reducing the LFL. Another advantage emphasised was that the sprinkler system is effective both for vented and sealed enclosures. Three of the case buildings in this study had a sprinkler system installed in the battery room.

According to the fire safety design documents for these case buildings, installation of a sprinkler system is based on compensating measures for other fire safety issues than the battery room.

2.7 Ventilation systems and strategies during fire

According to the Norwegian building regulations [5], all buildings where there is a risk of explosion must be designed and constructed with explosion vents so that personal safety and load-bearing capacity are maintained at a satisfactory level. In addition, the international NFPA guidelines [10] recommends that battery rooms containing LIB should be equipped with explosion prevention by deflagration venting as described in NFPA 68[31] or by a mechanical ventilation system as described in NFPA 69 [32]. The national building regulations also requires that ventilation systems are performed in such way that it does not contribute to fire and smoke spreading between fire compartments. A common solution to comply with the requirements is to install fire dampers that shuts down and seals off the fire compartment in case of alarm activation.

None of the battery rooms reviewed had explosion vents. Two of the case buildings, the school 2 and the office building, were equipped with a shutdown strategy in case of alarm activation. Combined with no explosion vent panels, a thermal runaway in the battery with gas release from the safety valve could lead to an explosion with a higher explosion pressure, given the presence of an ignition source. Experimental module scale tests performed by DNV on off-gas ventilation and explosion risk showed that limiting the oxygen to the fire reduced the module heat, but also increased the off-gassing from the module and hence increased the explosion risk [9]. These results indicate that a shutdown strategy for the ventilation system could increase the off-gassing and lead to a higher explosion risk.

The kindergarten case is equipped with exhaust ventilation directly to the outdoors. This procedure will ensure early detection mitigation measures. However, it is not known whether the activation of the exhaust fan will trigger the fire alarm. The advantage of using exhaust ventilation is, according to NFPA 855, that it may be an effective measure to remove battery off-gas, heat, and smoke, which are factors that may lead to hazardous conditions.

The cases school 2 and public building both had a ventilation solution based on a shared system with the rest of the building; school 2 shared supply air and had a separate extraction duct at floor and ceiling level.

According to NFPA 855[10], the ventilation system should be designed with extraction at ceiling level to ensure that gases from early thermal runaway is lead in the direction of ceiling mounted detectors. Five of six case buildings studied had extraction ducts at ceiling level, while the remaining case (public building) had extraction at mid-level on the wall.

Two of the case buildings, the school 2 and office building, had a ventilation strategy entailing a shutdown of the system with fire dampers. The container case had a dual strategy depending on which detector was triggered. If the gas detector was triggered, an exhaust fan would start in order to vent out the gases and keep the concentration of combustible gases below LFL. If the fire and smoke detector is triggered, fire dampers will close the exhaust vent and seal the fire compartment. NFPA 69 recommends that the gas concentration is kept below 25 % of the LFL [32].

In summary, these results indicate that the type of ventilation system installed, and ventilation strategy chosen during fire is highly variable among the six case buildings. The fire safety design concepts for the case buildings give few requirements for ventilation of the battery room. Hence, the factors that underlie the design of the ventilation solutions and strategies in the battery rooms remain unclear. It is therefore difficult to identify a common or best practice based on the survey of these case buildings. The findings indicate that there are design vulnerabilities regarding ventilation solutions for battery room surveyed. The ventilations strategies chosen could affect the consequences of accumulation of toxic and explosive gases and hence the safety of occupants in the building and the rescue service. It must be emphasised that the study is limited to six case buildings and should therefore be considered as indicative.

3 Conclusions

A case study investigating ventilation solutions and strategies for gas extraction in Li-ion battery rooms in six buildings has been conducted. The findings reveal significant variability in the choice made for gas venting and explosion prevention. None of the case buildings complied fully with established international guidelines. Decisions related to active fire safety measures appear to be driven more by compliance with building regulations and compensating for other safety issues than focusing specifically on the battery room. The varying amount of active fire safety measures implemented indicate that the experience and knowledge of the designers and other stakeholders involved in the process, and what is emphasised in the design phase, is of great importance when there are no guidelines present.

The key finding in this case study is the need for a holistic design strategy for battery rooms, considering factors like the room size and type of battery chemistry, type of suppression system, measures for early detection, and reduction of combustible gases. The design strategy must be based on a fire risk analysis considering the individual case. Development of national guidelines regarding optimal ventilation strategies and safety requirements for battery rooms would contribute to eliminate design vulnerabilities and ensure mitigating measures to reduce the consequences of a potential fire in Li-ion batteries in buildings.

The findings reported in this study suggest that a higher risk awareness and familiarisation with the active fire safety measures installed among stakeholders like building owners could be a way to close the knowledge gap regarding safe operation of battery rooms.

Further studies on the current topic are necessary to assess the effectiveness of the ventilation systems implemented based on battery size and type, room size and ventilation rates, in order to establish a best practice. The work should also include the effect of suppression systems. The case study should be extended with more buildings, and interviews with designers about the design process and factors involved in the design decisions.

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