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”*Flammable and Toxic Gases from Batteries in Thermal Runaway: Consequences and Mitigation*”

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**Keywords**: Lithium-ion; thermal runaway; fire; gas explosion; fire brigade interventions; gas composition; micro-mobility devices; BESS; recycling; waste ignition

**Abstract**

The widespread adoption of lithium-ion batteries (LIBs) across energy storage systems, electric vehicles, and consumer electronics is accelerating, yet the safety challenges associated with thermal runaway (TR) events remain incompletely understood. This report presents a structured review of current knowledge regarding flammable and toxic gas emissions from LIBs during TR, the consequences for fire behavior and explosion risk. Key application areas covered include battery energy storage systems (BESS), micro-mobility devices, emergency response practices, recycling processes, and emerging battery technologies.

The report identifies and evaluates experimental and modeling studies on gas composition, explosion dynamics, fire suppression, and fire brigade interventions. While substantial data exist for flammable gas emissions, significant uncertainties remain around toxic gas species such as hydrogen fluoride (HF), as well as particulate matter and mixed combustion products. Explosion modeling shows promise, but is limited by inconsistencies in gas composition data and a lack of real-world validation. Fire suppression strategies and inerting agents, have been explored but show mixed or potentially counterproductive results under certain conditions.

A comprehensive assessment of knowledge gaps reveals critical areas for future research: the need for realistic testing environments; better understanding of explosion risks in confined or complex geometries; validated, science-based firefighting tactics; and the urgent study of under-regulated segments such as micro-mobility devices and battery recycling operations. Additionally, emerging chemistries such as solid-state and sodium-ion batteries require proactive safety evaluations. Bridging these gaps is essential to improve safety standards, support regulatory frameworks, and guide societal adaptation to battery technologies.



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# 1 Introduction

## 1.1 Background

The increased use of batteries for energy storage and transport has the potential to contribute to a sustainable energy transition. The electrified society enables the phase-out of fossil fuels, and batteries can help increase the flexibility of the electricity system through energy storage. Developments in the battery sector are progressing rapidly, with continuous advancements through new technological solutions. However, these advancements are not without new, unknown, or lesser-known risks. The continued electrification of society and the establishment of battery factories, increased transportation, recycling, and building integration require knowledge about the potential risks associated with battery use. It is crucial both to prevent potential accidents and to ensure that users and emergency responders have an adequate understanding of how to act in the event of an incident.

A search on Web of Science with the keywords “Lithium-ion OR li-ion”+”thermal runaway”+”fire” yield 1268 scientific publications published in the time period 2015 – 2025, and less than 25 publications prior to that. As many as 104 publications are review papers, which summarize various aspects such as gas formation, heat release and fire prevention strategies. The search with these keywords may not completely capture the literature in the field, but still it is striking that about 8% of the published works covered by these keywords are reviews. The authors of the present report like to argue that the fundamental understanding of battery fires and firefighting strategies is relatively weak. Close examination of a range of review papers show that they build on scarce and often misinterpreted data. The plethora of review papers could potentially indicate that the field is mature, but this is far from the truth.

While the thermal runaway event itself has been investigated by many research groups, in particular experimental studies at single cell level, there is a lack in understanding of the consequences for the real-world applications. For electric cars there is a significant level of knowledge outside the scientific domain, in the companies developing and manufacturing the cars, however this is not publicly available.  When it comes to smaller electrical vehicles, so called micro-mobility devices, such as e-bikes and e-scooters the understanding is very limited. These micro-mobility devices are less regulated compared to electric cars, they are therefore more likely to have batteries of lesser quality, and the BMS (Battery Management System) is less advanced. In addition, they are in a higher risk of mechanical damage in everyday use and, since charging often take place inside buildings, there is an increased risk for humans being exposed to the fires. A combination of these factors have resulted in micro-mobility devices being the source of an increasing numbers of battery fires and lives lost.

In preparation of the present report a reference group including five persons from electric vehicle manufacturers and relevant state authorities, have assisted the authors in identification of topics. The starting point for selection of sub-topics to review was the perceived need for society to increase understanding.

## 1.2 Objective and aim

The aim of this report is to provide an overview of the current knowledge regarding the formation of flammable and toxic gases during thermal runaway in batteries and the resulting consequences in terms of fire, explosion, and exposure to toxic gases. A particular focus is on providing an overview of the extent, scale, and reach of fire, explosion, and toxicological risks associated with batteries from a societal perspective. This will cover the entire battery lifecycle, with a more specific focus on risks associated with the use and application of battery systems in the built environment, as well as emergency response measures. While the primary focus will be on lithium-ion batteries (LIB), emerging technologies such as solid-state and sodium-ion batteries will also be examined to the extent that literature is available.

The focus will be on the consequences of thermal runaway (TR), i.e., the emitted gases, heat development, and resulting fire, explosion, and toxicity. The underlying mechanisms causing thermal runaway will not be addressed.

# 2 General methodology

The overall project objectives were divided into subcategories to facilitate structured literature searches. Initially, these subcategories aligned with those identified in MSB's project call, and they were then refined further by the project group. Once subcategories were established, a meeting was be held with the project and reference groups to discuss and agree on the subcategories to be examined. The resulting list of most important subcategories were identified as the following:

- Gas composition with respect to flammable and toxic gases. This sub-category has been quite widely studied, in particular with respect to flammable gases, and our review partly rely on published review papers.
- Gas explosions
- Micro-mobility devices
- Fire brigade interventions is a key topic that is reviewed both from the perspective of national recommendations and scientific literature
- Risks related to recycling is a scarcely studied sub-category that is essential to society as amount of disposed LIB increase rapidly
- New battery technologies

After determining and prioritizing the subcategories, literature from various sources was gathered and organized. Scientific databases such as Scopus, Web of Science, and Lund University's library catalog (LUBsearch) was be used. Search terms selected were based on each subcategory, utilizing Boolean logic and variations of synonyms to ensure comprehensive searches. Google Scholar and traditional search engines (e.g., Google) were used to locate full-text articles and technical reports not published on journal platforms.

A literature review and mapping method based on the PRISMA-ScR methodology was applied to systematically identify and filter relevant literature. This method includes steps such as:

- Compilation of keywords
- Documentation of search results
- Title screening
- Abstract screening
- Full review and summary of articles

This is a well-defined method for structuring and documenting the entire literature search process, from keyword identification, search and screening to consolidation of literature resources. After analyzing the subcategories, a second reference group meeting was held where results were presented and discussed.

Details on search terms and strategies are provided for each subcategory in the chapters.

# 3 Gas composition

## 3.1 Overview

Battery vent gases mainly consist of carbon dioxide ($CO_2$) and flammable gases such as carbon monoxide (CO), hydrogen ($H_2$), solvent (mainly carbonates), methane ($CH_4$) and a range of other flammable hydrocarbons with 2 – 4 carbon atoms. Some of these components, mainly CO and carbonates, are also toxic. In addition, there are smaller amounts of highly toxic compounds such as hydrogen fluoride (HF), hydrogen chloride (HCl) and ammonia ($NH_3$). Information about amount and composition of gases vented from a LIB in thermal runaway is necessary for assessment of fire hazard and toxic hazard. In addition to gas properties it is also valuable to know the heat release from the battery, at the time scale of the venting process.

Studies on gases from LIB can either address the vent gases as they are released from the battery, or the product gases from a fire where the vent gases are consumed. Unfortunately, in the published literature there is often not a clear distinction between vent gases and combustion products, and therefore many comparisons are meaningless. Here we like to stress the different usefulness of the two types of data. For a more in-depth discussion on this we refer to the paper by Nilsson and Ahlberg Tidblad (2024).

As mentioned in the introduction; over the past decade, a growing number of review articles have addressed battery safety topics, including heat release, gas generation, and fire mitigation. An influential early review was published by Wang et al. (2012), with a more comprehensive update from the same group Wang et al. (2019). The later work remains one of the most detailed descriptions of chemical processes during abuse conditions in lithium-ion batteries (LIBs), although its coverage of gas emissions is limited.

Flammable gas composition has been extensively studied by many research groups, and a review is not done in the present work. In the following section we outline some significant challenges and recommend further reading. Toxic gas composition is less studied, and we give a more extensive review on that topic.

## 3.2 Flammable gases

More than a hundred experimental studies published in the open literature report on properties of gases vented from LIB. Although abuse tests provide insight into battery behavior under abnormal conditions, they do not fully replicate spontaneous failures such as internal short-circuit-induced thermal runaway (TR), which is more challenging to trigger and study under laboratory conditions. However, the experimental TR studies provide the best method for understanding the venting from LIB in TR.

Fernandes et al. (2018) summarized gassing studies up to 2017, and more recently, Qiu et al. (2023) reviewed the impact of ageing on vent gas production during thermal failure. Heat release has been addressed by Ghiji et al. (2021), who combined experimental and modeling approaches to study factors influencing fire risk. A meta-analysis by Rappsilber et al. (2023) highlighted significant inconsistencies between experimental studies on heat release and gas evolution, attributed to differences in test setups, analytical methods, and procedures.

Bugryniec et al. (2024) recently published a review focusing on off-gas composition and total gas volumes, analyzing 60 studies and identifying trends linked to SOC, cell chemistry, and cell design. They found a linear relationship between gas volume and cell capacity but noted substantial variability in other results, partly due to comparing studies conducted under different conditions, including both combustion and non-combustion environments. Misinterpretations can arise when comparing results without accounting for such differences, as illustrated by varying $CO_2$ measurements depending on whether gases were collected before or after combustion. In the review by Nilsson and Ahlberg Tidblad (2024) the literature data was critically assessed, highlighting methodological inconsistencies and gaps in knowledge. The main outcome of that analysis is summarized here, for more detail we refer to the original article.

The paper by Nilsson and Ahlberg Tidblad (2024) discusses several critical aspects influencing the understanding of gas emissions and one central theme is the analysis methods used to characterize the vented gases. Techniques such as Fourier Transform Infrared Spectroscopy (FTIR) and Gas Chromatography (GC), often combined with mass spectrometry, are the most frequently applied. While these methods can detect a wide range of chemical species, they require precise calibration to quantify the concentrations accurately. Moreover, reporting gas composition only as a percentage of total volume can be misleading if not all major compounds are detected.

Nilsson and Ahlberg Tidblad (2024) also stress that the design of experimental setups plays a decisive role in the quality and comparability of results. Factors such as the heating method, chamber atmosphere, oxygen concentration, and turbulence inside the test chamber all affect the nature and quantity of gases released during thermal events. Due to the variety in how these parameters are controlled across different studies, comparing results between experiments is challenging and can lead to inconsistent or contradictory conclusions.

Particular attention is given to the formation of carbon monoxide (CO) and carbon dioxide ($CO_2$), two of the most important vent gases. These can arise from various processes, including electrolyte breakdown, degradation of the solid-electrolyte interphase (SEI), and cathode decomposition. The oxygen content in the environment strongly influences which gas is formed: higher oxygen availability favors $CO_2$, while oxygen-poor conditions result in more CO. This distinction highlights the importance of performing gas analysis in an inert atmosphere; measurements conducted in air may lead to underestimating the CO content due to its rapid oxidation to $CO_2$.

The influence of the battery’s state of charge (SOC) and cathode chemistry on vent gas composition is also discussed by Nilsson and Ahlberg Tidblad (2024): While a general trend can be observed where increasing SOC leads to higher concentrations of reactive gases like CO and hydrogen and lower levels of $CO_2$, these relationships are not consistently reported across the literature. This inconsistency may stem from differences in experimental conditions, battery designs, or manufacturing differences. Even for cells with identical cathode chemistries, such as nickel-cobalt-aluminum oxide (NCA), studies have shown notable variations in gas emissions, suggesting that parameters beyond cathode chemistry—such as internal cell design and material quality—may significantly influence the outcomes. Another potential factor that has not been properly investigated is the dependence on electrolyte composition, which may actually be an important aspect influencing gas composition, due to variation in decomposition temperature and resulting gases from the carbonate solvents. The formation of specific gases depends heavily on the structure of the carbonate solvents used in the electrolyte, their chain lengths, and their interactions with lithium salts. Additionally, the presence of impurities such as water significantly affects which decomposition pathways dominate and, consequently, what gases are formed.

In conclusion, the work by Nilsson and Ahlberg Tidblad (2024) underscores the lack of standardization in experimental methodology and reporting practices as a major barrier to synthesizing reliable conclusions from LIB vent gas studies. To improve the comparability and usefulness of such studies, it is essential to provide comprehensive descriptions of battery specifications, test setups, and analytical techniques. The authors argue for the identification and prioritization of high-quality, well-documented datasets that can support meaningful risk assessments regarding fire hazards and gas toxicity from LIB failures.

## 3.3 Toxic gases

### 3.3.1 Bibliometric information

Most studies on toxic gases from LIB have a strong focus on HF, and therefore this compound was targeted in a range of searches.

*Table 1 Summary of search terms, number of papers and screening process. In all searches was included "Lithium-ion OR Li-ion"*

| Search term(s) | Source | Hits | Duplicates | Added | Total |
|---|---|---|---|---|---|
| AND hydrogen fluoride OR hf AND fire | WoS | 77 | 0 | 43 | 43 |
| AND hydrogen fluoride OR hf AND thermal runaway | WoS | 87 | | 14 | 57 |
| AND hydrogen fluoride OR hf AND toxicity | WoS | 31 | 22 | 2 | 59 |
| AND fire AND toxicity | WoS | 48 | 51 | 14 | 73 |
| Identified manually (references etc) | | | | | |
| | | | | Manually identified duplicates | |
| | | | | Removed after screening of title and abstract | -12 |
| | | | | Removed after full text review | 0 |
| | | | | **Included papers in review** | **61** |

In the manual check we removed works related to battery component (cathode, electrolyte) design, including works on including flame retardants in design. Also, a few references with no quantification of the toxics where removed.

### 3.3.2 Summary of literature

In Table 2 below the literature data on toxic minor gases is summarized. The blue area of the table indicates the type of study, for example the LIB configuration type, the green area has information on which toxic components were quantified.

*Table 2 Summary of literature on toxic gases and particulate matter from LIB in thermal runaway.*

| Review | Electrolyte | Cathode | Cell | Multiple cells | Module | Car/system | Dispersion | Exposure | Suppression | PM | HF | CO | HC | Other | Authors |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | X | | | | | | | | | | X | | | POF3 | Andersson, P; Blomqvist, P; Lorén, A; L |
| | | | model | | | | | | | | | | | | Baakes, F; Lüthe, M; Gerasimov, M; La |
| | X | | | | | | | | | | X | | | POF3 | Bertilsson, S; Larsson, F; Furlani, M; Alb |
| X | | | | | | | | | | | | | | | Bugryniec, PJ; Resendiz, EG; Nwophok |
| | | | X | | | | | | | X | | | | | Buston, JEH; Gill, J; Lisseman, R; Morto |
| | | | | | X | | | | | | X | X | | SO2, NO2, HCl | Christensen, PA; Milojevic, Z; Wise, MS |
| | | | X | | | | | | | X | X | | | HCl | Claassen, M; Bingham, B; Chow, JC; W |
| | | | X | | | | | | | X | | | | | Claassen, M; Bingham, B; Chow, JC; W |
| | | | | | | | | | X | | | | | | Deng, J; Chen, BH; Lu, JZ; Zhou, TN; W |
| X | | | | | | | | | | | | | | | Duan, J; Tang, X; Dai, HF; Yang, Y; Wu, |
| | X | | | | | | | | | X | X | X | X | HCN, SO2, NO2, HCl | Eshetu, GG; Bertrand, JP; Lecocq, A; G |
| | | | | | | | X | | | | | | | | Franqueville, JI; Archibald, EJ; Ezekoye |
| | X | | | | | | | | | | X | | | F | Han, JY; Jung, S |
| | | | | | X | | | | | | | | | Surface deposition | Held, M; Tuchschmid, M; Zennegg, M; F |
| | | | | | | | | | | | X | | | | Hercegovac, J; Frangos, J |
| | | | | | X | | | | | | X | X | X | NH3, HCl | Huang, ZH; Li, X; Wang, QS; Duan, QL; |
| | | | | | | X | | | | | X | X | X | HCl, HBr | Hynynen, J; Willstrand, O; Blomqvist, P; |
| | | | | | | | | X | | X | X | | | Li | Jo, MS; Kim, HP; Kim, BW; Pleus, RC; |
| | | | | X | | | | | | | X | X | | SO2, NO2, NO, HCl | Ke, W; Zhang, YL; Zhou, B; Wu, CY; Liu, |
| | | | | | | | X | | | | | | | | Krol, M; Krol, A |
| | | | | X | | | | | | | X | | | | Larsson, F; Andersson, P; Blomqvist, P |
| | | | | X | | | | | | | X | | | POF3 | Larsson, F; Andersson, P; Blomqvist, P |
| | | | X | | | | | | | | X | | | | Larsson, F; Andersson, P; Mellander, B |
| | | | X | | | | | | | | X | X | | electrolyte | Larsson, F; Bertilsson, S; Furlani, M; Alb |
| | | | | | | | | X | | | | | | | Lebedeva, NP; Boon-Brett, L |
| | | | X | | | | | | | | X | X | | SO2 | Lecocq, A; Eshetu, GG; Grugeon, S; Ma |
| | | | | | | | X | | | | | | | | Lejon, C; Vågberg, D; Schönfeldt, F; Lilj |
| | | | | | | | | | | | X | X | X | EC, DMC | Lin, LM; Ezekoye, OA |
| | X | | | | | | | | | | X | X | | | Liu, CC; Huang, Q; Zheng, KH; Qin, JW; |
| | | | X | | | | | | | | X | X | X | H2 | Liu, PJ; Li, YQ; Mao, BB; Chen, M; Huar |
| | | | | | | | | | | | | | | | Liu, PJ; Liu, CQ; Yang, K; Zhang, MJ; G |
| | | | | | | | | | | | | | | | Liu, PJ; Sun, HL; Qiao, YT; Sun, SJ; Wa |
| | | | X | | | | | | | | X | X | X | H2 | Liu, PJ; Wang, CD; Sun, SJ; Zhao, GJ; |
| | | | X | | | | | | X | | | | | F | Lombardo, G; Foreman, MRSJ; Ebin, B |
| | | | X | | | | | | | | X | X | X | H2 | Mao, BB; Liu, CQ; Yang, K; Li, S; Liu, P |
| | | | X | | | | | | | | X | X | | | Meng, XD; Yang, K; Zhang, MJ; Gao, F; |
| | | X | | | | | | | | | | X | X | | Na, S; Park, C; An, H; Park, K |
| | | | X | X | | | | | | | X | | | | Ouyang, DX; Chen, MY; Wei, RC; Wang |
| | | | | | | | | | X | | X | | | LiOH | Park, YJ; Kim, MK; Kim, HS; Lee, BM |
| | | | X | | | | | | | | X | X | | SO2, NO, NO2, HCl | Peng, Y; Yang, LZ; Ju, XY; Liao, BS; Ye, |
| | | X | X | | | | | | | | X | X | X | | Qi, C; Zhu, YL; Gao, F; Yang, K; Jiao, Q |
| | X | | | | | | | | | | X | X | | | Qiao, Y; Wang, SP; Gao, F; Li, XM; Far |
| X | | | | | | | | | | | | | | | Qiu, MM; Liu, JH; Cong, BH; Cui, Y |
| | | | | | | | | X | | | | | | x | Quant, M; Willstrand, O; Mallin, T; Hynyn |
| X | | | | | | | | | | | | | | | Rappsilber, T; Yusfi, N; Krüger, S; Hahn |
| | | | X | | | | | | | | X | X | | NO, SO2, HCl | Ribière, P; Grugeon, S; Morcrette, M; Bo |
| | | | | | | | | | X | | | X | | | Shi, YQ; Xing, ZX; Liu, YC; Peng, M; Qi, |
| | | | X | X | | | | | | | X | | | | Sturk, D; Hoffmann, L; Tidblad, AA |
| | | | X | | | | | | | | X | | | | Sturk, D; Rosell, L; Blomqvist, P; Tidblad |
| | | | X | | | | | | | | X | X | X | Wide range | Sun, J; Li, JG; Zhou, T; Yang, K; Wei, SP |
| | | | | | | X | | | | | | X | | | Takahashi, M; Takeuchi, M; Maeda, K; |
| | | | X | X | X | | | | | | X | X | | | Tschirschwitz, R; Bernardy, C; Wagner, |
| | | | X | | | | | | | | X | | | DMC, EC | Ubaldi, S; Conti, M; Marra, F; Russo, P |
| | | | X | | | | | | | | X | X | | DMC, EC | Ubaldi, S; Russo, P |
| X | | | | | | | | | | | | | | | Wang, X; Wang, MN; Jiang, RL; Xu, JN; |
| | | | X | | | | | | | | | X | X | H2 | Wei, G; Huang, RJ; Zhang, GX; Jiang, B |
| | | | X | | | | | | | | | X | X | | Zhang, HT; Xue, JY; Qin, YR; Chen, JK; |
| | | | X | | | | | | X | | | X | | | Zhang, L; Duan, QL; Liu, YJ; Xu, JJ; Sun |
| | | | X | | | | | | X | | X | X | | | Zhang, L; Duan, QL; Meng, XD; Jin, KQ |
| | | | X | | | | | | X | | X | X | | | Zhang, TW; Liu, H; Song, JW; Wang, B; |

The most widely studied toxic species from LIB is Hydrofluoric Acid (HF), and this compound was also used as one of the main search keywords. The studies targeting this compound range from studies of pure electrolyte and up to full scale fires. The data from the studies is not internally consistent, likely due to a variation in methodologies and systems. HF forms primarily from the thermal decomposition and hydrolysis of the $LiPF_6$ salt used in electrolytes. HF is extremely toxic and corrosive, capable of causing severe respiratory and dermal damage even at low concentrations. It is often co-emitted with phosphorus oxyfluoride ($POF_3$). It is toxic and contributes to the corrosive nature of the emission plume. Although less studied than HF, it appears frequently in gas-phase analyses of battery fires.

Hydrogen Chloride (HCl) is emitted from the combustion of chloride-containing polymers or additives in batteries. It causes respiratory irritation and corrosive damage. Often observed in combination with $SO_2$ and $NO_2$, HCl is a relevant but inconsistently measured toxicant.

Sulfur Dioxide ($SO_2$) is released during the combustion of sulfur-containing battery components, such as certain cathode materials or solid electrolytes. It acts as a strong respiratory irritant and may contribute to acid formation in the environment. $SO_2$ is frequently observed alongside $NO_2$ and HCl.

Carbon Monoxide (CO) is a common emission in battery fires, formed by the incomplete combustion of organic materials like binders and graphite. It is colorless, odorless, and lethal at high concentrations. Due to its prevalence and danger, CO is a standard target in emission monitoring.

Nitrogen Dioxide ($NO_2$) / Nitric Oxide (NO) are typically produced when nitrogen-based materials oxidize at high temperatures. They are harmful to the respiratory system and contribute to smog and acid rain. Emission levels depend on the battery's materials and the combustion environment.

Ammonia ($NH_3$) can be emitted during the decomposition of nitrogen-containing flame retardants or polymeric materials used in batteries. While highly irritating and toxic, $NH_3$ is rarely measured in battery fire studies. Its role in fire emissions remains underexplored despite its potential health impacts.

Hydrogen Cyanide (HCN) may be emitted from the combustion of nitrile-containing polymers or flame retardants. It is extremely toxic, interfering with cellular respiration. Despite its danger, HCN is not widely measured in battery fire research, highlighting a gap in safety assessments.

Lithium Hydroxide, LiOH may appear as a solid or aerosol byproduct during thermal degradation, especially from lithium-based electrolytes or anodes. It is corrosive and contributes to post-fire residue hazards.

Particulate matter (PM) is released with the vent gases, and this is a topic that has been studied only in the last few years, with only a handful of studies found. The ultrafine particles are composed of metals, carbon, and salts like lithium fluoride. These particles pose inhalation risks and can transport adsorbed toxic gases such as HF. We identify this area as an important topic for further studies given the relative toxicity of small airborne particles, especially under PM1.

CO and hydrocarbons (HC) are often measured in studies targeting flammable gases. The data in Table 2 is thus not exhaustive on this matter.

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# 4 Gas explosions

## 4.1 Literature survey

Searches were performed in two databases for scientific literature. The first is Scopus which is a well-established database for peer-reviewed scientific literature and the second was LUBsearch which is a database at Lund University with a wider scope and contains literature from a large number of databases. The results from the searches and screening process can be found below.

*Table 3 Summary of search terms, number of papers and screening process*

| Search term(s) | Source | Hits | Duplicates | Added | Total |
|---|---|---|---|---|---|
| Batter* AND "explosion vent*" | Scopus | 8 | 0 | 8 | 8 |
| Batter* AND "explosion protection" | Scopus | 17 | 2 | 15 | 23 |
| Batter* AND "explosion prevention*" | Scopus | 7 | 0 | 7 | 30 |
| Batter* AND deflagration* | Scopus | 48 | 2 | 46 | 76 |
| Batter* AND "explosion vent*" | LUBsearch | 42 | 12 | 30 | 106 |
| Batter* AND "explosion protection" | LUBsearch | 6 | 6 | 0 | 106 |
| Batter* AND "explosion prevention*" | LUBsearch | 7 | 6 | 1 | 107 |
| Batter* AND deflagration* | LUBsearch | 57 | 38 | 19 | 126 |
| Identified manually (references etc) | N/A | N/A | N/A | 9 | 135 |
| Manually identified duplicates | | | | | -1 |
| Removed after screening of title and abstract | | | | | -88 |
| Removed after full text review | | | | | -23 |
| **Included papers in review** | | | | | **23** |

The references are divided into four topic areas which is: Maximum pressure (13 papers), Pressure relief (9 papers), Ventilation (5 papers) and Interting (3 papers). The sum of those are more than 23 papers since a single paper can cover several topics.

## 4.2 Maximum pressure

The literature on maximum pressure is highly related to the literature on vent gas composition presented in chapter 3.2 since the gas composition obviously determines the burning velocity of the mixture. The papers most closely related to this topic are the papers by Baird et al. (2020), Marr (2013) and Somandepalli (2014) which, beside the description of the gas composition, also derive the maximum pressure ($P_{max}$) and pressure rise (dP/dt) which are both used for explosion vent sizing in some standards. These papers indicate that the maximum pressure is in the range of 7.5-8.5 for all chemistries at 100% SOC and that the pressure, Kg, is 65 m-bar/s for the tested battery (LCO at 100% SOC).

Most other papers in this topic investigate the pressure-time-relation using a combination of modelling and experiments from simple small channels (Henriksen et al., 2021; Zhang et al., 2022) to full size containers (Jin et al., 2021). In general, it appears that the established simulation software for gas explosions reasonably well reproduce the explosion pressure dynamics as long as the combustion properties of the gas mixture is properly derived. However, the level of obstructions in BESS differs quite substantially from, for example, the petrochemical industry so the traditional approach of using distributed porosity to capture the effects of these obstacles on the burning behaviour, might need to be further developed.

In one publication by Shen (2023), modelling of the BESS explosion in Beijing 2021 using FLACS was presented to derive additional lessons learned from the incident. One lesson was that the battery racks in the BESS likely contributed to flame acceleration and thereby the pressure rise and that the windows on the BESS reduced the maximum overpressure but led to significant external flaming. Similarly, Zalosh (2021) reviewed several BESS explosions and specifically investigated the well-known Arizona explosion in 2019 and used vent size and external flaming to estimate the amount of released gas in that case. Beside this, the paper also described arc flash explosions which is another cause of explosions beside gas explosions.

The PhD-thesis of Johnson Archibald (2021) include several studies related to battery safety, but in this context, the set of models gathered for the different stages of a BESS hazard studies, from gas properties, overpressure prediction to structural response can be mentioned in particular. This set of models is applied two actual accidents: an explosion in a single-family garage involving gases from an Hyundai Kona and also the event in Arizona previously mentioned. These cases illustrate how the set of models can be used to derive additional lessons from accidents as well as for design purposes.

Most of the work on gas explosions is focusing on situations when a combustible mixture fills the enclosure in a, more or less, homogeneous way. A gas explosion can, however, also occur when only a minor part of the enclosure has an ignitable mixture which is often called “localized gas explosion”. This have been investigated experimentally for a realistic garage by Sauer (2024) where correlations for localized explosions were developed.

Several studies investigate the sensitivity of the outcome to various parameters. Shan et al. (2023) found that while many risk parameters, such as gas volume flame and flame speed, is monotonically positively correlated with state-of-charge (SoC), some important parameters such as the lower and upper flammability limit (LFL/UFL) have a plateau at 30% or 50% of SoC where the highest risk (i.e. the lowest LFL or highest UFL) can be found. Similarly, Ogunfuye et al (2022) found that while most battery chemistries experienced a monotonic increase in reduced pressure[1], $P_{red}$, LFP experienced a plateau at 50% SoC even it started to increase again above 80% to reach a slightly higher value at 100% SoC compared to 50%. LFP was found to give consistently higher pressures than NCA and LCO over all SoC:s..

Hu (2024) also investigated the influence of various parameters such as enclosure, vent design and ignition location on the peak structure and magnitude and found that the results were highly sensitive to ignition location and that ignition near one of the boundaries led to significant external explosions outside the vents on the other side causing both overpressure and thermal impact on the surrounding.

Mao et al. (2024) investigated the effect of opening factor of the enclosure on the maximum pressure and found that the maximum pressure first increased with opening factor due to the availability of oxygen and then decreased as the opening served as a pressure relief. This indicate that certain levels of openings should be avoided to limit the maximum overpressures experienced.

[1] Reduced pressure is the maximum pressure after accounting for pressure relief vents

## 4.3 Pressure relief

Underwrites Laboratory (UL) performed experiments on different scales from cell-level to container sized BESS during their development of the UL9540A standard and the result is presented as both a technical report (Barowy et al., 2021) and a scientific paper (Barowy et al., 2022). The research covers many different aspects, but important findings is that data derived from cell-level tests can be used to calculate the maximum pressure after venting using the method described in NFPA 68.

For the pressure relief to be effective, it must be light enough to open relatively quickly. This was investigated experimentally by Chu (2025) who found a linear relationship between the reduced pressure and the specific weight (i.e. mass per unit area) of the hatch indicating that a light weight hatch should be prioritised.

Jin et al (2021) studied the influence of the pressure relief on the surrounding and found that direct flame impact and overpressures up to 4.5 kPa was observed for the containers surrounding the affected container based on a distance between containers of 3-4 meters. The overpressure led to opening of pressure relief on the neighbouring containers potentially serving as a path for spread of fire. Similarly, Hu (2024) investigated how the design of the vents together with ignition position influenced external explosions in both peak structure and magnitude.

Two of the studies, Peng (2023) and Ogunfuye (2022), were specifically concerned with development and validation of calculation models for vented battery explosions while Conzen (2023) provided a general overview of explosion hazards and code requirements for BESS installations.

## 4.4 Ventilation

The experiments by UL previously mentioned (Barowy et al., 2021; Barowy et al., 2022) also included calculations on required ventilation to maintain the gas concentration below 25% or 60% of LFL according to NFPA 69 based on the experimentally determined gas release rates. They found that, for their case, it was relatively easy to maintain the concentration below 60% of LFL, but not possible to reach 25% of LFL even with their highest tested flow.

Kapahi (2023) developed a performance-based approach to ventilation sizing based on CFD and then, in a publication later the same year, applied it to a commercially available setup (Kapahi, Alvarez-Rodriguez, Lakshmipathy, et al., 2023).

Information on code requirements on ventilation is provided in Conzen (2023).

## 4.5 Inerting

Three studies included investigation of explosion protection by addition of suppressants to the gas mixture. The aim of the agent is not to stop the thermal runaway, but rather to either prevent ignition of the gas mixture or reduce the peak pressures in the enclosure.

The technical report from Barowy et al (2021) investigated the effect of Novec 1230 on a full-scale container BESS setup. Even if the quenching of the potential burning of the battery vent gases as they leave the battery, the test series did not prove an increased risk in delayed ignition of the battery vent gases. I should, however, be noted that only three tests were performed and that scenario shows great similarities with the 2019 Surprise BESS incident in Arizona (McKinnon et al., 2020) where four fire fighters were injured after an explosion following a Novec 1230 activation. More information is needed before the potential risk increase from gas suppressants can be disproven.

The second paper, by Zhou et al. (2024) investigated the effect of $N_2$ and $CO_2$ on battery vent gases mixed with graphite powder (mimicking particle emissions from the battery). The study found that both gases could be used to inert the homogeneous gas mixture, but $CO_2$ was more effective than $N_2$. When $CO_2$ was instead injected with a jet into the enclosure, $CO_2$ could sometimes increase the overpressure due to the reaction $CO_2+C \rightarrow CO$ taking place in the hot enclosure.

The final paper, by Subash et al. (2025), investigated the effect of pyrotechnically generated aerosols (PGA) on the burning behaviour of battery vent gases using a small burner setup. They found that for highly reactive gas mixtures, certain concentrations of aerosols could have the reverse effect of intended sine the local cooling in the flame, due to particle evaporation, could lead to a corrugated flame increasing the burning rate.

## 4.6 Summary of explosion literature

The literature indicates that battery vent gases can basically be treated like any other combustible gas with some added complexity, such as:

- Gas properties (e.g. $P_{max}$, dP/dt, $S_L$) depending on chemistry, SOC etc
- Different gas properties in different stages of TR potentially inducing several stratified layers
- More complex determinants for gas release rate compared to gas leaks
- Small very densely obstructed regions

It would be of significant practical value to investigate if the great variation on gas composition found in the literature can be simplified by focusing on parameters needed for, for example, pressure relief design such as $S_L$,$P_{max}$ and dP/dt. The properties focus on macro scale behaviour of the mixture rather than specific specie concentrations which reduce the dimensionality of the problem. This could potentially be done by modelling based on the vast literature on gas composition in the literature.

Another important gap is gas explosions following TR in small mobility devices which appear to be lacking in the literature, but, apart from that, many of the needs are similar to gas safety in general such as improved models for non-homogeneous clouds, validation and development of improved models and more realistic tests for pressure relief hatches.

Ventilation to prevent the formation of a combustible mixture should be further investigated since this is essentially lacking in the literature. This should be performed both to generate general knowledge from modelling and experiments, but also to underpin guidance on which scenarios can and should be prevented.

The last topic covered above was related to interting which was found for Novec 1230, some inert gases and suppression aerosols. For the latter, the results indicate that aerosols could sometimes increase the burning velocity potentially increasing the consequences in some situations due to local flame cooling. It would be relevant if something similar could sometimes be observed for sprinklers or water mist since this have previously been identified for pure hydrogen.

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# 5 Micro-mobility devices

## 5.1 Bibliometric information

Micro-mobility devices include personal transportation devices powered by batteries, most commonly e-bikes and e-scooters, but including also for example hoverboards. A search with they keywords “Lithium-ion OR li-ion”+”fire”+“bike OR scooter” gave six hits on Web of Science, out of which two were found irrelevant upon a screening of the abstracts. The four selected papers are from 2024-2025, two of them are about the fire hazard and are summarized in the next section. Duff et al. (2024) and Warner Levy et al. (2024) report medical statistics on injuries.

## 5.2 Fire hazard

Torelli et al. (2024) investigated the extent and severity of e-mobility battery fires resulting from a single cell thermal runaway. In addition, various suppression techniques a user may attempt to implement if they experience a battery fire at home are tested. A household water hose was found unable to supply a sufficient amount of water to extinguish the thermal event, but the cell-to-cell propagation rate was slowed. Fire blanket tested were not able to contain the flames or debris ejected from the battery packs.

Fleischmann et al. (2025) present an investigation of the fire event when an e-scooter is over charged in a home-environment. The state that thermal runaway of LIBs used in micromobility devices, are large and portable enough to create an extremely rapid, hazardous fire in a residential scale building. Heat release from the battery pack itself as well as from complete vehicles were determined, to quantify the contribution from the different components.

## 5.3 References


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# 6 Scientific literature on Fire Brigade Interventions

## 6.1 Bibliometric information

Using the LUBsearch and Scopus databases, a total of approximately 802 initial journal papers were found. These were then compiled into an excel database, and following the general PRISMA protocol, taken through a set of filtering steps to extract the most useful papers for more detailed analysis.

*Table 4 - keywords used in search and the resultant number of documents found*

| Keywords | number of hits |
|---|---|
| fire AND brigade AND intervention AND for AND bess AND fires | 0 |
| fire AND fighting AND tactics AND battery AND fires | 0 |
| fire AND fighting AND battery AND fires | 114 |
| fire AND fighting AND bess AND fires | 2 |
| fire AND fighting AND electric AND vehicle AND fires | 46 |
| fire AND fighting AND tactics AND electric AND car AND fires | 0 |
| fire AND fighting AND tactics AND electric AND vehicle AND fires | 1 |
| fire AND suppression AND tactics AND electric AND vehicle AND fires | 2 |
| fire AND suppression AND battery AND fires | 225 |
| fire AND extinguishing AND battery AND fires | 248 |
| extinguishing AND tactics AND battery AND fires | 1 |
| suppression AND tactics AND battery AND fires | 2 |
| fire AND fighter AND tactics | 45 |
| fire AND fighting AND tactics | 116 |

## 6.2 Abstract screening and article review

In this stage, abstracts of the remaining articles are reviewed and the most relevant are highlighted and the full article is then reviewed. After first screening, the articles were reduced to 150, and then further reduced based on the review of the papers. The resultant papers were split into 2 categories:

The relevance of the articles to this project can be categorized into three main subject areas:

1. Articles that investigate directly fire fighting tactics for battery related incidents
2. Articles that investigate suppression and extinguishing methods

This decision was made, as the number of papers directly relatable to Fire Brigade Intervention (FBI) was minimal with only 7 papers in total directly related to “fire fighting or tactics”. The majority of the remain papers, approximately 50 in total, were solely aimed at investigating different types of manual or fixed fire suppression systems or agents. Of the 50 papers on suppression and extinguishing, many review papers were also found. A total of 16 review papers were also found.

## 6.3 Summary of findings

### 6.3.1 Fire fighting tactics

Few papers address fire fighting tactics with regards to battery related fires, a summary includes the following basic learnings from Sun et al. (2020):

- LIB fires are difficult to extinguish,
- They require large quantities of suppressant (i.e. water) to supress
- They may re-ignite.

Letting the vehicle or LIB pack burn out completely is one method to avoid these issues, however in practice, this needs to be decided on in a case-by-case basis likely by the attending fire services that can consider the surrounding environment and associated risks.

Poor access to the battery cells is also an issue for effective fighting and suppression of these fires. External application of water only affects the external surface of the battery pack, cooling it. It will also suppress visible flames that can prevent spread. However, this requires a large amount of water, and some tests have shown that over 10,000+ litres of water need be applied for EV fire depending on the size and location of the battery (Funk et al. 2023) and may increase the risk of explosion risks due to accumulation of combustible gases. In addition, the suggested flow rate is at least 200 L/min for extinguishing and cooling. This would lead to large quantities of fire-water run-off, which is potential also of concern, thus some balance is required (Bordes et al. 2024)

Water is preferable to gaseous systems, as investigated by Ubaldi et al. (2022),"Furthermore, intermittent spray with more spray pulses of shorter duration appear to perform better with regards to cooling effect. Although only based on 1 study, the cooling effect initially increases, and then decreases with decreasing duty cycle."

Of special note, was a finding from Zhang et al. (2022) "... the major toxic gases produced during thermal runaway are CO and HF, whose yield increases with an increase in the state of charge, <u>and the toxicity of these gases increases after the water spray. The findings of this study indicate that strict safety protection is needed when water spray is used to extinguish LIB fires."</u> This effect is something new and needs further study, but reiterates the complexity of these scenarios. HF is also notoriously hard to measure correctly, so further evidence is needed regarding this finding.

### 6.3.2 Suppression/extinguishing

Within the scientific literature, most papers just state the different methods that have been investigated, and how they work, but don't give much insight in to which methods are the best.

The tables provided below, and taken directly from Huang et al. (2024) provide a succinct summary of a large number of experimental studies on suppression systems, gaseous systems, and studies using water based systems.

*Table 5 Summary, by Huang et al. (2024), of research outcomes on fire suppression of Li-ion batteries using gaseous suppression systems.*

| Agent | Institutions | Battery type | Conclusions |
|---|---|---|---|
| $CO_2$ | Wang et al[23] | 50 A·h LTO battery | The $CO_2$ was hard to put out lithium battery fires |
| | Liu et al[24] | 38 A·h NCM battery | After $CO_2$ release, the battery reignited and lasted for about 1 min |
| HFC-227ea | Sun et al[25] | 117 A·h NCM battery | HFC-227ea can suppress open fire, but cannot prevent TR propagation |
| | Wang et al[26] | 50 A·h LTO battery | It can extinguish LTO module battery fire, but it may reignite after extinguishing |
| | Meng et al[27] | 243 A·h LFP battery | It is difficult to extinguish large capacity LFP battery fires in open space |
| $C_6F_{12}O$ | Zhang et al[28] | 50 A·h LTO battery | $C_6F_{12}O$ had the best fire extinguishing effect among the three gas extinguishing agents |
| | Zhang et al[29] | 243 A·h LFP battery | The TR propagation was successfully suppressed, demonstrating the effectiveness of $C_6F_{12}O$ in the fire of energy storage power stations |
| | Xie et al[30] | 150 A·h NCM battery | It can quickly extinguish fire, but as the concentration of the extinguishing agent decreases, the phenomenon of re-ignition occurs |
| | Liu et al[31] | 243 A·h LFP battery | With the increase in dose, the inhibitory effect changed from negative inhibition to inhibitory effect, and there was a critical inhibitory dose |
| | Liu et al[32] | 300 A·h LFP battery | The optimal inhibitory dose of 2.9 $g\cdot W^{-1}\cdot h^{-1}$ was determined based on fire extinguishing effect, cooling effect and systemic toxicit |
| Liquid nitrogen | Huang et al[33] | 18650-type LCO battery | It can delay or even stop TR, and has no significant effect on battery performance |
| | Wang et al[34] | 18650-type NCM battery | Short time to extinguish flame and reduce battery surface temperature to a safe value |
| | Huang et al[35] | 18650-type LCO battery | A novel strategy with liquid nitrogen to prevent TR propagation was proposed |

*Table 6 Summary, by Huang et al. (2024), of research outcomes on fire suppression of Li-ion batteries using water-based suppression systems.*

| Agent | Institutions | Battery type | Conclusions |
|---|---|---|---|
| Water | Zhang et al.[38] | 21700-type NCM battery | The cooling effect increases with the amount of water, and the 20.8 $g\cdot W^{-1}\cdot h^{-1}$ of water can prevent TR propagation |
| | Ji et al.[39] | 12 A·h NCM battery | The effects of water mist flow rate, initial velocity and particle size on the fire extinguishing effect were studied by numerical simulation |
| | Zhang et al.[40] | 21700-type NCM battery | Water immersion will damage the electrochemical and thermal stability of the battery |
| | Xu et al.[41] | 94 A·h NCM battery | Water mist can effectively extinguish the battery fire, compared to $CO_2$ and HFC-227ea |
| | Xu et al.[42] | 18650-type NCM battery | Water mist can reduce TR and fire risk, and can inhibit TR propagation with increasing application time |
| | Said et al.[43] | 18650-type LCO battery | Water mist with a mass flow rate of 1.0 $g\cdot s^{-1}$ and 1.6 $g\cdot s^{-1}$ prevented TR propagation by 40% and 50% |
| | Liu et al.[44-46] | 18650 A·h NCM battery | The water consumption of $1.95\times10^{-4}$ $kg\cdot W^{-1}\cdot h^{-1}$ can prevent TR propagation |
| | Xu et al.[47] | 18650 A·h NCM battery | Water mist can reduce the damage caused by high temperature shock to the battery |
| | Larsson et al.[48] | 7 Ah LFP battery | The application of water mist will increase generation of HF |
| Additive water | Luo et al.[49] | 80 A·h LFP battery | Adding 5% F-500 water mist greatly improves fire extinguishing efficiency and cooling performance |
| | Zhou et al.[50] | 94 A·h NCM battery | Water mist with low conductivity compound additive can not only effectively inhibit TR, but also reduce the damage of water immersion short circuit |
| | Zhou et al.[51] | 18650-type LCO battery | The synergistic effects of the physical and chemical additives (FC-4430 (0.17%), TEOA (0.2%), urea (0.32%), and KCl (2.5%)) can significantly improve the ability of water mist to suppress lithium battery fires |
| | Wang et al.[52] | 18650-type LCO battery | The fire extinguishing mechanism of water mist containing compound additives was revealed |
| Foam | Russo et al.[53] | 7 A·h LFP battery | The foam extinguishes the flame within 20 s and effectively reduces the battery temperature |
| | Cui et al.[54] | 38 A·h NCM battery | The foam dose of 0.743 $m^3\cdot kW^{-1}\cdot h^{-1}$ can effectively inhibit TR |

Overall, water still seems the most practical and effective solution, especially when considering fire brigade intervention. Some other more advanced methods (e.g. Yin et al. (2024); Wang et al. (2024); Huang et al.(2022); Li et al. (2024); Huang et al. (2021); Xiao et al.(2024); Zhu et al.(2023); Tianwei et al. (2022); Zhang et al. (2020)), do show some improvements, however these are mostly for fixed systems, where more technical suppression systems can be installed that employ more advanced or multiple suppression agents to achieved higher suppression results.

## 6.4 References


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# 7 Fire brigade interventions: “non-peer reviewed” recommendations

In this section a review of guidelines and recommendations from around the world was performed. Referenced documents and the below summaries come from various governmental and institutional sources found through basic web-search techniques. Many of these sources do not provide the origins of recommendations, thus their validity needs to be considered. However, due to the lack of other sources (i.e. scientific papers) on fire brigade intervention (FBI), it is considered prudent to review these sources as well. However, this review is just an overview, highlighting some of recommendations found, the Danish Institute of Fire and Security Technology (DBI) recently put out a report[2], giving a more complete overview of guidelines and recommendations from the Danish and international perspective. Readers should refer to this and the other referenced publications for a more complete overview.

## 7.1 Battery Energy Storage Systems (BESS)

### 7.1.1 Sweden

For BESS systems, RISE Sweden has written some guidance document on the fire protection.[3] With regards to FBI, the follow extracts from this document are given:

<u>Separation distances:</u> The minimum separation distances of BESS units that are classified as buildings are regulated by Swedish law. For BESS units that are not classed as buildings, safety distances to other buildings are not yet regulated. Furthermore, the separation distances in BBR consider the fire safety between buildings but do not account for explosions.

<u>Emergency response plan:</u> To provide important information about a building or facility to support firefighters in their decision making during an operation. Buildings with BESS should have an emergency and response plan. According to Brandskyddsföreningens Insatsplan 2019.

An emergency response card, should present the following information:

- A table with important information to the first responders such as placement of emergency shutdown, battery chemistry, capacity, voltage, structural fire protection, detection, ventilation, gas detectors, fire gas ventilation, extinguishing system, piping and drainage, pressure vents, remote shutdown, and contact information to operating personnel and the manufacturer/installer of the BESS.
- A floor plan of the floor containing the BESS.
- Explanatory image of emergency shutdown and pressure vents.
- Explanatory image of the inside of t BESS.

### 7.1.2 Denmark

Recently, the Danish Institute of Fire and Security Technology (DBI) put out a report, giving an overview of guidelines and recommendations from the Danish and international

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[2] Battery energy storage systems (BESS) - Overview of guidelines from Denmark, Belgium, Sweden, UK,USA and other selected countries, Dainsh institute of Fire and Securtiy technology DBI (2025)
[3] Guidelines for the fire protection of battery energy storage systems, Grönlund et al., RISE Report 2023:117.

perspectives. In addition, the Danish Emergency Management Agency (DEMA) has also put out guidance on fire protection of large storage of LIB and BESS[4]

### 7.1.3 Germany[5]

From the "*Technical Committee for Preventive Fire and Hazard Protection of the German Fire Brigades*" (DFV), [machine translated] the document: *Preventive and defensive fire protection for lithium-ion large-scale storage systems*, by the "*Working Group of the Heads of Professional Fire Brigades and the German Fire Brigade Association*" provides a set of recommendations that "reflect the basic fire protection assessment and the possible course of action of the emergency services."

Room requirements: if BESS is to be integrated into a building, fire-resistant partition walls in solid construction with at least fire-resistant, tight and self- closing doors are required. If there is no classification in accordance with Section 29 Paragraph 2 No. 2 MBO, the partition walls between the storage facility's installation location and the other parts of the building should generally be designed to be at least as fire-resistant as the load-bearing and bracing components of the floor.

Rooms or spaces must have some form of pressure relief, Ideally, these pressure relief devices should be installed directly on the outside wall. If this is not possible due to local conditions, these openings are to be made specifically.

Secure access is also required.

Water requirements: To ensure an adequate supply of fire extinguishing water, the current specifications of the DVGW W 405 worksheet in conjunction with the AGBF technical recommendation 2018-04 "Fire extinguishing water supply from hydrants in public traffic areas" are considered sufficient.

Recommendations for the Operational Tactics of Large-Scale Lithium-Ion Storage Systems:

This document states "*The fire service's extinguishing agent of choice is water, even for large storage tanks; the addition of wetting agents is possible*".

Other recommended tactics are:

- Ensure that unnecessary water damage is avoided, especially inside buildings.
- Fire-fighting attack should be carried out from cover if possible.
- The installation rooms should be ventilated as quickly as possible and preferably directly to the outside to avoid potential gas accumulation and explosion risks.
- Gases and/or vapors that are released should be quenched with a spray jet if possible.
- In practice, the "critical" temperature of approx. 80 degrees Celsius (cf. DIN VDE 0132) on the outside of the lithium-ion battery (module housing) has proven to be

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[4] Vejledning om brandsikring af større oplag af litiumionbatterier samt BESS." Beredskabs Styrelsen, https://www.brs.dk/da/nyheder-og-publikationer/publikationer2/allepublikationer/2023/vejledning-om-brandsikring-af-storre-oplag-af-litiumionbatterier-samt-bess/

[5] Empfehlungen der Arbeitsgemeinschaft der Leiter der Berufsfeuerwehren und des Deutschen Feuerwehrverbandes - Vorbeugender und abwehrender Brandschutz bei Lithium-Ionen-Großspeichersysteme. Fachausschuss Vorbeugender Brand- und Gefahrenschutz der deutschen Feuerwehren (FA VB/G) c/o Branddirektion München.

effective in order to protect the battery against fires that are necessary for the fire brigade.

The document also provides some guidance on protective clothing, dealing with HF, after the fire/handover considerations.

#### 7.1.4 USA

NFPA standard 855, released in 2020, applies to the design, construction, operation maintenance and installation of BESS. That standard followed the research from the NFPA's Property insurance Research Group (PIRG) due to the significant fire hazard with lithium-ion batteries. the NFPA research foundation also has an ongoing project "Landscape of Battery Energy Storage System Hazards and Mitigation Strategies" Task 3 in this project aimed in part to "Identify and summarize mitigation strategies (e.g., automatic fire protection systems and manual response actions) deployed and implemented by professional design and engineering communities, emergency responders, and others for Li-ion BESS", however the final report on this project appears unavailable at this point.

Fire Safety Research Institute (FSRI) have done extensive work on fire safety aspects with Li-ion batteries and has an extensive set of resources available. They also offer a free course on: "Fire service considerations with lithium-ion battery ESS". This course provides an overview of a case study on the incident at Surprise- Arizona, incident overview, incident analysis, following experimental study overview and then tactical considerations are discussed.

#### 7.1.5 United Kingdom[6]

Essex County Fire and Rescue Service (ECFRS) provides a set of guidances that BESS developers must consider ensuring the risk of fire is minimized. However, most of these are for the design phase, considering separation distances, and adequate thermal barriers between switch gears and batteries. water requirements must be a minimum of 1900l/min for 120 minutes. The site design should include a safe access route for fire appliances to manoeuvre within the site (including turning circles) and an alternative access point and approach route should be provided.

#### 7.1.6 Australia

Currently being developed and investigated under the SARET program[7].

### 7.2 Electric Vehicles (EV)

#### 7.2.1 Germany[8]

The document by VDIK – Verband der Internationalen Kraftahrzeughersteller e.V. – "*Technical quarantine areas for damaged vehicles with lithium-ion batteries*" gives recommendations for fire brigade intervention and setting up quarantine areas around an EV that has crashed, is damaged or at risk of fire.

[6] Essex County Fire and Rescue Service (ECFRS) (https://www.essex-fire.gov.uk/fire-service-guidance-bess-developers)

[7] https://www.fire.nsw.gov.au/page.php?id=9395

[8] Summary here is based on a machine translate version of: Technische Quarantäneflächen für beschädigte Fahrzeuge mit Lithium-Ionen-Batterien, published by: Verband der Internationalen Kraftahrzeughersteller e.V.

### 7.2.2 USA

The document from the National Highway Traffic Safety Administration (NHTSA) – "*Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped With High Voltage Batteries*" gives some general guidance to various stakeholders that may be involved (general public) or come to an incident (e.g. EMS, Fire, Police) of a crashed EV. The latest NFPA Electric vehicle emergency field guide also provides a detailed instruction on how to handle vehicle fire accidents incidents involving hybrid and electric vehicles.

General recommendations are summarised below:

In the event of damage to or fire involving an electric vehicle (EV) or hybrid-electric vehicle (HEV):

- Always assume the high voltage (HV) battery and associated components are energized and fully charged.
- Exposed electrical components, wires, and HV batteries present potential HV shock hazards.
- Venting/off-gassing HV battery vapours are potentially toxic and flammable.
- Physical damage to the vehicle or HV battery may result in immediate or delayed release of toxic and/or flammable gases and fire.

For fire department first responders, the following process is also outlined:

- Identify vehicle
- Immobilize vehicle
- Disable vehicle
- Then different guidance is provided for crash and/or fire considerations.

Interestingly, at the beginning of the document, the NHTSA makes the following statement: "*NHTSA does not believe that electric vehicles present a greater risk of post-crash fire than gasoline-powered vehicles. In fact, all vehicles—both electric and gasoline-powered—have some risk of fire in the event of a serious crash. However, electric vehicles have specific attributes that should be made clear to consumers, the emergency response community, and tow truck operators and storage facilities…*"

Individual states also seem to provide guidance, an example from the Delaware valley regional planning commission (DVRPC)[9] is quite comprehensive, with the objective of: "*Identifying best recommended practices for emergency personnel to provide safe and effective mitigation of electric vehicles (EVs) with lithium-ion batteries (hybrid, plug-in hybrid, electric plug-in vehicle, or extended-range electric plug-in vehicle) through a coordinated multi-agency response.*" The guide is divided in four sections:

- Incident Operations
- Arrival to Scene
- Tactics and Strategy
- Special Considerations

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[9] DVRPC Electric Vehicle Emergency Operating Best Practices V.1 (May, 2024)

- Specific considerations for EVs
- Appendices with additional protocols, (e.g. Hydrofluoric Acid Emergency Medical Management)

It is intended to for first responders, as a guide on how to approach and address electric vehicle roadway incidents.

### 7.2.3 Australia

Identifying an EV or HEV is a point that is bought up in most country guidelines and recommendations. For the fire department this is especially important when arriving on scene. In Australia, there is a requirement that all EV/HEV should have a blue “EV” sticker/badge on the number plate to indicate that it is an electric or hybrid vehicle.


The various states in Australia, may provide their own guidance.

# 8 Risks related to recycling

## 8.1 Bibliometric information

Searches were performed in the Web of Science database for scientific literature, a well-established database for peer-reviewed scientific literature.

*Table 7* Summary of search terms, number of papers and screening process. In all searches the search term “li-ion OR lithium-ion” was included. WoS – Web of Science.

| Search term(s) | Source | Hits | Duplicates | Added | Total |
|---|---|---|---|---|---|
| Fire AND spent | WoS | 26 | 0 | 11 | 11 |
| Fire AND waste | WoS | 41 | 3 | 18 | 26 |
| Fire AND recycling | WoS | 55 | 11 | 8 | 34 |
| Ignition AND recycling | WoS | 13 | 4 | 2 | 36 |
| Identified manually (references etc) | | | | | 1 |
| | | | | Manually identified duplicates | -1 |
| | | | | Removed after screening of title and abstract | - |
| | | | | Removed after full text review | -4 |
| | | | | **Included papers in review** | 33 |

## 8.2 Overview

End-of-life management has become a critical environmental and safety concern. Risks related to recycling is a scarcely studied field, but the need to understand the risks is pressing since the extensive use of LIB make them an increasing part in the waste handling and recycling systems. Out of the 32 papers included in this review all except two are published in the last five years. However, already in 2011 Lisbona and Snee highlighted that the potential severity of incidents may be larger in storage, transport and recycling, compared to the more regulated regular use of the batteries. As pointed out by, among others, Srinivasan et al. (2025) the safety aspects are integrated part of the overall sustainability of LIB, including considerations of regulatory aspects. The various safety aspects are comprehensively listed by Chen et al. (2022). The fate of spent LIB was comprehensively reviewed by Mrozik et al. (2021), who identified and categorised the environmental impacts, sources and pollution pathways, for various disposal practices including illegal disposal. Work from the same group, by Christensen et al. (2021) reviewed the status of safety over the full life cycle of LIB in electric vehicles, including end of life as a result of accidents and risks in waste management facilities. Huang and Li (2022) present key challenges for grid scale LIB energy storage, and point out the safety as one of the challenges.

Risks related to used LIBs and recycling may occur in the following steps:

- Disposal at waste treatment facility, correctly by disposing the batteries in dedicated containers, or incorrectly by disposing them with general waste
- Sorting
- Storage and transport
- Stabilization, for example discharge
- Dismantling, including mechanical treatment such as shredding and crushing
- Separation to achieve the “black mass” material for recycling, by for example sieving, magnetism

- Material recovery including hydroprocessing and pyroprocessing

## 8.3 Waste handling

As LIBs are becoming a commodity and present in a wide range of devices used in everyday life, from electric cigarettes to electric cars, the amount of spent batteries are inevitably increasing. Spent batteries pose a great risk since they may have been mistreated during regular use, which increase the risk of TR. The user needs to responsibly dispose the used LIB in dedicated containers, to avoid the serious risk of batteries disposed in regular waste. Using Austria as an example, outlined in a paper by Nigl et al. (2020b) it is shown that more than 800 metric tons of portable batteries are misplaced into non-battery-specific collection systems, the majority of them entering residual waste collection. A potential risk is also that considerable amounts of batteries are stockpiled, stored or hoarded in households.

For overviews of various reasons for fires in waste handling, we refer to an investigation in and Austrian context by Nigl et al. (2020a), and in a Taiwanese context by Juan et al. (2023). A Scandinavian perspective on fires in waste handling facilities is given by Mikalsen et al. (2020), who also conclude that self-heating is a common source of fire. It is, however, important to note that number and severity of fire incidents in waste management can vary significantly between countries depending on their waste handling strategies.

The literature on risks of fire in waste treatment facilities can be divided into two groups; disposal of LIBs in general waste, and disposal in dedicated containers for LIBs. Regarding dedicated containers for LIBs and also related to storage of large ensembles of new batteries, self-heating may cause fire (He et al., 2022).

LIBs disposed in general waste can result in fire incidents already in waste collection vehicles, which is by Nigl et al. (2021b) considered as a smaller risk, while fully developed fire in a treatment plant is a large risk. The same authors conclude that ”No other substance or material has ever comparably endangered the whole waste industry.”. A work looking at LIB incidents at municipal waste treatment facilities in Japan report that there is more than 0.1 ignition or other incident per ton of waste, mainly during crushing/shredding phase, and that 80-90% of this could be attributed to LIB (Terazono et al., 2024).

A few studies address specific devices or processes in waste handling. Sterkens et al. (2024) investigated aspects of disassembly of small electronic devices powered by batteries. Gausden and Cerik (2024) investigated the potential for single-use vapes to act as an ignition source in waste and recycling streams, they did conclude that for a common disposed vape with SOC <50% the amount of heat produced was not sufficient to ignite general waste.

## 8.4 Discharge pre-treatment

This sub-topic includes seven original research papers and two review papers. The importance of discharge pre-treatment before recycling is strengthened by a study by Nigl et al. (2021a) who after examination of 980 waste batteries concluded that 24% of the cells had a residual SOC of at least 25%, half of them being above 50% SOC. High charge increase the risk of both self-heating a thermal runaway, and therefore present a significant safety risk.

Disposal and recycling of spent LIB can be problematic due to their residual charge, which can lead to short circuits resulting in fire, explosion and toxic gas emissions during crushing, milling and shredding in the recycling process. Discharge pretreatment is a step in the recycling process that ensures the safe and efficient handling of spent batteries. The primary objective of this process is to eliminate any remaining electrical energy within the cells before disassembly, thereby reducing the risk of thermal runaway or accidental ignition. Without proper discharge, the interaction of residual charge with external forces, such as mechanical stress or exposure to conductive materials, can lead to hazardous incidents during the recycling process. For an overview of discharge methods, we refer to the review by Liu et al. (2025) and Shi et al. (2024).

Various methods have been developed to achieve effective discharge, broadly categorized into physical and chemical discharge techniques. Physical discharge methods, such as using external resistors, conductive powders, or controlled short circuits, allow for the controlled dissipation of stored energy. However, these methods can generate excessive heat, which must be carefully managed. Physical discharge methods also has the limitation that they require physical handling of the LIB to connect discharge device, which is not practically feasible when handling enormous amounts of small LIB cells.

Chemical discharge methods involve submerging batteries in electrolytic solutions, such as saltwater or sulfate-based solutions, to facilitate controlled electrochemical reactions that safely neutralize the residual charge. While chemical discharge methods can be effective and scalable, they may introduce secondary pollution due to the dissolution of heavy metals and other hazardous compounds from the battery materials. They can also result in electrolysis of the solution (Amalia et al., 2023), resulting in corrosion and in production of flammable gas such as hydrogen or toxic such as chlorine gas. A popular choice is NaCl solution, which corrode the positive terminal of the LIB, another solution is NaOH which lead to build up of solid residue at the negative terminal (Amalia et al., 2023). Other potential solutions are zinc acetate, found promising by Fang et al. (2022), $MnSO_4$, FeSO4 and Kac. Torabian et al. (2022) looked at NaCl, $Na_2S$, MgSO4 in 12-20% on 3.82V Apple Iphone batteries, NaCl was most efficient. Salt water was used on EV modules by Lee et al. (2023).

As described by Zhao et al. (2024) a charged battery immersed in a salt solution similar to sea water will produce $H_2$ and $Cl_2$. Safety valve was corroded and destroyed after 4 h in sea water solution. Hydrolysis of electrolyte and electrodes Immersion in salt can, however, pose a risk. Zhao et al. showed in experiments on 18650 cylindrical cells that LIB immersed in 3.5% salt solution can go into thermal runaway

Wu et al. (Wu et al., 2022) suggest a new approach, faster and safer than salt solution, for discharge of different types of LIBs. Graphite plates (electrode) replaced the tabs, and the LIB was immersed, this decreased corrosion. Adding reductant to electrolyte solution shortened discharge speed.

A method resulting in no corrosion is immersing in iron flakes solution. Copper conductor did prevent corrosion in a 20% salt solution (Urtnasan and Wang, 2024).

The selection of an appropriate discharge method depends on multiple factors, including battery type, residual charge level, environmental considerations, and economic feasibility. As recycling technologies continue to evolve, research is focusing on optimizing discharge processes to enhance both safety and sustainability. The development of more efficient and environmentally friendly discharge solutions is crucial to advancing lithium-ion battery recycling.

## 8.5 Recycling process

The research on risks in the recycling process is limited to four original research papers. Here we include the steps of dismantling, separation and material recovery as being part of the recycling process.

The mechanical treatment in the dismantling process include risk of fire and explosion as a result of thermal runaway, if the battery include some residual charge. Numerous experimental studies include mechanical abuse in the form of nail penetration, for example the work by Christensen et al. that were among the papers identified with the search terms included in the present literature search. Further insight on the material that can be expelled from a LIB in TR can be found in two recent papers by Claassen et al. (2024a, 2024b). The only mechanical abuse study that directly address recycling scenarios is the one by Diaz et al. (2019), where LIB cells of different geometry and cathode chemistry are subject to nail penetration. They conclude that off-gas toxicity from mechanical land thermal abuse is a significant hazard and that different types of LIBs, with respect to cathode chemistry, pose different level of risk. The results indicate that LFP is the worst in terms of toxicity.

Less violent compared to thermal runaway but still a risk of fire is the escape of electrolyte solvent. The solvent and the fluorinated electrolyte also present risks of toxicity, as investigated by Xiao et al. (2023). The risks related to electrolyte are to a large extent the same as discussed in a previous section on gassing from LIB. Xiao et al. performed gas measurements during mechanical treatment of of cylindrical 18650 cells and concluded that among the fluorinated compounds HF was the main toxic. They also found significant amount of carbonates (solvent) evaporating during the mechanical process. A potential way to decrease the risk during dismantling is to perform it in a liquid environment, as discussed by Uda et al. (2022) who performed crushing of LIB cells immersed in lime water. The included cells of various charge and concluded that the immersion in liquid did not completely remove the risks of thermal runaway, but actually smoke merged from the immersed cells.

The processes of mechanical treatment generate a fine particulate matter called ”black mass”, a combustible dust that poses explosion risks. The work performed by Huang et al. (2025) is an experimental investigations into dust explosions by black mass. In the study one sample generated an explosion overpressure exceeding 6 bar at a dust concentration of 300 g/m³ with an ignition energy of 20 kJ, illustrating the potential severity of such incidents. The explosivity of black mass is further influenced by factors such as particle size and moisture content; finer particles present greater reactivity due to their larger surface area, while moisture can either suppress or intensify the hazard. In particular, residual lithium in the dust may react with water to produce hydrogen gas, creating a risk of secondary explosions.

Risks related to hydrometalurgical process for metal recovery were outlined by Jain et al. (2024), who identified risks of fire and explosion, corrosion and toxicity.

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# 9 New battery technologies

## 9.1 Bibliometric information

Searches were performed in the Web of Science database and in Google Scholar for scientific literature. Web of Science is a well-established database for peer-reviewed scientific literature, and enables searching for specific keywords to get a good perspective of the field. Google Scholar is less useful for a complete picture of the field but the top results often give a good starting point for manually searching for papers.

*Table 8 - keywords used in search and the resultant number of documents found*

| Search term(s) | Source | Hits |
|---|---|---|
| "Solid state battery" AND "Thermal Runaway" | Web of Science | 22 |
| Solid state battery safety (published since 2024) | Google Scholar | N/A |
| "Sodium ion battery" AND "Thermal Runaway" | Web of Science | 19 |
| | **Included papers in review** | **6** |

The topic of new battery technology is a relatively new research field, where significant development has been made only very recently. Thus, this review only included papers published in 2024, as this is when the most updated and relevant studies have been made. Some of the search results were concerned with manufacturing or recycling batteries, which is outside the scope of this work, so these were screened out. Among the search results, 6 papers were chosen for deeper review as they represented either real experimental data or a comprehensive and useful review on the risk for thermal runaway in other battery types. This section focuses on solid-state batteries (4 papers) and sodium-ion batteries (2 papers).

## 9.2 Solid-state batteries

A review article from Energy & Environmental Science (Luo, 2024), discusses safety concerns for solid-state lithium-metal batteries (SSLMBs). Four types of solid-state electrolytes (SSEs) have been developed—oxides, sulfides, hydrides, and halides—all highly sensitive to moisture. Oxides are the most stable but can form surface layers in humid air that hinder performance and increase lithium dendrite growth, leading to short circuits. Sulfides can release toxic $H_2S$ gas when exposed to water, hydrides can produce flammable $H_2$, and halides can generate corrosive HCl in humidity. While studies focus on gas formation during synthesis, moisture sensitivity remains a safety risk during operation, especially if batteries are damaged. Despite SSEs being more stable than liquid electrolytes, interfacial reactions at the cathode/SSE interface pose fire hazards. Solid polymer electrolytes (SPEs) can release $O_2$, $CO_2$, and $H_2$, increasing fire risk, particularly with $LiCoO_2$ or NCM cathodes. Sulfides, though highly conductive, can decompose at high temperatures (400–500°C), producing flammable by-products like $Li_2S$ and S, with potential thermal runaway at 275°C due to lattice $O_2$ reactions. Halides are generally stable but may release toxic $Cl_2$ gas at high temperatures and degrade into flammable $H_2$ under voltage stress. The review does not quantify gas release risks, highlighting the need for further study. Fire suppression strategies, such as delayed combustion systems, are underexplored for solid-state batteries but essential for post-thermal runaway safety. The conclusion in the review article is that future research should focus on developing SSEs with broader electrochemical stability to enhance safety and efficiency in SSLMBs.

An article from ACS Applied Energy Materials in (Darmet, 2024) presents the first experimental assessment of thermal runaway (TR) in all-solid-state batteries (ASSBs). Using high-speed X-ray imaging and pressure measurements, the study examined ignition time, propagation time, and TR reaction duration. Results showed that a reassembled ASSB-like cell can undergo TR from overheating and propagate it to adjacent cells. Compared to lithium-ion battery (LIB) packs, TR propagation in ASSBs was five times faster due to greater heat flow from ejected gases, flames, and incandescent particles. The heat flow from the ASSB trigger cell was ten times higher than that of the LIB trigger cell, significantly accelerating TR kinetics and compromising pack integrity. Despite ASSB cells releasing half as much gas as LIBs—potentially lowering explosion risk—the study confirmed that TR propagation remains a major concern, potentially leading to rapid failure of all cells. Further research is needed to fully assess risks, including the effects of electrical coupling and lithium metal. This first experimental test highlights the need for extensive studies to properly evaluate TR in ASSBs.

Another new study from Journal of Energy Chemistry (Yersak, 2025) confirms that sulfide solid-state electrolytes (SSEs), β-$Li_3PS_4$ (LPS) and $Li_6PS_5Cl$ (LPSCl), are flammable solids, releasing sulfur vapor in oxidizing environments at temperatures below 300°C. Since sulfur vapor is highly flammable and can auto-ignite, an $O_2$-S gas-phase reaction may contribute to thermal runaway in all-solid-state batteries (ASSBs). Combustion analysis using TGA/DSC-GCMS highlights the need to investigate the sulfur release mechanism and assess the flammability of other sulfide SSEs. To improve safety, ongoing research focuses on eliminating oxygen sources by modifying cathode materials and developing SSEs with reduced sulfur volatilization.

Finally, a study from November 2024 in the Journal of Power Sources (Zhang, 2024) examines the safety of solid/liquid hybrid electrolyte lithium-ion batteries (HS-LIBs) under thermal, electrical, and mechanical stress. Compared to conventional LIBs, HS-LIBs exhibit lower thermal stability and higher thermal hazards due to the instability of the silicon-based anode and uneven solid electrolyte interphase (SEI) formation, leading to premature decomposition and increased thermal runaway risks. Under external overheating, HS-LIBs showed shorter reaction times and higher maximum temperatures, worsened by heat production from the solid electrolyte (SE) and the flammability of the pouch cell's aluminum film. Overcharging further compromised electrical safety by increasing heat generation from the SE. However, in mechanical abuse tests like nail penetration and crushing, HS-LIBs demonstrated better mechanical safety, as the SE acted as both an electrolyte and separator, preventing internal short circuits. While HS-LIBs offer high energy density, their poor thermal and electrical safety underscore the need for further research on interfacial stability and thermal runaway mechanisms to ensure safer implementation.

## 9.3 Sodium-ion batteries

The review paper from Batteries (Bhutia, 2024) highlights safety concerns in sodium-ion batteries (SiBs). While SiBs offer lower costs and abundant sodium resources, safety research remains limited. Existing studies indicate that SiBs use flammable non-aqueous electrolytes, posing similar fire and thermal runaway risks as lithium-ion batteries. However, lithium-ion safety strategies cannot be directly applied, as SiBs require tailored electrolyte engineering to stabilize interfaces, and their solid electrolyte interphase (SEI) is more vulnerable, increasing thermal runaway risks. SiBs also lack a standardized chemistry, meaning each variant requires specific safety testing. Some studies suggest that aluminum current collectors enable safer zero-volt storage, improving handling and shipping, while certain SiB chemistries (e.g., NVPF||HC or O3-type layered oxides) have shown no flaming combustion under abuse conditions. However, research on these safety aspects remains limited, underscoring the need for further investigation.

An article from Journal of Power Sources (Huang, 2025) compares the thermal and gas characteristics of 26700 sodium-ion (SIB) and lithium-ion (LIB) batteries, using a qualitative thermal hazard assessment model. Key parameters include safety valve opening temperature, thermal runaway onset temperature, maximum temperature rise rate, peak temperature, mass loss, and toxicity metrics (FED and FEC). The study finds that NTM SIBs have lower thermal stability than LFP LIBs but undergo less intense internal reactions, resulting in lower overall gas-related risks. LFP LIBs primarily emit highly flammable $H_2$, while NTM SIBs release mostly $CO_2$, which is non-flammable but can cause asphyxiation. The gases from LFP LIBs were found to be more hazardous and irritating. Regarding toxic gases, the study evaluates HF formation pathways, concluding that SIBs generate less HF than LIBs due to differences in decomposition mechanisms. CO and HCN were identified as key asphyxiant gases in both battery types, with $CO_2$ levels in SIBs exacerbating asphyxiation risks. Overall, the toxicity of gases from LFP LIBs was greater than that from NTM SIBs.

## 9.4 References


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## 10 Summary: Knowledge gaps

Despite extensive research on TR, its consequences and mitigation strategies, significant knowledge gaps remain across the battery lifecycle. Addressing these gaps is essential to improve safety, guide regulations, and inform emergency response. Here we summarize some key issues that need to be addressed by the research community in the near future.

**Real-world relevance of laboratory data**

Fundamental understanding of gas emissions and fire behavior rely on controlled laboratory tests, often at single-cell level. There is a lack of data from full-scale or system-level scenarios that more accurately represent real-world failures. This includes incomplete understanding of gas emissions in real fire scenarios and their dispersion in indoor versus outdoor settings.

**Uncertainty in gas composition and measurement methodologies**

While the composition of flammable gases is relatively well-documented, toxic gas emissions, particularly hydrogen fluoride and particulate matter, are less consistently measured and reported. Methodological differences lead to inconsistent data across studies, making it difficult to form standardized risk assessments or design safety systems.

**Modeling capability for explosion dynamics in battery systems**

The explosion potential of vent gases has been modeled for some cases (e.g., BESS and EV incidents), but the predictive capability of current models remains limited due to variable gas compositions and enclosure conditions. There is limited understanding of explosion dynamics in "localized" scenarios and insufficient validation of explosion models across different chemistries and states of charge.

**Ventilation and pressure relief in built environments**

Although some studies investigate gas ventilation and explosion venting in battery energy storage systems, more realistic, scenario-based modeling is needed — particularly for densely packed indoor installations. Design criteria must account for ignition location, stratified gas layers, and the interaction of pressure relief systems with adjacent spaces.

**Effectiveness and risks of suppression and inerting strategies**

Various suppression methods (e.g., water mist, $CO_2$, Novec 1230, and aerosols) have been tested, but their effectiveness under different gas compositions, temperatures, and enclosure geometries remains uncertain. In some cases, these measures may even exacerbate hazards (e.g., delayed ignition or increased pressure). More systematic studies are needed to evaluate the trade-offs and risks.

**Fire Brigade Interventions: Gaps in scientific basis**

Current firefighting strategies are often based on non-peer-reviewed recommendations or isolated studies. There is a critical need for scientifically validated guidelines that consider the rapidly evolving battery landscape, especially for emerging technologies and configurations (e.g., micro-mobility, stacked BESS units).

**Micro-Mobility Devices: An understudied risk**

Compared to electric vehicles, there is a stark lack of studies on fire hazards from micro-mobility devices (e.g., e-scooters, e-bikes), which are growing in number and often use less robust battery systems. This segment poses significant fire risks due to lower manufacturing standards, less effective battery management systems (BMS), and high exposure to mechanical abuse.

**Battery recycling and waste handling**

The increasing volume of LIBs entering waste streams creates new safety challenges. Research on gas emissions during battery disassembly, handling of damaged cells, and pre-treatment for recycling is sparse. Especially lacking are safety assessments of fire and gas risks in large-scale recycling facilities.

**New battery chemistries**

Emerging technologies such as solid-state and sodium-ion batteries promise improved safety, but current understanding of their failure modes, gas emissions, and thermal behavior is minimal.

# Appendix A – PRISMA flow charts

References for the various areas can be found in the different sections.