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Environmental Impact of Lithium-Ion Battery Incidents Compared to Other Common Incidents

Final Report by:

Benjamin Truchot, PhD, Caroline Gaya, PhD, Arnaud Bordes, PhD, Anis Amara, PhD, Karen Perronnet, PhD, and Amandine Lecocq
INERIS, Verneuil-en-Halatte, France

Joshua Lamb, PhD and Loraine Torres-Castro, PhD
Sandia National Laboratories, Albuquerque, New Mexico, USA

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1 Batterymarch Park, Quincy, MA 02169 | Web: www.nfpa.org/foundation | Email: foundation@nfpa.org

Foreword

Lithium-ion battery usage is currently under development for many applications, including for instance cell phones, laptops, electric micro-mobility but also stationary energy storage using battery energy storage systems (BESS). With this fast subsequent developing market, the risk of fire (and sometimes explosion) events might increase if appropriate attention is not paid to safety assessment, design selection, and mitigation practices. As for other types of fire, there is an increased awareness that the potential impact of such events on human health and the environment need to be thoroughly assessed. Consequently, a prerequisite and urgent issue to be fulfilled is a reasonable description of potential emissions of such BESS fires.

To meet these emissions characterization objective, the first significant step is to have a good description of the system itself, including a global overview of materials used in those BESS together with the distribution and configuration. Then, to address the environmental impact, (i) the emission pathway is firstly discussed based on the analysis of several accidents that occurred in the last decade; (ii) secondly, based on an in depth survey of peer-reviewed open literature, data retrieved consolidating current knowledge on lithium-ion battery fire emissions are discussed, considering both gaseous and particles emissions to the atmosphere and to firefighting run-off water.

The study underlines some particularity of LIBs fire. At first HF may appear as a potential marker of LIBs emission, having in mind it strongly reacts during dispersion. Also, while particle matter emitted in LIBs fire emission are lower than the one of fires with high smoke production but contains large amount of metals, while metal contamination is clearly an issue of LIBs fire. Also, it was stressed out that emission factors or many substances, such as PAH or VOC need further analysis.

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Report number: FPRF-2025-04

Project Manager: Victoria Hutchison Lutz

Project Technical Panel

Bill Jones, Environmental Protection Agency

Birgitte Messerschmidt, NFPA

Brian Meacham, Meacham Associates

Chris Gallo, US Army Corps of Engineers

Cameron Barda, Edmonton, Alberta Fire Department

David Butry, National Institute of Standards and Technology (NIST)

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Kenan Ozekin, Water Research Foundation

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Environmental impact of lithium-ion BESS incidents compared to other types of fires

FOREWORD

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Authors: Caroline GAYA, Joshua LAMB, Arnaud BORDES, Loraine TORRES-CASTRO, Anis AMARA, Karen PERRONNET, Amandine LECOCQ, and Benjamin TRUCHOT
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Executive summary

The usage of lithium-ion batteries is rapidly advancing across various applications, including smartphones, laptops, electric micro-mobility devices, and stationary battery energy storage systems (BESS). Among these, BESS have the unique capability to cover a wide range of energy needs, with capacities ranging from several hundred kWh for residential applications to several MWh in industrial cases. However, the significant onboard energy associated with BESS raises safety concerns, particularly regarding the potential environmental impact of fires. These concerns are especially relevant given the rapid development of the lithium-ion market. If appropriate attention is not given to safety assessments, design selection, and mitigation practices in the rush to keep pace with market demands, the risks of fire (and, in some cases, explosion) could increase. Although notable progress has been made in reducing the failure rates of BESS, the number and scale of these systems have surged dramatically. Consequently, large BESS fires often capture public attention, as seen in the recent Moss Landing fire on January 16, 2025. Public concern is also growing regarding the potential effects of battery fires on human health and the environment, particularly in terms of air quality, water resources, and soil health. Despite the acknowledgment of these issues, there remains a significant gap in assessing the true impact of such fires on public health.

To assess the environmental impact of BESS fires, it is essential to establish a comprehensive understanding of the potential emissions generated by such incidents. This study aims to highlight the current state of knowledge regarding emissions from BESS fires and propose an initial dataset of emission factors specific to these events.

To meet these emissions characterization objectives, the first step proposed for this study was to provide a comprehensive description of a BESS, including an overview of the materials used, their distribution, and their configuration. BESS systems enable the storage and delivery of energy on demand, facilitating the energy balance required by grid-connected systems (e.g., renewable intermittent energy production devices such as photovoltaic systems) or reinforcing the energy grid through peak shaving and responding to user demand. Each BESS system consists of a combination of electrochemical cells that, depending on the chosen configuration, meet specific voltage, current, power, and energy requirements.

A BESS is composed of two parts: the components related to the electrochemical cells (such as the anode, cathode, electrolyte, and separator), which account for 60 percent of the BESS mass, and those unrelated to the cells [the connecting tabs and cables, battery management system (BMS), casing, cooling systems, etc.]. In summary, the main materials that make up a BESS include metallic compounds (nickel, manganese, cobalt, lithium, iron, aluminum, copper, steel); carbonaceous species; binder materials, including PFAS, plastic components [e.g., polyethylene terephthalate (PET)], non-aqueous electrolytes (carbon-based solvents with lithium salts that also contain fluorine), and electronic components. It is worth noting that the composition may depend on the specific system, especially in regard to the selected battery chemistry [with lithium fer phosphate (LFP) being the most widely used chemistry in BESS compared to nickel cobalt aluminum (NCA) and nickel manganese cobalt (NMC)].

These components, or their degraded forms, can become exposed to the environment once a BESS fire is triggered and can potentially lead to pollution. One mode of pollution is the sedimentation of the smoke plume, which is often diluted at some distance from the incident. Another possible pollution pathway is via the extinguishing agents used, typically water, which can carry emissions emanating from the damaged battery. Additionally, fire residues contribute, either directly or after deposition, landfilling, or recycling, to soil and water pollution. While these emission pathways are well identified, determining the emissions to be considered for BESS is not trivial, as it depends on multiple parameters (such as the combustion mechanism, particle size distribution, BESS design, and lithium-ion cell composition). Because environmental contamination depends on a fire's characteristics, defining the fire scenario is a crucial issue. Given that numerous fires have occurred in BESS during the last decade, it makes sense to use lessons learned from those incidents to study the emission pathways.

To provide an accurate overview of BESS fires, an analysis of several incidents that offer insights into the environmental impact of BESS fires was performed. Incident reports also provided the opportunity to study the methods used (e.g., firefighting methods) and develop recommendations (e.g., wasted water retreatment). For instance, after a fire at a battery recycling facility in Saint-Quentin-Fallavier (France, 2012), no heavy metal pollution was found in the river into which rainwater run-off was poured (most likely due to heavy rainfall dilution). The report for the Perles-et-Castelet fire (France, 2020) noted the need to collect wastewater after the extensive use of water directly onto the container. The BESS fire in Geelong (Australia, 2021) demonstrated a common firefighting method of spraying water around the BESS rather than directly onto the burning container while still collecting the water for treatment.

The Morris fire (USA, 2021) led to legal action regarding the release of pollutants into the air and water. The Hwaseong case (Korea, 2024) highlighted the human risks associated with battery fires, as it led to the deaths of 22 people. Meanwhile, the Moss Landing site (USA) has now reported three large incidents in 2021, 2022, and 2025.

While the majority of BESS fire scenarios tend to correspond to failures within a single container, several cases of propagation and explosion have been reported, complicating firefighting operations. In addition, while heat release rates with BESS fires are moderate compared to similarly sized fires of other types, that does not necessarily mean there is less of an environmental impact, as a high concentration of contaminants tends to be deposited in the immediate vicinity of a BESS fire due to lower smoke dilution.

To assess the emission factors, a review of scientific literature primarily found data obtained from small-scale cases. Whether these results can be used to predict the effects of larger fires is sometimes questioned; however, these results still provide insightful data and can occasionally be extrapolated to represent larger fires. For instance, a study evaluating extinguishing water pollution after thermal runaway of NMC batteries considered the dilution ratio of real fire cases and highlighted that the pollution could potentially affect nearby water ecosystems based on the concentrations.

More generally, the state-of-the-art review yielded a broad overview of the pollutants emitted by BESS fires, summarized below:

- **Gaseous emissions**: Toxic and flammable gases are released during thermal runaway. The composition of the gaseous mixture evolves depending on many factors (such as battery chemistry, state-of-charge, and thermal runaway progression) and may include liquid electrolyte vaporization; carbon monoxide; carbon dioxide; dihydrogen; hydrocarbons (like methane, ethane, ethylene); polycyclic aromatic hydrocarbons (like benzene, toluene, styrene, biphenyl); fluorinated compounds (especially hydrogen fluoride and phosphoryl fluoride); and other toxic species such as acrolein, hydrogen cyanide, ammonia, and sulfur dioxide. Notably, the literature review underscores the lack of studies analyzing polycyclic aromatic hydrocarbons (PAHs) and volatile organic compound (VOC) emissions.
- **Aerosol emissions**: The aerosols emitted by BESS fires are made up of particles ranging from micrometers to nanometers, combined with liquid droplets. Depending on the battery chemistry, different types of particles have been observed (in terms of morphology, composition, and quantity), resulting in aerosol solid particles composed of a mixture of metallic (Ni, Al, Cu, Co, Mn, and Li) and non-metallic (C, O, F, Si, P, and S) species. The risk of environmental pollution and threat to human life cannot be dismissed, as some aerosol particles contain toxic elements and can be inhaled due to their size. In addition to aerosol particles, solid particles larger than a millimeter were also found.
- **Wastewater**: Generally, wastewater is loaded with ions, metallic elements, and organic compounds, and the resulting toxicity is significantly affected by the water's exposure to battery fragments and smoke, as well as by the resulting dilution ratio. Consequently, water pollution greatly depends on the intervention method selected (whether water is applied directly to the battery/system, to the surroundings, or used via an immersion tank). Available studies highlight the potential sources of pollution linked to wastewater.

While the literature provides awareness of the pollution caused by battery thermal runaway, it is difficult to define the lithium-ion battery emission factors due to a lack of large-scale data; insufficient information (e.g., gas concentrations without total emission volume); variations in gas analysis methods; and the wide range of lithium-ion battery (LIB) chemistries and formats considered. Moreover, the absence of mass loss reporting for BESS fires impedes the definition of their emission factors in grams of emitted gas by gram of fuel burned (typically performed in combustion research).

A methodology for calculating LIB emission factors was proposed, normalizing the emission factor to the nominal energy stored (expressed in Wh). The values were normalized based on data provided in literature or by using a generic LIB value (160 Wh/kg for a full battery and 250 Wh/kg for a cell or group of cells without external systems). Three approaches were used to calculate emission factors:

- The emission factors considered for building the database were estimated directly from the scientific papers reviewed, with verification of the measurement methods used and the test conditions performed.
- Emission curves from scientific papers were integrated, when available, to estimate the total amount produced by a given gas. The results were then normalized with the potential available energy based on the sample mass.

- Results from previous in-house studies were also considered.

Emission factors for LIBs, obtained using this methodology on the available data, were then compared to those for hydrocarbons, internal combustion engine (ICE) vehicles, battery electric vehicles (BEV) vehicles, and tires, leading to the following observations:

- Emission factors for CO and CO_2 are not significantly different for LIBs compared to other fuels, such as hydrocarbons, or vehicles (with a cautionary note that the CO/CO_2 ratio for LIBs does not directly illustrate the fire ventilation conditions, as LIBs release CO and O_2 in vented gases).
- Nitrogen oxide emissions appear to be higher for LIBs (though this requires further investigation). Regarding halogenated acids, as expected, the emission factor for hydrofluoric acid (HF), while not necessarily high, is greater for batteries and BEVs than for ICE vehicles.
    - Both halogenated acids and nitrogen oxides (NOx) are particularly concerning as they strongly pollute soil and water and deplete the ozone layer.
- Particle matter production also appears to be lower for LIBs. However, it is important to note that the composition of this particle matter, or more significantly, the particles, likely differs between carbon-based fuels and LIBs, mainly due to the presence of metals in the particle matter from LIBs.
    - One of the key potential pollutants with long-term effects for LIBs may be metals. Fire tests underscore a significant emission factor for this type of fuel, much larger than for other fuels, even tires, which are one of the classic fuels with the largest metal emission factors.
    - Among the metals found, cobalt and nickel are particularly concerning due to their toxicity to humans and the environment.
- The emission factors for VOCs and PAHs for LIBs seem to be of the same order of magnitude as those observed for other fuels.

Several key issues were raised, including the need to clarify the emission factors for each chemical composition of LIBs. In addition, as metallic pollution is a particular concern with LIBs, it was decided that a specific screening of metallic species should be implemented after a LIB fire, as each metal impacts the air and water is different ways. Guidelines were also provided for collecting relevant information for improving emission factors. For instance, continuous gas analysis and mass loss rate measurements were recommended, as were studies dedicated to assessing battery environmental impact. The dependence of emission factors on battery chemistry, triggering methods, and system configurations also warrants further investigation in future studies.

To further study the environmental impact of LIBs, fire modeling based on previously defined emission factors and considering three representative cases was conducted (covering past events and anticipating future potential events with large BESS). The resulting scenarios for LIBs were compared to the same scenarios for hydrocarbons, PVC, and tire storage (for a general overview, as the emission factors remain uncertain). The main findings from the simulations indicated that LIB fires generally have limited thermo-kinetic energy in the fire plume, resulting in reduced atmospheric dispersion. Consequently, PAH and similar product deposits may be higher for a LIB fire than for a classic fuel fire with the same emission factor magnitude, mainly due to this lower atmospheric mixing. In addition, metals appear to be one of the most critical pollutants when considering potential deposits from LIB fires. A cautionary note remains, as these results should be analyzed in light of the difficulties encountered in defining robust emission factors for specific pollutants emitted by LIB fires, particularly metals, which remain a significant unknown parameter in assessing the environmental impact of LIB fires.

As with any fire, BESS fires represent a potential source of environmental pollution. Several pathways exist for contamination, which highly depend on the specific scenario and the firefighting methods used. Emission factors for LIBs were proposed but rely on limited available data. The main conclusion of this study is that the emission of particles containing metallic compounds caused by LIB fires represents a significant concern specific to LIB fires. Other toxic species emissions, such as PAHs and VOCs, were reported and require further analysis. Improvements in measurement and reporting values were suggested for future studies to enhance knowledge on LIB emissions.

While emission factors strongly influence environmental impact, they are not the only parameter. Indeed, the dispersion of the plume is also a critical factor. A particularity of LIB fires highlighted in this study is the limited dilution of the fire plume due to the kinetics involved, which affects the indirect contamination of soil and water. Finally, more extensive analyses of contamination in real cases and large-scale testing

are recommended to broaden and gather more consistent data for future environmental impact assessments of LIB fires.

Abstract

L'utilisation de batteries lithium-ion est actuellement en plein développement pour de nombreuses applications, notamment les téléphones, les ordinateurs, l'électromobilité et le stockage stationnaire d'énergie (BESS). Parmi ces applications, les systèmes BESS ont la particularité de couvrir un large éventail de solutions, leur capacité pouvant aller de quelques centaines de kWh, pour une application résidentielle, à plusieurs MWh dans le cas d'une application industrielle. Dans l'éventualité d'un incendie, l'énergie embarquée plus importante des BESS soulève des questions à la fois en termes de sécurité et d'impact sur l'environnement. Ces préoccupations grandissent d'autant plus lorsque l'on considère le développement rapide du marché des batteries Li-ion. En effet, le risque d'incendie et d'explosion peut augmenter si, pour suivre l'évolution du marché, un manque d'attention est apporté lors de l'évaluation de la sécurité des systèmes, la sélection des matériaux, la conception du système et le choix des solutions de mitigations. A noter, des progrès remarquables ont été accomplis puisque le taux de défaillance des BESS a considérablement diminué. Dans le même temps, le nombre et la taille des systèmes BESS ont également augmenté de façon spectaculaire et les incendies de BESS sont alors largement médiatisés, comme l'illustre l'incendie de Moss Landing du 16 janvier 2025 amplement relayé. Le public s'inquiète de plus en plus de l'influence potentielle des incendies de batteries sur la santé humaine et l'environnement (qualité de l'air, eau et sols). Cependant, même si la problématique est clairement identifiée, l'impact réel de ces incendies sur la santé publique est encore peu évalué.

Pour évaluer l'impact environnemental des incendies de BESS, il est urgent et indispensable de définir les émissions associées à ces incendies. Dans ce contexte, l'étude, présentée ci-après a été menée pour mettre en évidence l'état actuel des connaissances sur les émissions des BESS. Elle propose également un premier ensemble de jeu de données associé aux facteurs d'émission spécifiques aux incendies de BESS.

Pour atteindre cet objectif de caractérisation des émissions, la première étape proposée dans l'étude a été de fournir une description du système incluant une vue d'ensemble des matériaux utilisés ainsi que les différentes configurations rencontrées pour répondre aux applications variées. Les systèmes BESS offrent ainsi la possibilité de stocker et de fournir de l'énergie à la demande pour répondre, par exemple, à l'équilibrage requis par l'utilisation de systèmes connectés au réseau (par exemple, des dispositifs de production d'énergie renouvelable intermittente comme le photovoltaïque) ou pour renforcer le réseau (par écrêtement des pics de consommation ou pour répondre à la demande d'énergie de l'utilisateur). Chaque système BESS est composé d'un ensemble de cellules électrochimiques qui, selon la configuration choisie, répond à des exigences spécifiques en matière de tension, de courant, de puissance et d'énergie. La composition du BESS peut être divisée en deux parties, l'une liée aux cellules électrochimiques (anode, cathode, électrolyte et séparateur) pouvant représenter 60 % de la masse du BESS, et le reste du système (connectique, système de management de la batterie (BMS), enveloppe mécanique, systèmes de refroidissement, etc.). In fine, les principaux matériaux intégrés dans les BESS sont les suivants : composés métalliques (nickel, manganèse, cobalt, lithium, fer, aluminium, cuivre, acier), espèces carbonées, liants polymères incluant des PFAS, composants plastiques (par exemple le PET), électrolyte liquide (solvant non-aqueux avec un sel de lithium parfois à base de fluor) et composants électroniques. Il convient de souligner que la composition peut évoluer en fonction du système considéré et en particulier de la chimie de la batterie choisie (le LFP étant la technologie la plus répandue dans les BESS par rapport au chimies NCA et NMC).

Lors de l'incendie d'un BESS, les composants susmentionnés ainsi que leurs formes dégradées, sont susceptibles d'être rencontrés et peuvent potentiellement polluer l'environnement par différentes voies. L'une d'entre elles est la sédimentation du panache de fumée, souvent après dilution, à une certaine distance de l'incident. Une autre voie possible de pollution est liée à l'utilisation d'agents d'extinction, généralement de l'eau, qui peuvent transporter avec eux les polluant émanant de la batterie endommagée. De même, les résidus d'incendie participent à la pollution du sol et de l'eau soit directement soit après dépôt/enfouissement/recyclage. Si les voies d'émission sont bien identifiées, la détermination des émissions à prendre en compte pour les BESS n'est pas aisée car elle dépend de plusieurs paramètres (fonction du BESS impliqué et des compositions initiales des cellules Li-ion, du mécanisme de combustion, de la distribution de la taille des particules, etc.). Étant donné que la contamination de l'environnement dépend fortement des caractéristiques de l'incendie, la définition du scénario de l'incendie est une question cruciale. Afin d'être représentatif et compte tenu des nombreux

incendies de BESS rapportés tout au lors de la dernière décennie, il semble opportun de tirer les leçons de ces incendies pour construire et définir les émissions associées.

Une analyse, de plusieurs incidents donnant un aperçu de l'impact sur l'environnement, a été réalisée afin de fournir une vue d'ensemble précise des incendies de BESS. Les rapports d'incidents offrent également la possibilité d'extraire certaines observations (e.g. la méthode de lutte contre l'incendie utilisée) et recommandations (e.g. le retraitement des eaux d'extinction). A titre d'exemple, certains cas ont été décrits comme l'incendie d'une usine de recyclage de batteries à Saint-Quentin Fallavier (France, 2012) qui a mis en évidence l'absence de pollution par les métaux lourds de la rivière dans laquelle les eaux de ruissellement ont été déversées (très probablement en raison d'une forte dilution dues aux pluies); l'incendie de Perles-et-Castelet (France 2020) qui a mis en évidence l'utilisation importante d'eau directement sur le conteneur pour gérer l'incendie et la nécessité de collecter ces eaux; l'incendie du BESS à Geelong (Australie, 2021) qui montre une méthode communément utilisée de lutte contre l'incendie consistant à pulvériser de l'eau autour du BESS et non directement sur le conteneur en feu tout en collectant l'eau pour la traiter; l'incendie à Morris (États-Unis, 2021) qui a donné lieu à une action en justice concernant le rejet de polluants dans l'air et dans l'eau ; l'incendie Hwaseong (Corée 2024) qui rappelle les dangers des incendies de BESS (22 morts) et les larges incendies répétés à Moss-Landing (États-Unis) en 2021, 2022 et 2025. Bien que la majorité des scénarios d'incendie de BESS tendent à se limiter à la défaillance d'un seul conteneur, plusieurs cas de propagation et d'explosion sont signalés, ce qui complique les opérations de lutte contre l'incendie. En outre, même si le dégagement de chaleur est modéré par rapport à des incendies de taille similaire, ceci n'implique pas directement des impacts environnementaux moindres car une forte concentration de contaminants tend à se déposer dans le voisinage immédiat de l'incendie en raison de la faible dilution des fumées.

Pour estimer le facteur d'émission, un état de l'art de la littérature scientifique a été réalisé et a permis d'extraire des données obtenues lors d'essais à petite échelle. La représentativité de ces données vis-à-vis des incendies réels est parfois remise en question, toutefois certaines extrapolations sont proposées. Par exemple, une étude évaluant la pollution de l'eau d'extinction après l'emballement thermique des batteries NMC a pris en compte le taux de dilution d'un cas d'incendie réel pour mettre en évidence une potentielle pollution des écosystèmes aquatiques proches compte tenu des concentrations obtenues. Plus généralement, l'examen de l'état de l'art a donné un large aperçu des contaminants pouvant être rencontrés comme le résume le tableau ci-dessous :

- Émission de gaz : Des gaz toxiques et inflammables sont libérés lors de l'emballement thermique. La composition du mélange gazeux évolue fonction de nombreux facteurs (chimie de la batterie, état de charge de la batterie et évolution de l'emballement thermique) mais reste notamment composé d'électrolyte vaporisé , de monoxyde de carbone et de dioxyde de carbone, de dihydrogène, d'hydrocarbures (comme le méthane, l'éthane, l'éthylène), d'hydrocarbures aromatiques polycycliques (comme le benzène, le toluène, le styrène, le biphényle), de composés fluorés (en particulier l'acide fluorhydrique et le fluorure de phosphoryle), et d'autres espèces toxiques comme l'acroléine, le cyanure d'hydrogène, l'ammoniac ou même le dioxyde de souffre. Il est à noter que la revue de la littérature souligne le manque d'articles analysant les émissions de HAP et les COV.
- Émission d'aérosols : L'aérosol émis conduit à la libération de particules, dont la taille varie de l'échelle du µm à celle du nm, combinées à des gouttelettes de liquide. En fonction de la chimie de la batterie, différents types de particules (morphologie, composition, quantité) sont observées, les particules solides restant composées d'un mélange de composés métalliques (Ni, Al, Cu, Co, Mn et Li) et non-métalliques (C, O, F, Si, P et S). Le risque de pollution de l'environnement et la menace pour la vie humaine ne peuvent donc pas être écartés car certaines particules d'aérosol sont composées d'éléments toxiques, et certains aérosols peuvent être respirés en raison de leur taille réduite. Outre les particules d'aérosol, on retiendra que des particules solides sont également émises avec une taille supérieure au millimètre.
- Eaux usées : En général, les eaux usées sont chargées d'ions, d'éléments métalliques et de composés organiques, dont la toxicité est fortement influencée par l'exposition aux fragments de batterie et aux fumées, ainsi que par le taux de dilution. Par conséquent, la pollution de l'eau dépend fortement de la méthode d'intervention choisie (fonction si l'eau est appliquée directement sur la batterie/le système ou plutôt sur les éléments environnant la batterie ou si un réservoir d'immersion est préféré). Les études disponibles mettent en évidence la pollution potentielle liée aux eaux usées.

Alors que la littérature scientifique mets facilement en évidence le risque de pollution induite par les feux de batterie, des difficultés ont été rencontrées pour définir des facteurs d'émission, en raison du manque de données à grande échelle, du manque d'informations fournies dans les publications (par exemple indication de la concentration des gaz sans le volume total émis), de la diversité des méthodes d'analyse des gaz mise en place, de la diversité de chimies et de formats batteries étudiées. En outre, l'absence de valeurs sur la perte de masse empêche la définition des facteurs d'émission à exprimer en grammes de gaz émis par gramme de combustible brûlé (comme généralement défini dans le domaine de la combustion).

Une méthodologie dédiée à la définition du facteur d'émission des LIBs a donc été proposée en utilisant la normalisation du facteur d'émission par rapport à l'énergie nominale stockée (exprimée en Wh). Les valeurs ont été normalisées par rapport aux données fournies par la littérature ou par une valeur générique si l'information n'était pas fournie (160 Wh/kg pour une batterie complète et 250 Wh/kg pour une cellule ou un groupe de cellules sans système externe). Trois méthodes ont été ensuite appliquées pour collecter les valeurs de facteur d'émission :

- Le facteur d'émission considéré pour construire la base de données est estimé directement dans l'article scientifique examiné. Seule une vérification des méthodes de mesure utilisées et des conditions d'essai est alors effectuée.
- L'intégration des courbes d'émission dans les articles scientifiques est effectuée, lorsqu'elles sont disponibles, afin d'estimer la quantité totale produite pour un gaz donné. Les résultats sont ensuite normalisés par l'énergie potentielle disponible en fonction de la masse de l'échantillon.
- Les résultats des précédentes études menées en internes Ineris et Sandia sont pris en compte.

Les facteurs d'émission pour les LIB, obtenus avec cette méthodologie sur la base des données disponibles, ont ensuite été comparés à ceux des hydrocarbures, des véhicules avec moteur à combustion interne (ICE), des véhicules électriques (EV) et des pneus, ce qui a permis d'aboutir aux conclusions suivantes :

- Les facteurs d'émission de CO et de CO_2 ne sont pas significativement différents pour les LIBs par rapport à d'autres carburants tels que les hydrocarbures ou les véhicules (attention le rapport CO/CO_2 des LIBs ne traduit pas directement la ventilation du feu car les LIBs libèrent du CO et de l'O_2).
- Les émissions d'oxyde d'azote semblent augmentées dans le cas des LIBs (à approfondir). En ce qui concerne les acides halogénés, comme attendu, le facteur d'émission du HF, sans être nécessairement élevé, est plus important pour les batteries et les EV que pour les véhicules ICE
    - A noter, les acides halogénés et les NOx sont particulièrement préoccupants car ils polluent fortement le sol et l'eau et détruisent la couche d'ozone.
- La production de particules semble être plus faible pour les LIB. Toutefois, il est important de souligner que la composition des particules diffère, principalement en raison de la présence de métaux dans la matière particulaire des LIB.
    - Les principaux polluants des LIBs avec effet à long terme sont probablement les métaux. Les essais feu témoignent de facteurs d'émission significatifs pour ce type de combustible, beaucoup plus important que pour d'autres combustibles, même les pneus qui sont pourtant l'un des combustibles classiques avec le plus grand facteur d'émission de métaux.
    - Parmi les métaux trouvés, le cobalt et le nickel sont très préoccupants en raison de leur toxicité vis-à-vis des êtres humains et de l'environnement.
- Les facteurs d'émission des COV et HAP des LIBs semblent être du même ordre de grandeur que ceux observés pour d'autres combustibles.

Certains verrous encore à lever ont été mis en avant, comme la nécessité de clarifier le facteur d'émission en fonction de la composition chimique des LIBs. En outre, la préoccupation liée aux émissions de métaux amène à préconiser un contrôle spécifique des espèces métalliques après les feux de batteries, contrôle à réaliser tout s'attachant à l'impact spécifique de chaque métal sur l'environnement, à la fois dans l'air et dans l'eau. Des recommandations ont également été proposées pour collecter les informations pertinentes à l'amélioration des facteurs d'émission. Par exemple, l'analyse en continu des gaz et de la perte de masse est conseillée pour toute étude dédiée à l'évaluation de l'impact environnemental des feux de batteries. La dépendance des facteurs d'émission aux chimies

de batteries, aux méthodes d'initiation de l'emballement thermique et aux diverses configurations système reste également une piste à creuser dans les études futures.

Pour approfondir l'étude de l'impact environnemental des batteries Li-ion, une modélisation des incendies a été réalisée en se basant sur les facteurs d'émission définis précédemment tout en prenant en compte trois cas représentatifs (couvrant les événements passés et anticipant les potentiels futurs événements associés aux feux de larges BESS). Les scénarios feux ont été comparés pour différents carburants stockés : LIBs, hydrocarbures, PVC et de pneus (comparaison réalisée pour donner seulement un ordre de grandeur compte tenu de l'incertitude associée à la définition des facteur d'émission LIBs). Les principaux enseignements tirés des simulations sont, tout d'abord, la dilution réduite du panache d'incendie pour les incendies de batteries. En effet, les incendies de batteries sont associés généralement à une énergie thermocinétique réduite du panache de fumée, entraînant alors une dispersion limitée dans l'atmosphère. Par conséquent, les dépôts de HAP et de produits similaires peuvent être plus importants lors d'un incendie de batteries LIBs en comparaison d'un incendie de combustible classique ayant le même facteur d'émission, principalement en raison de cette dilution atmosphérique plus faible. En outre, les métaux ont été identifiés comme les polluants potentiellement les plus critiques en regards des dépôts à la suite des feux batterie. Une mise en garde demeure, car ces résultats doivent être analysés à la lumière de la difficulté rencontrée pour définir des facteurs émission robustes pour les polluants spécifiques émis par les batteries, notamment les métaux, qui restent une inconnue dans l'évaluation de l'impact des environnemental des incendies de batterie.

Comme tout incendie, les incendies de BESS représentent une source potentielle de pollution de l'environnement. Il existe plusieurs chemins de contaminations qui dépendent fortement du scénario envisagé et de la méthode de lutte contre l'incendie utilisée. Des facteurs d'émission dédiés aux LIBS ont été proposés, mais ils reposent sur peu de données disponibles. La principale de conclusion de cette étude est l'émission de particules contenant des composés métalliques dans les incendies de BESS et ce contenu métallique représente une préoccupation majeure spécifique à ce type d'incendie. L'émission d'autres espèces toxiques comme les HAP et les COV a été signalée et nécessite une analyse plus approfondie pour être consolidée. Des améliorations en termes de mesures et valeurs à fournir ont été proposées pour les futures études menées pour améliorer les connaissances sur les émissions des LIBs. Bien que les facteurs d'émission influencent fortement l'impact environnemental, ils ne constituent pas le seul paramètre. En effet, la dispersion du panache est également un paramètre clé essentiel. Une particularité de l'incendie de LIBs mise en évidence dans l'étude est la dilution limitée du panache d'incendie en raison de la cinétique impliquée, ce qui affecte la contamination indirecte du sol et de l'eau. En conclusion, une analyse plus approfondie de la contamination en situation réelle et lors d'essais à grande échelle est conseillée afin d'élargir et de rassembler plus de données cohérentes pour l'analyse future de l'impact environnemental des incendies de LIBs.

Keywords: Li-Ion batteries, environmental impact, fire

ABBREVIATION

AES: Atomic emission spectroscopy
BESS: Battery energy storage system
BEV: Battery electrical vehicle
DEC: Diethyl carbonate
DMC: Dimethyl carbonate
EC: Ethylene carbonate
EMC: Ethyl methyl carbonate
ESS: Energy storage system
EV: Electric vehicles
FPA: Fire propagation apparatus
GC: Gas chromatography
MS: Mass spectrometer
MSS: Micro-soot sensor
ICE: Internal combustion engine
ICP: Inductively coupled plasma
IDLH: Immediately dangerous to life and health
IEC: International electrochemical commission
ISO: International Organization for Standardization
EEPS: Engine exhaust particle sizer
FTIR: Fourier transform infrared
LCO: Lithium cobalt oxide
LFP: Lithium fer phosphate
LIB: Lithium-ion battery
NCA: Nickel cobalt aluminum
NMC: Nickel manganese cobalt
NFPA: National Fire Protection Association
PCCD/F: Polychlorinated dibenzodioxins and dibenzofurans
PFAS: Per- or poly-fluorinated alkyl substances
SMPS: Scanning mobility particle sizer
SOC: State of charge
PAH: Polycyclic aromatic hydrocarbons
PN: Particulate matter
SEM-EDS: Scanning electron microscope and electronic differential system
TC: Technical committee
TG-DTA: Thermo-gravimetry differential thermal analysis
UL: Underwriters Laboratories
VOC: Volatile organic compounds
WG: Working group

1 Context and introduction

Lithium-ion batteries (LIBs) have become a leading energy storage solution, enabling today's market and use of a diverse range of applications, from consumer products to fully industrial systems, including mobile devices, power tools, electric vehicles, and grid-connected energy storage systems. LIBs play a crucial role in advancing renewable energy solutions as LIBs can regulate their intermittent nature. However, the increasing prevalence of LIBs has raised significant safety and environmental concerns, particularly the consequences of fires associated with one component, typically an individual container, of these stationary battery energy storage systems (BESS). These BESS may reach the tens of gigawatts of power range based on their modular design and very high storage capacity. This report investigates the environmental ramifications of BESS fires, comparing them to other types of fires.

The safety risks of BESS fires are well known; however, the environmental impacts are not as well documented. As with fires in most structures or equipment, these incidents lead to the release of toxic and hazardous materials into the environment, affecting air quality, water resources, and soil health. While the batteries themselves have distinctive compositions, there is limited information on if LIB fires pose a higher risk of environmental contamination than other large structure fires. This report represents an effort to collect what information is available and identify what knowledge gaps exist in understanding any increased environmental risks from large battery fires. This report draws on a variety of sources, including recent research findings, detailed case studies, and input from experts in the field, to understand the environmental impact of Li-ion BESS fires within the wider energy sector. The impact of mitigation strategies on the emission and contamination are also reported to provide insights on different fire cases (depending on the mitigation method used).

This report consists of an extensive public literature review combined with in-house experimental results analysis and considers several fundamental aspects of the environmental impact of fire. The report also elaborates on the development of emission factors and a comparison of the potential environmental impacts of LIB fires compared to fires involving other fuels. The report is structured as follows:

- *Detailed composition of BES*S – Identifying all the materials potentially involved in a fire and those that could influence the smoke composition, such as catalytic materials for PCCD/F (polychlorinated dibenzodioxins and dibenzofurans) formation, fire water run-off, and other potential liquid leaks.
- *Fire development scenarios* – Using scientific literature and available data on fires, facilitated by Ineris participation in TC120 and involvement in investigations for the French Bureau of Investigation and Analysis of Industrial Risks (BEA-RI), established after a large chemical fire disaster in Rouen in 2019. Fire scenario identification will help distinguish toxic product emissions, their pathways, and subsequent environmental impacts (air, soil, and water).
- *Data on gaseous and particulate emissions* – Including condensable and particulate emissions to the air in the case of battery fires and other identified materials compared to other common fires.
- *Data on combustion products transferred to soil and water* – Including water run-off containing toxic products compared to other common fires. This section also considers the contamination of edible vegetables through deposits or water run-off.
- *Mitigation measures* – Reflected by IEC TC 120 (*Electrical Energy Storage Systems*) and related standards published or under development at their working group (WG) 4 (environmental issues). The analysis is facilitated by the active participation of the Ineris team in this technical committee (TC).
- *Discussion on emission factors* – Based on available data in the literature and highlighting the limitations in test methods to obtain such values.
- *Comparative environmental impact evaluation* – For fires involving LIBs and similar fires with other fuels. The objective is not to estimate the real impact of such fires due to the many uncertainties of emission factors but to provide a comparison of the potential impact.

Ineris and Sandia used their extensive access to scientific literature to perform create this report. Ineris' connection with the French ministry in charge of the environment was crucial for accessing detailed accident reports with several post-accident measurements. We also leveraged our connections with various organizations that provided similar data in other countries, particularly through recent

collaborations with Paul Christensen's extensive fire-brigade community network[1] and the EV FireSafe Australian initiative[2].

In addition to available data, Ineris and Sandia used historical experimental results based on tests on LIBs carried out at their respective organizations. Both organizations are equipped for gas and particle emission measurements and have collected data that can be used to qualify and potentially reduce the environmental impact of LIB fires. Data from IEC TC 120 on past accidents was also used as a reference, especially regarding failure modes and information on thermal runaway spread in BESS, as this strongly affects the environmental impact of fires.

A list of pollutants was developed to consider when dealing with BESS fires' environmental impact. Each pollutant's origin was identified, whether from the casing, separator, electrolyte, or other compounds, based on previous work done by Ineris on parts of these batteries. The pollutant is a fundamental issue when highlighting the differences between various Li-ion chemistries and considering the influence of the state of charge (SOC), or failure mode, on potential emissions.

[1] Prof from University of Newcastle-on-Tyne (UK)
[2] https://www.evfiresafe.com

2 Literature review

This chapter presents the state of the art regarding LIBs, particularly applied to BESS. It begins with a description of a BESS system and a brief overview of the environmental impact concept. Next, it examines major LIB fires and the available knowledge from scientific literature.

2.1 Description of BESS

By nature, electricity cannot be stored directly as “electrons”; therefore, a physically storable form of energy capable of delivering electricity through some reversible conversion auxiliary system is needed. Hence, an (Electrical) Energy Storage System [(E)ESS] is one or more devices assembled, capable of storing “physical” energy, usually in some mechanical, gravitational, thermal, or electrochemical form, to supply electrical energy at a future time. For instance, this can be used for grid-connected systems to balance electrical energy supply and grid user demand, or for peak shaving purposes. BESS provides energy storage through an assembly of electrochemical cells (the physical energy storage subsystem) that can deliver the required operating voltage and current levels. A detailed description of each system is given in the Sandia Report. (1)

Before describing the system, it is important to note that NFPA 855, *Standard for the Installation of Stationary Energy Storage Systems*, provides guidance for the installation of energy storage systems, including battery energy storage systems. (2) While NFPA 855 does not require listing to UL 9540 (3), it requires a hazard mitigation analysis if the BESS is not listed to UL 9540.

Ultimately, regulation of energy storage systems in the United States will fall upon the local authority having jurisdiction (LAHJ), which may adopt model codes and standards in their entirety, in part, or alongside their own code of regulation. NYSERDA (New York State Energy Research and Development Authority) has, for instance, put in place a model law and permit process for the installation of stationary energy storage systems. They have also chosen in NY state to develop a specific fire code for BESS[3]. This model law requires reviews under the relevant jurisdiction’s environmental quality and review laws but does not specify specific environmental requirements or mitigations. Regardless of how the LAHJ regulates BESS, an energy storage system fire is not a normal event, so environmental emissions from such fires are generally not covered.

2.1.1 Lithium-ion elementary cell composition and preliminary risk identification

Lithium-ion cells commonly have the following components:

- Anode:
  - Graphite
  - Conductive carbon
  - Binder materials – typical binders include PFAS (polyfluoroalkyl substances)
  - Copper current collector
- Cathode:
  - Layered mixtures of metal oxides such as NMC (nickel manganese cobalt), NCA (nickel cobalt aluminum) or phosphate-based systems [LFP (Lithium Fer Phosphate)] – decomposition can result in metal oxide particulates
  - Binder materials – can include PFAS
  - Aluminum current collector
- Electrolyte:
  - Non-aqueous liquid electrolyte, typically combining organic carbonate-based solvents and a lithium salt – decomposition can produce hydrogen, hydrocarbons, and unreacted solvents
  - Salt – $LiPF_6$ salt can react with other components to produce HF (hydrogen fluoride)

[3] https://www.nyserda.ny.gov/About/Newsroom/2024-Announcements/2024-07-26-Governor-Hochul-Announces-Draft-Fire-Code-Language-That-Addresses-Recommendations

- Separator (polypropylene/polyethylene):
  - Polypropylene and polyethylene debris

It should be noted that a variety of options for all four key elements are already in use or under development in the pursuit of better performance, cost containment or reduction, and safety managements. Often, key additives remain undisclosed because they are considered proprietary to the market stakeholders.

2.1.2 BESS specificities

Beyond the materials present as key components of the cells, BESS will always contain additional structural materials and electronic components, as they are needed for system operability. Argonne National Laboratory developed the EverBatt model to estimate the environmental impacts of energy storage systems, and this was used to develop a Bill of Materials by Accardo *et al.* (4) as shown in Table 1 below.

	NMC111	NMC622	NMC811
Cell components	kg/kg of battery pack		
Cathode Material	0.287	0.263	0.253
Graphite	0.16	0.171	0.168
Carbon Black	0.02	0.018	0.014
Binder	0.025	0.024	0.029
Copper	0.134	0.134	0.131
Aluminum	0.069	0.069	0.068
LiPF6	0.018	0.018	0.021
Ethylene Carbonate	0.05	0.05	0.057
Dimethyl Carbonate	0.05	0.05	0.057
Polypropylene	0.012	0.012	0.011
Polyethylene	0.003	0.003	0.003
Other components			
Copper	0.003	0.002	0.003
Aluminum	0.184	0.0186	0.187
Steel	0.007	0.004	0.006
PET	0.005	0.004	0.005
Electronic components	0.037	0.037	0.038

Table 1: Mass distribution of the different BESS components.

Figure 1 shows a typical composition in the form of a balance sheet of the elements making up an electric vehicle module (6.5 kWh), consisting of 93 NMC (111) pouch cells. This graph shows the variety of materials used and their nature. A similar bill of materials is expected for all BESS modules, as the arrangement may be different for different BESS.

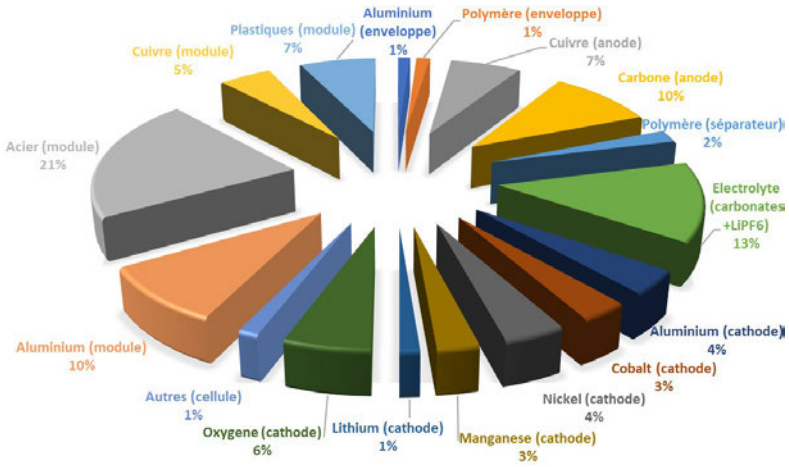


Figure 1: Overview of components used in a Li-ion NMC battery module, adapted from (5).

A similar analysis was published by Carvalho (6), comparing NMC and LFP chemistries as shown in Figure 2. It is important to note that LFP is more commonly used in BESS [in 2021, LFP was used in 50 percent of BESS, NCA was used in 20 percent, and NMC811 was used in 7 percent (7)]. LFP's predominance in BESS is even reinforced by political action, such as the LFP ban in medium to large ESS passed by China's National Energy Administration (8). A more generic overview of the percentage of each component was published by Sommerville (9).This publication provides the mass proportion of each compound in large pouch cells typically used in electric vehicles, as shown in Figure 3.

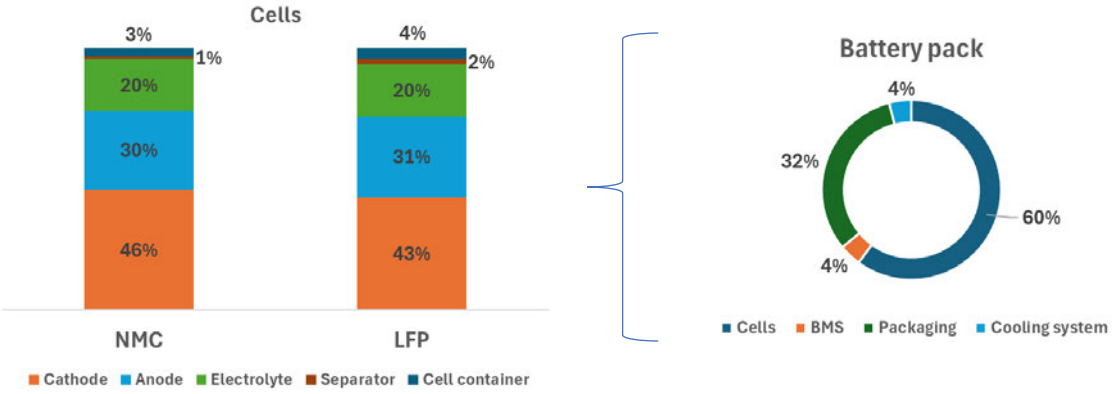


Figure 2: Battery pack and cell mass composition, reproduced from (6).

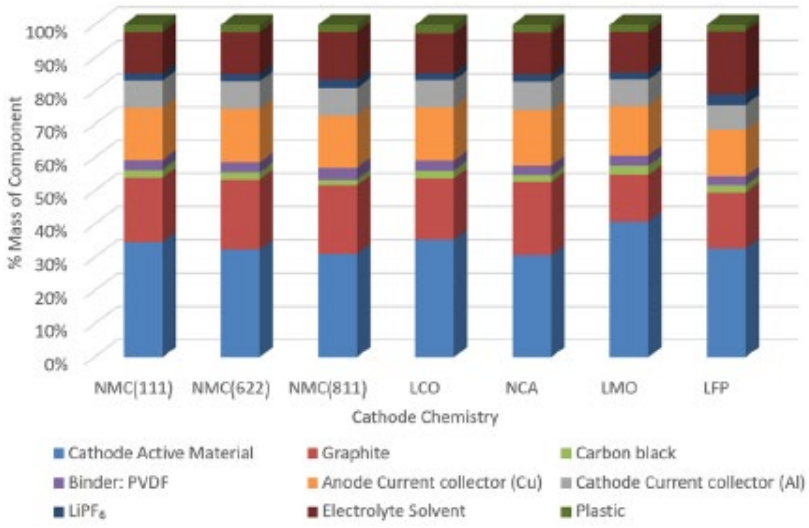


Figure 3: Component percentage of large pouch cells used in electric vehicles (6).

Another compound rarely detailed in such analysis is the fluids used in active battery cooling. These are generally water-based, but some additives can be used (for example, ethylene glycol). Getting information on these additives remains a challenge.

In addition, new cooling systems are in development, and possible new technologies such as immersive cooling could be integrated within BESS and introduce new hazardous compounds. So far, such dialectic fluids as hydrocarbon oils, silicone oils, and fluorinated hydrocarbons have been considered (as indicated in a research dedicated review paper) (10).

Moreover, mitigation materials integrated within BESS could contribute to the overall fire toxicity issue, such as FK-5-1-12, with the following chemical formula: $C_6F_{12}O$ (11).

2.1.3 BESS fire emissions

As highlighted by recent feedback, fire risk cannot be neglected with LIBs. This concern applies to all types of installations, from the smallest battery to the largest BESS (there have already been more than 50 fire events involving BESS). The EPRI database[4], provides a good overview of these events. In the event of thermal runaway, systems containing LIBs are known to produce emissions which may be liquid (electrolyte), gaseous, or particulate. These emissions can then interact with the environment and lead to pollution.

Figure 4, reproduced from a publication by W. Mrozik *et al.* (12), illustrates the various ways these emissions can pollute the environment. One mode is the sedimentation of the smoke plume, often diluted, at some distance from the incident. Another possible pollution pathway is linked to the extinguishing agents used, typically water, which can carry with them the emissions emanating from the damaged battery. Before embarking on the characterization of environmental impact, we need to understand what compounds are likely to contaminate it.

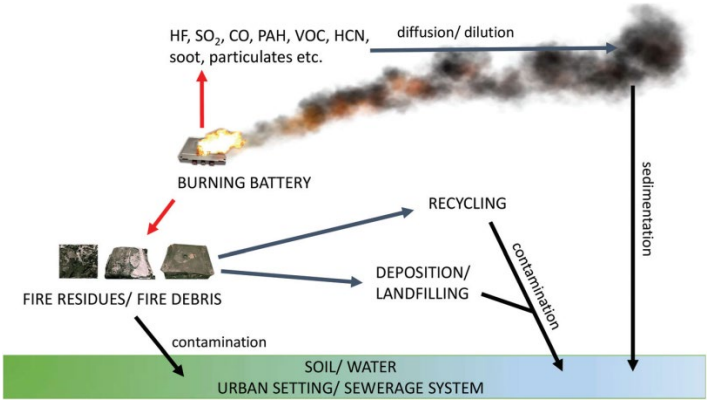


Figure 4: Emission pathways from fires (adapted from ISO, 2011; Stec et al., 2019) (12).

Emissions obviously depend on the materials making up the system. As illustrated in the previous section, these materials vary from one Li-ion battery chemistry/geometry to another, and from one system to another. However, the phenomena involved and expected effects remain broadly similar.

For the purposes of emissions analysis, the percentages shown should be weighted according to the physical state of the materials, which may influence related emission factors. The particle size of burnt material was already proven to impact the combustion mechanism (13), and the particle size distribution has been found to affect the reaction front speed of metal mixing with the air (14). In the case of a battery — for example, a nickel battery — a constituent of the cathode's active material in the NMC chemistry and differences in terms of combustion and emission factor are expected. As nickel is present in powder form (chemically in more or less lithium oxide form) and steel is present in a bulk form, it is expected that nickel will be more easily dispersed than steel.

[4] https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

Thus, based on the component analysis, a LIB's potential emissions may be linked to the different metals used. Those metals can lead to potential pollution. However, this analysis also shows that LIBs contain many more common products and usual emissions from polymers like polycyclic aromatic hydrocarbons (PAH) and volatile organic compounds (VOC), which must also be considered carefully. This analysis provided some warnings about the products mentioned in the coming literature analysis about fire emissions.

In addition to these materials, typical of the electrochemistry of a Li-ion battery, if an incident occurs on a system-wide scale, other materials will be involved in the production of emissions, such as plastics, electronic components, and electrical cables.

2.2 Environmental impact

The environmental impact of fires has previously been considered for different types of fuels (15, 16) and, as discussed in those references, it is a major concern when a fire occurs. The large battery fire that took place in Viviez, France, recently in a recycling plant demonstrated once more the great interest of both the authorities and the population on the environmental impact of such fires. But, in addition to these generic concerns, it is important to define "environmental impact."

In ISO 26367-1 (17), environmental impact is defined as: "any change to the environment, whether adverse or beneficial, wholly or partially resulting from an accidental fire." This standard also includes a definition of the environment: "surroundings within which a fire occurs, including air, water, land, natural resources, flora, fauna and humans, and their interrelation." For the purposes of this part of ISO 26367-1, "the environment" includes the following:

- Local: within the perimeter of a burning enclosure (this part of ISO 26367-1 is not applicable to burning enclosures during a fire).
- Immediate: vicinity within a short distance (e.g., 1 km) of the fire and excluding the local area of an enclosure fire.
- External: area outside the immediate vicinity of a fire; the extent of this depends on weather.
- Different conditions and types of emissions: For example, air, water, or land, with short-term or long-term consequences.

Based on this definition and the physical mechanism associated with a fire, a scheme is proposed in this document to visualize the environmental impact of fire pathways, as shown in Figure 5.

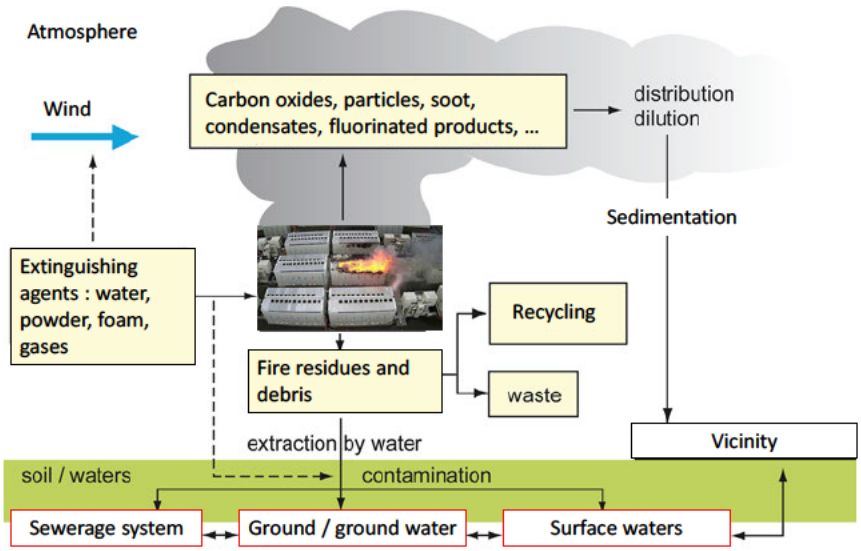


Figure 5: Emission pathways from fires, adapted from (11).

Having those definitions and mechanisms in mind, any characterization of the potential environmental impact of a fire requires defining the corresponding toxic substances that can induce any damage to the environment. Following ISO 26367-3 (18), the compounds to be considered when dealing with the

environmental impact of a fire should be identified. The effect of each pollutant is also detailed in ISO 26367-2 (19). A critical issue is typically the environmental phase that the compounds will affect according to their specific dispersion mode and specific potential toxicity.

Pollutant	Environmental phase
Halogenated acids (HX)	Air
Metals	Air, surface water, groundwater, sediment, soil
Nitrogen oxides (NOx)	Air
Particulates	Air, deposition on surface water and soil
Sulfur oxides	Air
Volatile Organic Compounds (VOC)	Air
NOTE Additional background information is provided in ISO 26367-2 on pollutants having short-term effects.	

Pollutant	Environmental phase
Metals	Air, surface water, groundwater, sediment, soil
Particulates	Air, deposition on surface water and soil
Perfluorinated compounds (PFC) [a]	Surface water, groundwater, sediment, soil
Polychlorinated biphenyls (PCB)	Air, deposition on surface water and soil, sediment
Polychlorinated dibenzodioxins (PCDD) [b]	Air, deposition on surface water and soil, sediment
Polychlorinated dibenzofurans (PCDF) [b]	Air, deposition on surface water and soil, sediment
Polycyclic aromatic hydrocarbons (PAH)	Air, deposition on surface water and soil
Volatile organic compounds (VOC) [c]	Air, surface water, groundwater, sediment, soil
[a] Analysis of a broader spectrum of PFAS compounds (perfluorinated and polyfluorinated substances) may be relevant to analyse in a detailed investigation.	
[b] Polybrominated dibenzodioxins (PBDD) and polybrominated dibenzofurans (PBDF) shall be analysed if the fuel load has a significant bromine content, e.g. in the case of materials containing brominated flame retardants.	
[c] Semi-volatile organic compounds (SVOC)) may be relevant to analyse in a detailed investigation. This class of compounds include, e.g., plasticisers (phthalates) and some fire retardants (e.g. polybrominated biphenyls, PBB).	
NOTE Additional background information is provided in ISO 26367-2 on pollutants having long-term effects.	

Table 2: List of pollutants to be considered and associated environmental phase, reproduced from (18).

To deal with the environmental impact of a BESS fire, the first question should concern the potential presence of specific compounds in the emissions and, if they could be present, the associated emission factors in both smoke and water. It should also be mentioned that some country-specific guidelines may exist, either for evaluating the environmental impact, such as in France (20), or for the steps to follow after the fire for cleaning operations, as in the US (21, 22). In both cases, those documents deal with all types of fires and can be applied to BESS fires, as well.

2.3 Toxic compound emission pathways

Because environmental contamination depends on a fire's characteristics, defining the fire scenario is the first crucial issue when discussing the environmental impact of a fire. One can meet such an objective using a generic risk analysis or by utilizing a fire database. Because numerous BESS fires have occurred during the last decade, it seems more representative to use lessons from those fires to build the emission pathways. To meet this objective, the data obtained in real fire cases should be analyzed while considering the limitations of the sampling and characterization methods used. Also, a fire database analysis should be done while keeping in mind the potential failure modes (root cause, battery chemistry, battery SOC, battery configuration, etc.), which are also described in (23).

Another important parameter when dealing with the environmental impact of fire is the firefighters' strategy for such fires. While water remains one of the most efficient solutions for Li-ion battery fires, the water application strategies may differ. While for small to medium size systems, submerging the battery into a large quantity of water appears to be an efficient solution (24–26), this is not possible with BESS. In such large systems, two methods of application during an emergency are considered:

- Application by the automatic suppression system when such a system is installed
- Application by firefighters

With these different application methods, the potential contamination of water will vary.

This water application strategy will be more explicitly detailed in the following section related to the description of relevant fires to establish a link with the existing water contamination analysis that can be done in a laboratory.

Although the actual health impact due to toxic/pollutant emissions is beyond the scope of this study, it may be useful to note that overall toxicity rating in practice remains a complex issue, despite decades of dedicated research on the matter. It differs depending on the effects considered, the exposure time, and even the method used (explaining gaps from one country to another). For illustration, Table 3**.** provides various toxicity indicators for the inhalation oral exposure route. The values presented in the table correspond to short-term exposure — about 10 minutes — to represent a typical exposure time during an evacuation process. While AEGL n°1 corresponds to the concentration at which the general population will suffer from reversible discomfort or irritation after exposure, the AEGL n°2 threshold represents the occurrence of irreversible and severe effects that can last over a long period of time. The AEGL n°3 threshold also indicates the value at which death can be induced after exposure.

Chemical	Approximate odor threshold [ppm]	AEGL 1 10 min/30 min [ppm]	AEGL 2 10 min/30 min [ppm]	AEGL 3 10 min/30 min [ppm]
Carbon monoxide	—	—/—	420/150	1700/600
Hydrogen chloride	< 5	1.8/1.8	100/43	620/210
Hydrogen fluoride	< 5	1.0/1.0	95/34	170/62
Nitrogen dioxide	0.5	0.5/0.5	20/15	34/25

Table 3: Various toxicity indicators for oral route contamination, ref EPA/AEGL.

Table 3 illustrates that the critical threshold value may vary significantly based on the chemical and exposure time, so care must be taken when considering emissions both in terms of toxic species identification and related emission factors.

2.3.1 Analysis of most relevant fires

2.3.1.1 General context

Many fires involving LIBs have occurred in the last decade. Because they are used in so many installations (e.g., mobility, stationary, and portable device applications), many have occurred in BESS. The objective of this section is not to give a detailed description of each event but to provide the most relevant accident parameters in the context of the present report, i.e., the potential environmental consequences of such a fire. This shortlist considers fires in the United States, but also in the UK, France, Australia, and Korea, where more than 30 fires involving BESS have occurred in less than a decade (some 40 percent of the total recorded BESS failure events to our knowledge). These short descriptions of relevant fire events mainly aim to describe the potential environmental impact with a focus, when available, on the emission pathway, both in the atmosphere and through fire water run-off resulting from firefighting operations.

It should also be noted that some databases have been created to provide an updated listing of fires involving batteries, such as Electrical Power Research Institute's (EPRI) BESS Failure Incident Database in the U.S.: https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database. Statistics confirm that the failure rate in BESS has significantly decreased nowadays (in terms of the number if gigawatts installed) compared to early events that occurred at the beginning of BESS development. However, as more and more BESS are installed, fires in BESS remain a reality, as confirmed by the number of fire events in 2021, 2022, and 2023 (Figure 6) (27).

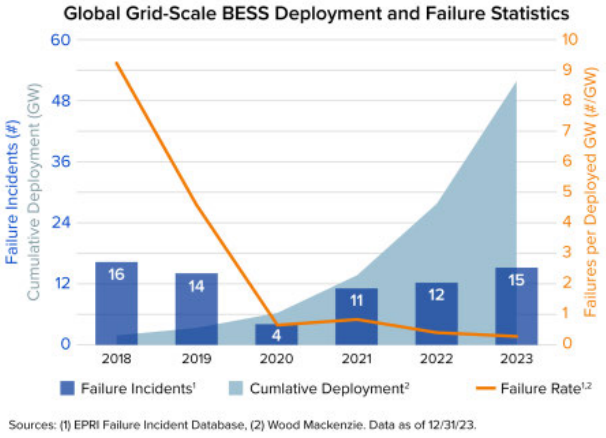


Figure 6: Some statistics drawn from the EPRI Failure Incident Database (extracted from the EPRI database website, as accessed June 2024) (27).

While the failure rate normalized to deployed gigawatts (GW) has reduced over time (usually due to system maturity and improvement) (Figure 6), it should be noted that the absolute number of incidents has increased due to the increased deployment of BESS.

During incidents involving Li-ion batteries, effluent analyses are sometimes (though rarely) mentioned, but neither the sampling conditions (method, location, duration after the incident, etc.) nor the results are reported. Among the events presented below, no significant environmental pollution is mentioned, except in the case of the Portland incident, for which legal action is underway.

An important aspect when analyzing after an event is the limitation of post-accidental analysis. It is generally very difficult because data sampling is not systematic when a fire occurs and sampling can be polluted by other sources, even considering that analysis requires a comparison to a zone that has not been exposed to smoke from the fire. It is clear that, when a fire occurs, defining zones where deposit might occur and the species to be measured is very challenging. Moreover, once this first challenge is overcome, post-accidental sampling remains imperfect as it depends on the sampling method used, sampling location, and analysis method used. For the fires described in the following paragraphs, the available measures are discussed.

2.3.1.2 Examples of fires involving LIBs

Hereafter is a list of some fires that occurred in the last decade involving LIBs. This list is focused on BESS but not limited to them, as some other fires are relevant for the present analysis (for instance, pointing out water contamination, post-thermal runaway (TR) emissions, large plume formation, and so on).

- **Saint-Quentin-Fallavier, France, 2012:** A fire started in a vehicle battery recycling facility. The firefighters pumped out the extinguishing effluent, but rainwater run-off reached the nearby canal. Samples taken by the Regional Directorate for the Environment, Development, and Housing (DREAL) showed no heavy metal pollution in the river, possibly due to heavy rainfall that diluted the chemicals.
- **Surprise, AZ, USA, 2019:** A utility-scale battery storage facility (with a container configuration) experienced a thermal runaway event that led to an explosion, injuring four firefighters. The incident raised awareness about the hazards of LIB storage, including the risk of post TR-driven flammable and toxic gas emissions and the need for emergency responders to be trained specifically for battery fire incidents.
- **Liverpool, UK, 2020**: This incident was monitored by a Hazardous Materials and Environmental Protection Officer. On arrival at the scene, around 3 hours after the incident started and 2 hours after water was used, the officer took pH measurements of the water, which had a pH of 8. An hour later, the measurements revealed a pH close to 7 (neutral). At the end of the intervention, the extinguishing water still had a neutral pH, but the stagnant water inside the container had a pH close to 14 (28). A potential presence of base alkali in the water was suspected. All the water was drained off without being retained. To explain the basic or neutral pH in the water evacuated by the drain, the report mentions it could be due to the presence of calcareous elements in the

drains or the high dilution of the extinguishing water. In the container, the basic water was explained as being due to the presence of metals such as Co, Ni, or Mn, though their presence wasn't confirmed by the analysis.

- **Perles-et-Castelet, France, 2020:** Excerpts from the Investigation Report on the fire in a battery storage container at an RTE transformer substation in Perles-et-Castelet (09): "In total, taking into account the extinguishing phase and the monitoring phase of the fire, which required intermittent spraying, BEA-RI estimates that around 180 m^3 of water was needed to manage the fire (29). Some of this water vaporized during the extinguishing phase. The facts that the site is not fully waterproof, and the absence of a retention basin, make it difficult to estimate the volume of extinguishing water that may have seeped into the ground."
  "The accident at Perles-et-Castelet showed that the container alone could not retain the fire water (too much water, damage to the floor during the fire). It is therefore necessary to provide for physical or organizational measures to avoid impacts linked to extinguishing water, especially when environmental issues are identified in the plant's environment (surface water, sensitive groundwater, catchment and protection perimeter, etc.)."
- **Geelong, Australia, 2021:** In this incident, it was decided not to attack the burning container directly, but to spray the surrounding area to prevent propagation to adjacent systems. The water used to protect the adjacent containers, which was therefore unlikely to be affected by combustion products, was collected by Tesla and analyzed by a third-party laboratory. The laboratory found that under the intervention conditions decided by the responders, "the probability of the fire having had an impact on the water is minimal." As a precaution, however, the 900 m^3 of water used was pumped out and reprocessed. The fire plume is visible in Figure 7.

Figure 7: The starting fire plume at the Geelong BESS module (taken from web source: https://www.abc.net.au/news/2021-09-28/fire-at-tesla-giant-battery-project-near-geelong-investigation/100496688, accessed June 2024).

- **Morris, IL, USA, 2021:** During this major incident, which lead to the burning of 184,000 pounds of stored lithium batteries (30), the Environmental Protection Agency (EPA) monitored air quality in real-time by analyzing the surrounding air (via VOC, O_2, H_2S, CO, explosimeter, HF, and particulate matter measurements) and other potential environmental hazards resulting from the fire. The EPA also did soil and water sampling to determine whether contaminants from the fire impacted surrounding communities or water sources (such as the nearby Illinois River). Unlike the air analysis data, the results of the water analyses are not known, but the EPA is taking legal action, particularly regarding the "release of pollutants into the air and water."
- **Colomiers, France, 2021:** A large fire occurred in a warehouse that stored LIB batteries for bikes. During this incident, Eau de Toulouse carried out an initial visual inspection and took samples to measure any pollution in the natural environment. Few details are available, except that the samples did not suggest any pollution.
- **Moss Landing, CA, USA, 2021 and 2022:** This facility experienced two separate events of overheating, the first in 2021 and the second in 2022 in the largest BESS fire at that time. In September 2021, multiple battery modules overheated. The overheating was detected by the facility safety system, activating several sprinklers targeting the overheating modules. This resulted in the facility being temporarily shut down until July 2022. In September 2022, the separate Elkhorn BESS, a single battery pack within the system, caught fire and was contained.

Local residents were briefly advised to shelter in place due to the risk of hazardous material release. The larger Moss Landing BESS was not affected in the latter incident.

- **Ulsan, Korea, 2022 (the 34th accident in Korea with this type of installation):** This event involved a huge installation, a 51 MWh system with more than 2,000 batteries on three floors. According to the system's specific geometry, as shown in Figure 8, the firefighters' response was difficult.
- **Ubo-Myeon, Korea, 2022 (35th accident in Korea):** Some days after the previous event, this fire happened on a relatively smaller installation — 1.5 MWh — but it remains interesting as this system was equipped with a detection and automatic extinguishing system meant to prevent thermal runaway propagation from one rack to another. The safety systems were activated during the fire but did not prevent the fire propagation. A noisy explosion was also noted during this accident, which was likely similar to that in the Surprise, Arizona, case.
- **Poggio, France, 2022:** A BESS container caught fire in the small hamlet of Corsica. The firefighters chose the “let it burn” option based on the environmental conditions and to protect only the container by applying water. A water shield ensured some smoke abatement. This intervention led to limited polluted water spread, as only 600 m^3 of water was sprayed, but it resulted in significant smoke emissions.
- **Aghione, France, 2023:** A major incident was recorded at one of the two on-site containers of a photovoltaic power plant, also in Corsica. A fire started in a 4.2 MWh container. A succession of water projection and resting periods with IR camera monitoring was used for four days to suppress the fire and impede its propagation to the second container. In the end, a significant amount of water was used and potentially polluted (evaluated at between 10,000 m^3 and 15,000 m^3), but most of the BESS was preserved.
- **Viviez, France, 2024:** This event does not involve a BESS, but it is relevant to dealing with the environmental impact of fire as it induced a significant smoke plume (as shown in Figure 9) and involved about 900 tons of LIBs. Due to concern for the population, the firefighters conducted toxic measurements in the neighborhood during the fire [as can be seen on the Cartam website (31)]. Those located within 500 meters from the fire were confined for the whole day. This event highlights the importance of predicting the potential environmental consequences of a LIB fire.
- **Hwaseong, Korea, 2024:** A major fire occurred in a Li-metal battery manufacturing plant (32). This large fire led to at least 22 deaths and produced a major plume that covered the neighboring industrial area.

Figure 8: Picture from the Ulsan fire (Korea), which occurred on a 51 MWh BESS.

Figure 9: Picture of the fire plume during the battery fire in Viviez (France).

- **Moss Landing Vistra Power Plant Fire, CA, USA, 2025[5]:** A lithium-ion battery fire broke out at the Moss Landing Vistra Power Plant on Thursday, January 16, 2025. As of the date of writing this report, the cause of the fire remains unknown. The incident began on January 16th, when a blaze broke out in the 300 MW Phase 1 building of the facility, which houses lithium-ion batteries used for energy storage (BESS). The fire prompted the evacuation of approximately 1,500 residents due to concerns over toxic smoke and potential health hazards. On January 22, 2025, Monterey County's Board of Supervisors unanimously approved a state of emergency.

  Vistra Energy, the plant's operator, initiated efforts to de-link damaged batteries to prevent future incidents. However, on February 18, the fire reignited at the Vistra Moss 300 structure. The flare-up was eventually contained to a previously burned structure from the initial January 16th incident. On February 19th, the flare-up began to burn down and was contained, though agencies have continued to monitor the site. Some wisps of smoke were still visible in the following days.

  Several investigations have been undertaken since mid-January by several agencies to assess the potential impact of the fire on the area. The investigations include the following:

  1. *Soot model*[6]: This model was formulated using real-time and predictive weather modeling for three 24-hour periods during which the fire was burning, along with information about the materials involved in the fire. The soot model was produced by the Interagency Modeling and Atmospheric Assessment Center (IMAAC). These models were designed to be conservative and provide the highest level of public health protection, assuming that all the batteries burned. The model indicates a general impact area extending approximately 0.6 to 1.2 miles from the fire site, with winds toward the east and north.

  2. *Air investigations*: During the period from January 16 to January 21, 2025, the Monterey Bay Air Resources District (MBARD) initiated air quality monitoring for particulate matter following the Moss Landing fire. Additionally, the U.S. Environmental Protection Agency (EPA)[7] conducted its own air quality assessments. Air monitoring efforts focused on monitoring

[5] 2025 Moss Landing Vistra Power Plant Fire | County of Monterey, CA
[6] Soot (Particulate Matter) Air Monitoring Model | County of Monterey, CA
[7] EPA Completes Air Monitoring Near Moss Landing Vistra Battery Fire | US EPA

hydrogen fluoride (HF) 2.5 and 10 μm particulate matter (PM2.5 and PM10) from nine measurement stations. Two stations were installed on-site, and four were set up just outside the site, including one in Moss Landing. Additionally, three stations were positioned in communities located to the east of the fire, to the south near Castroville, and to the north near Moss Landing Middle School.

The monitoring stations were positioned to account for variations in wind direction and potential drift toward neighboring communities. The findings indicated that hazardous compounds monitored at the onset of the incident were not detected above health action levels. Furthermore, particulate matter levels remained within good to moderate thresholds on the Air Quality Index (AQI), suggesting that air quality was largely acceptable during this time.

The Center for Toxicology and Environmental Health (CTEH) conducted community air monitoring (real-time air monitoring using handheld monitoring equipment) in the area surrounding the fire (including two elementary schools and one high school). Air monitoring was performed using direct-reading instruments to assess potential community exposure to hydrogen fluoride (HF), hydrogen chloride (HCl), carbon monoxide (CO), hydrogen cyanide (HCN), and particulate matter (PM2.5). During this monitoring period (from January 17 to 22), no detections occurred, except for PM2.5. The AQI for PM2.5 monitoring during the reporting period was in the "good" range based on the average particulate concentration.

3. *Soil and water investigations*: on January 24, 2025, the Department of Toxic Substances Control (DTSC) collected samples of soil/sand and surface water from multiple locations near the battery facility (surface soil was taken from eight locations, surface sand from one location, and surface water from nine locations). Metals and polycyclic aromatic hydrocarbons (PAHs) were analyzed as fire-related chemicals. The Office of Environmental Health Hazard Assessment (OEHHA) evaluated the results and compared them to human health screening criteria.

Preliminary results of soil testing showed that metal and PAHs concentrations in six of the eight samples were below residential soil screening levels. Site 8 (the closest to the facility) had cobalt levels exceeding both the residential soil screening level and regional background levels, but PAHs remained within safe limits. Site 5 (located to the southeast, approximately 3.5 miles from the facility) had PAH concentrations exceeding residential screening levels. This latter location will be further investigated to better understand the high levels of PAHs.

Research scientists at San José State University's Moss Landing Marine Laboratories (MLML)[8] also detected unusually high concentrations of heavy-metal nanoparticles in marsh soils at Elkhorn Slough Reserve following the fire.

4. *Surface wipe sampling*[9]: On January 24, 2025, a community organization conducted an environmental sampling to assess heavy metal contamination on surfaces potentially resulting from smoke plume emission fallout from the fire. A total of 124 surface wipe samples were collected from areas within and around the greater Monterey Bay area including locations near the facility (the source of the fire plume), as well as within areas as far as 30+ miles out. The sampling utilized prescribed sampling collection media and standardized wipe collection methods. The samples were analyzed to identify the presence and evaluate the extent of potential "marker" contamination known to be associated with lithium battery fire emissions including the heavy metals lithium (Li), nickel (Ni), manganese (Mn), and cobalt (Co). The samples were collected from identified outdoor (non-metallic) surfaces believed to be exposed to potential fallout from the smoke plume.

The analytical results (μg/100cm²) indicated elevated contamination levels on certain surfaces within approximately 15 miles of the fire site for all four target metals in the collected dust

[8] https://elkhornslough.org/moss-landing-battery-fire/
[9] Community Organization Conducts Surface Sampling for Heavy Metals Following Moss Landing Fire: Indybay

deposits. The highest surface concentrations of the four targeted metals were found in samples collected to the east of the facility, as well as in Watsonville.

At this stage, no comparison to any local reference or baseline values has been mentioned and no results were correlated with the evolution of the fires and smoke plumes, considering their directions and intensities, to better understand the geographic extent of the fire's impact and the associated dynamics. Only a qualitative assessment between areas can be conducted.

However, to accurately assess the health and environmental impacts of the fire, it is crucial to conduct comprehensive analyses across multiple exposure matrices, including air, soil, water, and food products. These assessments should focus on key pollutants, such as PAHs, PCDD/Fs, VOCs, PCBs, metals, and others, while also considering their respective environmental phases.

Since February 22, 2025, a multiagency public health assessment team has been mobilized to conduct a comprehensive evaluation of potential public health risks and environmental hazards associated with the site. Indeed, preliminary results from the assessment underscored the necessity for continued environmental monitoring, particularly in areas exhibiting elevated levels of contaminants.

2.3.1.3 Fire cause analysis

BESS, like any other types of Li-ion (23), can suffer from thermal runaway, which can lead to a fire. Several root causes have been identified and can be classified into four main categories:

- Electrical abuse
- Thermal abuse
- Mechanical abuse
- Internal defect

Depending on the root cause, the resulting thermal runaway behavior can be modified as demonstrated by Wei *et al.* (33). At the BESS level, a large variety of solutions/processes can reduce the occurrence of such abuse; for instance:

- A battery management system (BMS) that can limit electrical abuse
- A cooling system that can reduce potential overheating
- Maintenance procedures that can limit potential mechanical abuse or formation of electric arc by tools that are dropped

However, even though such protections have been proposed, the risks of BESS misconception (e.g., underestimation of the cooling system required, insufficient current segmentation systems, accumulation of moisture, inefficient cell balancing, improper definition of the sensor location compared to battery size, misleading alert flag definition, and so on) cannot be ignored. Also, an internal defect (e.g., insertion of metallic particles during the fabrication process or dendrite that can build up during the life of the battery) can still affect thermal runaway, as detecting such defects is quite challenging.

When it comes to evaluating the major causes leading to BESS fires, EPRI white papers can provide some insights. According to EPRI’s research, the root causes of BESS fires can be attributed mostly to integration, assembly, and construction issues (accounting for 36 percent of the cases studied), while the second most common root cause is operation (29 percent). The rest is attributed to BESS design (21 percent) and manufacturing (14 percent) (27).

In addition, an analysis recently published by Clean Energy Associates (CEA) (34) shows that the integration of lithium-ion cells in BESS may lead to significant quality issues. Based on the inspection conducted by CEA, it appears that more than 25 percent of existing BESS system suffer from quality issues related to automatic detection and firefighting systems. This analysis aligns with observations from past BESS fire events, which have frequently reported malfunctions in safety systems.

Furthermore, the same inspection report reveals that nearly 1 in 5 containers suffer from quality issues in their thermal management systems. This is particularly concerning given the crucial role of thermal management in preventing thermal runaway events, which can lead to catastrophic failures and fires.

It is worth pointing out that even if great care is taken in both cell selection and integration and it is confirmed with robust quality control, risk will always remain. Given the large number of cells integrated into BESS (23) and the inherent risk of internal defects, there is always a probability of encountering a cell defect within a BESS.

2.3.2 Learnings about environmental impact of BESS fires

Lessons learned and post-event analysis of BESS fires have been largely limited to the safety impacts on first responders and the public. After the 2019 BESS fire in Surprise, AZ, a technical analysis report was published by DNG LV, and a first responder report was published by the UL Fire Safety Research Institute. The UL report specifically noted that current HAZMAT training curricula do not cover basic hazards from energy storage systems. To fill the gap, NFPA has proposed dedicated training, such as their NFPA 855 course on energy storage systems, which they offered in London in May of 2025. In France, several events have been investigated by the BEA-RI, [such as in the case of (29)] a newly established public office with authority to investigate industrial accidents. While the immediate risk of explosion and acute toxicity remains the primary focus, those reports commonly mention the measures taken to prevent pollution.

The fires themselves are known to release compounds that may lead to acute toxicity threats depending on the concentrations and exposure time, including CO, HF, hydrogen cyanide (HCN), and electrolyte solvent mist. A battery fire can also release particulate matter that is normally contained within the battery and may contaminate the immediate environment. Research on these particle emissions is still in its infancy (35–37), although it has been identified as a real topic of interest in the recent review from Li *et al.* (38), as shown in Figure 10. One certainty to consider: particle emissions differ considerably from conventional particle matter emitted in hydrocarbon fires, particularly due to their metal content.

To broaden the knowledge of BESS fire environmental impacts gathering real case data is of paramount importance. As seen in accident analysis, very few data are shared, some also remain partially performed as not all environmental media are analyzed, which impedes to get the general overview of fires impacts on environment. To fill the gap, Figure 10 summarize the approach to implement to get relevant samples method to carry a full environmental impact study considering all media: soil, water and air. While at first, pollution of air and extinguishing water is advised along the event, in immediate follow-up soil and surface water (as lake and rivers for instance) should be scrutinized. Then, after the event, contamination of soil, surface water is still required with in addition a focus on plants and farming products as well as groundwater might be required.

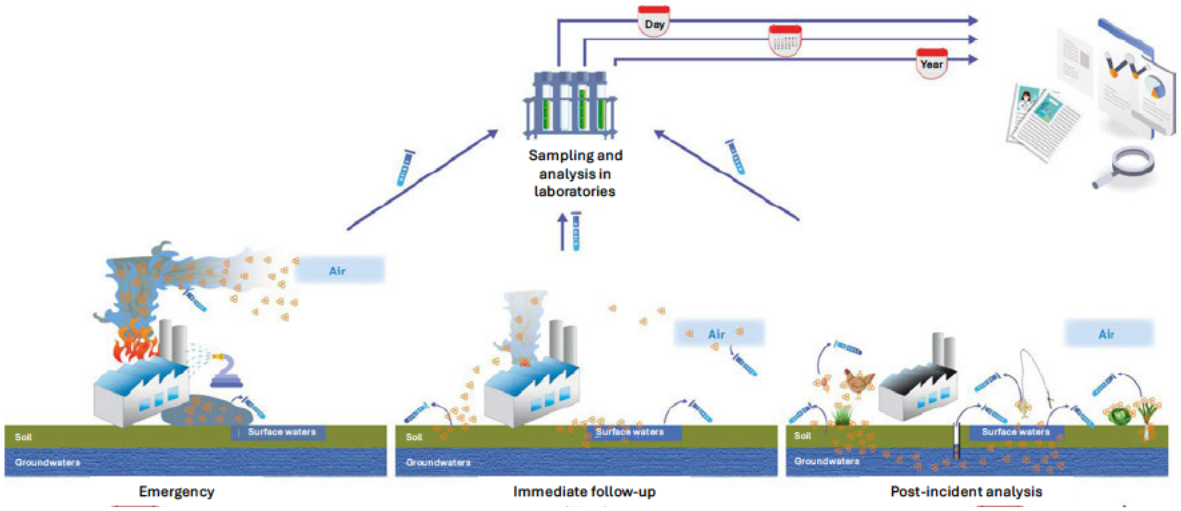


Figure 10: Sampling required on several environmental media during and after a BESS fire.

Reference	Battery characteristics	Achievements	Limitations/comments
Li et al.	50 Ah NMC311, prismatic	Mass, size, and composition of particle measurements	Few elements were analyzed
Li et al.	50 Ah NMC311, prismatic	Full element content of particle analysis	Lack of composition analysis of particles
Essl et al.	41 Ah NMC/LMO, pouch	Particle morphology analysis using SEM couples with EDX to detect particle elements	Gas analysis without particle analysis
Chen et al.	2.6 Ah NMC/LOC, 18650	Thermal characteristics of emitted particles with the influence of boundary, SOC ... The explosive properties of the powder were also examined	
Wang et al.	50 Ah NMC 311 prismatic	Thermal oxidation characteristics and particle size distribution, focus on the reactivity of smaller particles	Limitation of the analyzed components
Wang et al.	42 Ah NMC 111 prismatic	XRD analysis of particle composition	Limitation of the analyzed components
Premnath et al.	2.3 Ah LFP 18650	Total emissions and solid real time PN/sier, real time carbon black, organic carbon, and elemental carbon distribution	Limited species analysis (only elemental detection) with granulometry
Barone et al.	NMC, LFP, and LTO	Morphological and elemental composition characteristics of explosion particle emissions	Limited species analysis (only elemental detection) without granulometry
Yang et al.	NMC311 and NMC811	Particle size, morphology, and element comparison between the two chemistries	The battery information is unclear
Buston et al.	1.75 Ah NMC pouch	Metals in the smoke particles found to come primarily from the cathode and slight differences in the composition of particles at different locations	Only metal contents analyzed
Bordes et al.	NMC111 (pouch cells 70 Ah)	Elemental composition of particles emitted by cells, clusters, and modules	Elemental analysis limited, performed on a 3-cell cluster
Niu et al.	NMC811 modules	Morphology and element differences for various SOCs	Morphology differences are not explained, elemental analysis is incomplete
Wang et al.	NMC 111, NMC 523, and NMC 311	Particle characteristics comparison	Reduced gas analysis, no particle analysis

Figure 11: Brief analysis of recent studies focusing of battery particle emissions, inspired by Li et al. (38).

The remains of a BESS must also be collected and disposed of as hazardous waste. A large BESS might represent significant solid waste generation, and any comprehensive analysis of this waste has not generally been reported. Typical battery components provide some insight into potential battery residues, including metal oxide particulates and various metals.

Water used to extinguish fires may mitigate the release of pollutants into the air, but the water itself may become contaminated with pollutants from the battery, turning it into a potential carrier of pollutants. Bordes *et al.* (39) demonstrated that run-off water is susceptible to carrying metals mixed with carbonaceous contaminants, as expected based on the compound analysis. These emissions can potentially be released as particles in the nano-size range or as nanostructured metals. Quant *et al.* (40) noted that a significant amount of PFAS compounds were present when the interior of a battery was flooded with water to extinguish a fire. The presence of PFAS compounds, which are known for their persistence and potential health risks, highlights the need for careful consideration of firefighting methods and the subsequent handling of contaminated water.

Furthermore, the environmental impact of these pollutants extends beyond immediate contamination. Nano-sized particles and nanostructured metals can have long-term ecological effects, potentially entering water bodies and soil, thereby affecting aquatic life and plant growth. The persistence of PFAS compounds in the environment further complicates remediation efforts, as these substances are resistant to natural degradation processes. Comprehensive waste analysis and the development of effective disposal and remediation strategies are essential to mitigating the environmental impact. Additionally, the adoption of best practices for firefighting and post-incident management can help minimize the release and spread of hazardous pollutants. Defining a generic strategy is a utopic task because contamination depends on many parameters, such as the presence or absence of a water basin, the local natural surface or ground water distribution, the urbanization surrounding the installation, etc. However, it should be kept in mind that, in some situations, letting the BESS burn could limit the environmental consequences.

2.3.3 Selection of relevant fire scenarios

When analyzing fire scenarios, the factors affecting the scenarios must be considered. For instance, the heat release rate (HRR) highlights the energy released by a combustion. Different types of combustion ranging from smoking to strong flaming combustion can be observed depending on the scenario and can also impact the fire development. In addition, the location of a fire source, as well as topography and environmental conditions such as wind speed can influence a fire scenario.

To select the relevant scenarios for this study, emission pathways observed during the events were considered. Indeed, to draw a link between past fire events and the potential environmental impact, as mentioned in the environmental impact definition, the emission pathways must be categorized. This work was done in the past for other fuels (41) and, thus, is not presented here. The analysis in the present report is focused only on LIB fires and their behavior (explosion or not, significant propagation, high HRR, etc.).

In some cases, the BESS fire records describe a medium peak heat release rate compared to what was expected. Also, in many cases, the fire was limited to one container (when such a modular configuration was used). There are, however, some examples of propagation:

- A fire in Australia propagated to the second container through the roof
- In a case in Beijing, the propagation of gases through cable tunnels led to an explosive atmosphere formation in another location

Furthermore, with the Liverpool fire in 2020, the fire was quite significant. The dynamics of that fire were probably affected by the propagation of the flame and a door being opened, which can lead to a blast event. In addition, the fire that occurred in Hwaseong, Korea, in 2024 in a manufacturing facility is another example of how LIBs can lead to very large fires.

Having a limited heat release rate seems to have a positive effect in terms of thermal spread. However, the consequences for the environment are not so obvious. A limited heat release rate can lead to limited smoke dilution in the atmosphere and, potentially, high deposit concentrations in the vicinity.

Regarding firefighting strategy, most of the events involved using large amounts of water to prevent fire propagation. To prevent cell-to-cell or module-to-module thermal runaway, the fire response at such events have lasted several hours or even days. This means that thousands of cubic meters of potentially polluted water was released, first by the fire effluents and then by the solid waste remaining after the fire.

These pollutants carried by water could impact the environment via the groundwater or, depending on their size and composition, the pollutants could be trapped in the soil, reducing the impact on downstream pollution but increasing soil pollution (which can also result in reactive geochemistry). Understanding the fate of these contaminated particles requires deeper understanding.

It must also be considered that, sometimes, the objective of BESS is to provide electricity in different locations that don't have ample infrastructure or commodities, such as a water supply. In such a scenario, there is sometimes no water run-off basin, so any water used spreads directly to the surrounding environment.

Finally, a key criterion that governs environmental contamination in the case of fire is the thermal runaway propagation kinetic and the resulting number of cells involved during an event. Most of the available data regarding emissions from lithium-ion batteries comes from small scale tests that used a small number of cells. It is clear that comparing the results of those small-scale tests to large-scale fires must be considered carefully. A key criterion for large-scale fire analysis is the number of cells involved in a fire, data that is rarely available post-accident.

2.4 Scientific literature about emission factors

2.4.1 Scientific publication dynamics analysis

While scientific literature focusing on Li-ion batteries is abundant, the number of studies focused on "Li-ion battery" and "safety" is quite significant, as 4,677 papers have been released on the topic since 1993 according to a Web of Science database analysis (as performed 5/14/24). This immense collection of scientific literature highlights the concerns related to safety hazards introduced by LIBs. However, it is worth pointing out that this safety topic only started to draw significant attention from the scientific community around 2010, with only a few papers released from 1993 to 2010.

In the safety field, there has been less of a focus on emissions analysis. Compared to the scientific literature, since 2008, only 230 papers have been released by safety officials using the keywords "Li-ion battery" and "gas emission" and 18 with "Li-ion battery" and "emission hazard."

The lack of extensive data on emission factors could impede a deeper understanding of the underlying risks. The following section focuses on several interesting publications that highlight the characteristics of Li-ion emissions. These characteristics have been broadened with Sandia and Ineris know-how based on their internal experimental characterization campaigns.

It is also important to note that, while it has become a critical topic, PFAS emissions were not, up to now, considered when measuring emission factors.

2.4.2 State of the art

To understand the emission factors induced by LIB thermal runaway, these emissions should first be defined. As a baseline, they can be divided into three main categories, each with a different potential impact on environmental targets:

- Gas emissions
- Aerosol emissions with particles ranging from µm to nm scale, combined with liquid droplets
- Solid particle releases with sizes from mm to above

All these emissions are released into the air and can deposit on soil, leading to pollution. Additionally, they can be transferred to water from extinguishing systems or the surrounding environment. The resulting contaminated water can also pollute soil, groundwater, and rivers as it spreads. Consequently, analyzing scientific papers on water and soil pollution might also provide insights into the characteristics of these emissions.

An important aspect to keep in mind here is that most of the data were obtained at a small-scale, making the real fire analysis difficult. When available, some data coming from intermediate-scale tests have been included in the state-of-the-art description to highlight scale impact. Indeed, as seen in Figure 12,

the results as gas composition evolves with time highlight the impact of upscale on results (emission composition change with propagation of module failure).

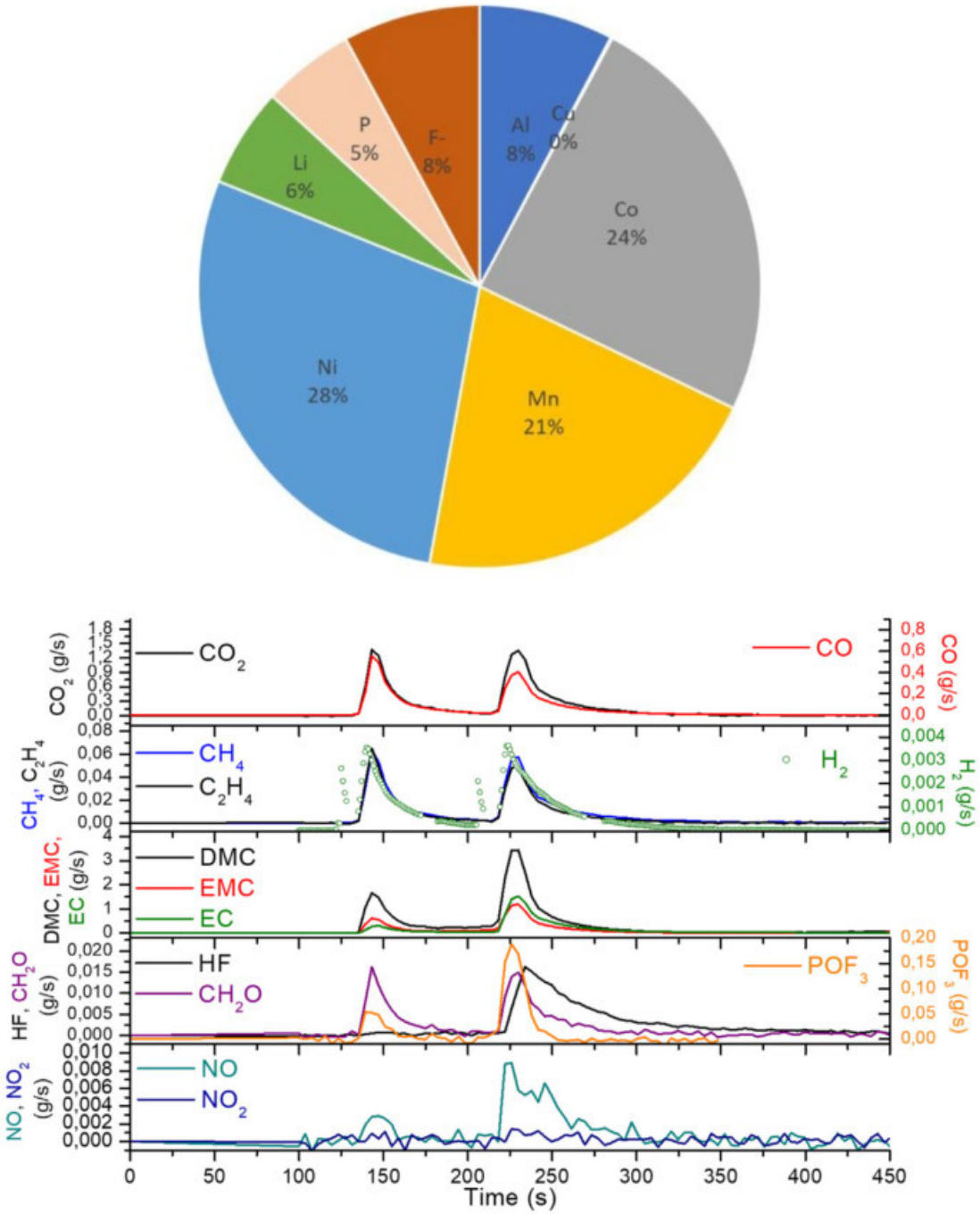


Figure 12: Particle and gas analysis obtained after module short-circuit test (5).

2.4.2.1 Gaseous emissions

Extensive analysis of gas emissions is available in scientific literature. A study by Nedjalkov *et al.* performed on NMC pouch cells triggered by nail penetration highlighted the presence of carbonates resulting from liquid electrolyte vaporization (EMC, EC, DMC), as well as carbon dioxide and carbon monoxide. Other components such as acrolein, benzene, toluene, styrene, biphenyl, and hydrogen fluoride (HF) were also detected, and their associated risks were identified as shown in Table 4 (42). A specific consideration for this table is the absence of other sulfur compounds, mainly SO_2, which is sometimes detected in decomposition products. It is important to note that such products are quite challenging to measure.

Subtance	Hazards According to EU CLP Regulation Act 1272/2008	Flammable	Toxic
EMC	Eye irritation; flammable liquid; H226; H315; H319; H335; skin irritation; specific	O	
DEC	Target organ toxicity – single exposure	O	O
EC	Eye irritation; flammable liquid; H226; H315; H319; H335; skin irritation; specific	O	
Benzene	Target organ toxicity – single exposure		O
Toluene	Eye irritation; H315; H319; H335; skin irritation; specific target organ		O
Styrene	Toxicity – single exposure		O
Biphenyl	Aspiration hazard; carcinogenicity; eye irritation; H225; H304; H315; H319; H340		O
Acrolein	H350; H372; germ cell mutagenicity		O
CO	Aspiration hazard; flammable liquid; H225; H304; H315; H336; H361d; H373	X	
COS	Reproductive toxicity; skin irritation; specific target organ toxicity – repeated exposure; flammable gas		O
Hydrogen fluoride	Acute toxicity; eye irritation; flammable liquid; H226; H315; H319; H332; H361d	X	O

Table 4: Hazards associated with some substances that could be released by damaged batteries as identified by Nedjalkov et al. (42).

Amano *et al.* tested NMC cells (19 experiments) and noted the release of CO, CH_4, C_2H_6, and C_2H_4, as well as H_2O and some HCN. NH_3 emission was also reported in a given test series (43).

Maloney *et al.* scrutinized commercial LCO cell gas emissions and concluded they were mostly composed of CO_2, CO, H_2, and total hydrocarbon (THC) (44). Golubkov *et al.* overlooked two Li-ion chemistries. They analyzed the emissions related to commercial 18650 LFP and NCA cells initiated in thermal runaway by a thermal ramp. The main gases detected were similar to those aforementioned. Similar to tests done on NMC cells, H_2, CO_2, CO and some hydrocarbons (such as CH_4, C_2H_4, and C_2H_6) were seen. The gas amount produced reached 317 mmol for NCA cells vs. 61 mmol for LFP cells (45).

Larsson *et al.* underscored the large quantity of hydrogen fluoride (HF) emissions ranging from 20 to 200 mg/Wh, as well as phosphoryl fluoride emission (POF_3) between 15–22 mg/Wh for seven different commercial Li-ion cells (46). Lecocq *et al.* confirmed the release of HF as well as SO_2 and attributed it to salt anion decomposition. They also highlighted the larger amount of CO_X emitted with an SOC increase (47), while Maloney *et al.* highlighted a significant increase of H_2 and CO production with an SOC rise for LCO cells and a more pronounced production of flammable gases above a 50 percent SOC. The increase of overall gas was also clearly demonstrated (44). An illustration of the SOC impact on the total gaseous emissions of thermal runaway proposed by Willstrand *et al.* is reproduced hereafter (48).

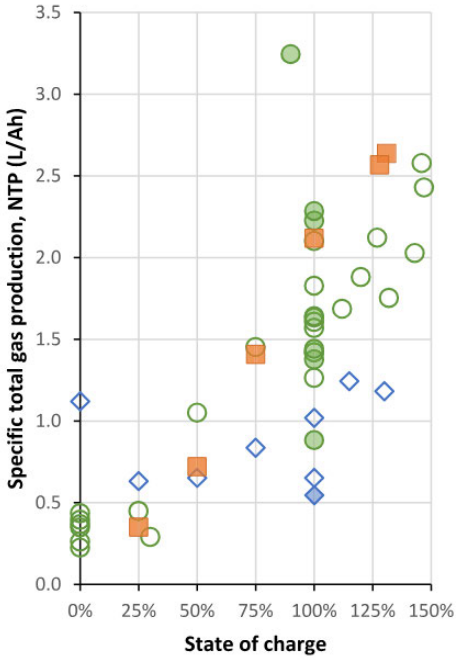


Figure 13: Influence of the SOC on the total gaseous emissions for LIBs, ◊ LFP, ○ NMC/NCA/LMO/LCO ■ values produced by Willstrand et al. (48).

HF production was also compared for NMC, LMO, and LFP cells triggered in inert atmosphere (combustion was limited, so the results reflected vented gas emissions before any further oxidation from outside air supply occurred) by Sturk *et al.* (49). Significantly larger gaseous emissions were observed with NMC and LMO (approximately 180 L/kg) compared to LFP (vs. 42 L/kg), while the same total amount of HF was detected with LFP. The study found that, in proportion, LFP tends to produce more HF than other chemistries, which highlights the gaseous composition of the cell's chemistry (49).

In addition, even for a given chemistry, the gas composition might change with respect to the venting phase or depending on the type of thermal runaway behavior. For instance, Goupil *et al.* found vaporized electrolyte (DMC) emissions with some CO_2 emissions during the first step of venting NCA commercial cells. Meanwhile, the combustion phase led to mostly CO_2 emissions combined with H_2O, DMC, and H_2 at a lower ratio (37).

Based on the most relevant publications, large discrepancies exist when comparing a cell's gaseous emissions depending on the chemistry, conditions, and methods used, as shown by Rappsilber *et al*. (50). While the gas analysis for battery emissions primarily concerns common gases related to combustion, such as CO_2, CO, carbonates, and H_2, it must also consider the specific gases directly linked to key components of the battery field (electrolyte vapor, for instance). For example, HF has emerged as a common emission that must be considered.

This trend is emphasized by the RIVM report (51), which focuses on firefighter exposure risks. The report highlighted the risk of HF damaging skin while also underlining the hazard's limitations, as HF is most likely to be deposited quickly near the location of smoke emissions (51). Overall, most battery fire emissions are made up of CO_2, CO, H_2, vaporized electrolyte, hydrocarbons, HF, and some traces of other toxic and/or flammable gases (SO_2, POF_3, HCN, NH_3, etc.). It is worth pointing out that POF_3 toxicity is assumed to be comparable to HF, though little data is available. Therefore, more attention should be paid to POF_3 release (the few data sources that are available mention just that the compound was present).

While the presence of these gases is well documented, the toxicity of the final gaseous cloud can vary and depends on the combustion taking place (mostly outgassing, for instance, with LFP vs. flaming combustion for NMC). A relevant example is the study of Bugryniec *et al.*, which focused on CO and HF release by NMC vs. LFP Li-ion cells. According to the study, considering the same capacity (10 Wh), an LFP battery leads to higher toxicity (considering the surrounding polluted volume) than an NMC battery. Also, with the reduction of the SOC, which promotes outgassing behavior, a higher toxicity is attributed at 0 percent SOC for LFP compared to NMC (due to both higher CO and HF emissions) (52).

Also, it should be noted that, among all those publications, only gases that could induce an acute toxicity threat or risk of explosion were considered. Products such as PAH and VOC were generally not considered. PAH and VOC were usually involved in the analysis only when dealing with water pollution, as will be discussed below.

2.4.2.2 Aerosol emissions

While many studies have been published regarding gaseous emissions, aerosol emissions from Li-ion batteries have not been that extensively examined. Some publications still provide insights, such as Barone *et al*. (35), which compares aerosol composition with respect to electrode composition (NMC, LFP, and LTO). Abundant aerosol was produced by NMC commercial 18650 cells, with various particle sizes (0.03–0.1 µm nanoparticles, 0.1–3 µm microspheres, and 5–10 µm fragments). The NMC microsphere aerosol contained nickel, aluminum, and a mixture of carbon, fluorine, and oxygen, as well as fragments made up of transition metals, nickel, manganese, and cobalt. A more homogenous aerosol resulted from LFP cells 26650 subjected to thermal abuse, with cenospheres ranging from 0.6–5 µm and containing carbon, silicon, and fluorine. Aerosols produced by LTO cells included a mix of the NMC and LFP emissions, as 0.1–4 µm cenospheres were noticed as well as particles containing cobalt and titanium. In the end, no matter the chemistry, aerosols in the respirable size range were released by the NMC and LTO cells, which poses a health risk due to the presence of cobalt and other transition metals (35). Production of aerosol in the respirable range was also confirmed by an EPRI study that found high levels of PM2.5 (up to 1432 g/hr) after four NMC cells were exposed to thermal abuse in different heating conditions (53).

The finding that more particles were produced with NMC cells compared to LFP cells is supported by Bergström *et al.*, as the total suspended particle detected reached 1.4 g/m^3 for LPF1, 5.37 g/m^3 for LFP2, 7 g/m^3 for NMC1, and 5 g/m^3 for NMC2. It is worth pointing out that the gap for LFP was significant in between trials compared to NMC. On average, 36.5 g/m^3 were detected by ICP-MS for LFP while 47.5 g/m^3 were detected for NMC (54).

Buston *et al.* focused on emitted smoke and deposited residues coming from LCO, NMC, and NCA commercial cylindrical cells under thermal runaway. All the metal species expected found in the samples based on cathode composition were found no matter which cell was considered; only a change of the ratio was detected with respect to sampling location (55). Moreover, Wang *et al.* described a change of composition ratio when classifying the particles based on their size (for NMC prismatic cells triggered in TR). They divided the particles collected after deposition (particle size ranging from 1 to 2000 µm) into five categories. When the particles were analyzed, Ni and Al appeared to be the two major metallic species, in addition to Cu, Co, Mn, and Li. Nonmetallic species were also found (C, O, F, Si, P, and S) with the majority being C, O, and F (56). Zhang *et al.* confirmed the presence of metallic and non-metallic species in particulate matter (aerosol particles up to fragments of several mm), with 40 percent of the matter being made up of nonmetallic components. The particulate matter (considered up to a size of 8 mm) accounted for 11.20 percent of the cell's mass and was mainly made up of matter below 0.85 mm (198 µm) (57).

Smaller particulate emissions were also recorded by Goupil *et al.* for NCA 18650 cells. A bimodal distribution was recorded, as shown in Figure 14, with a peak below 50 nm and another around 125 nm (37).

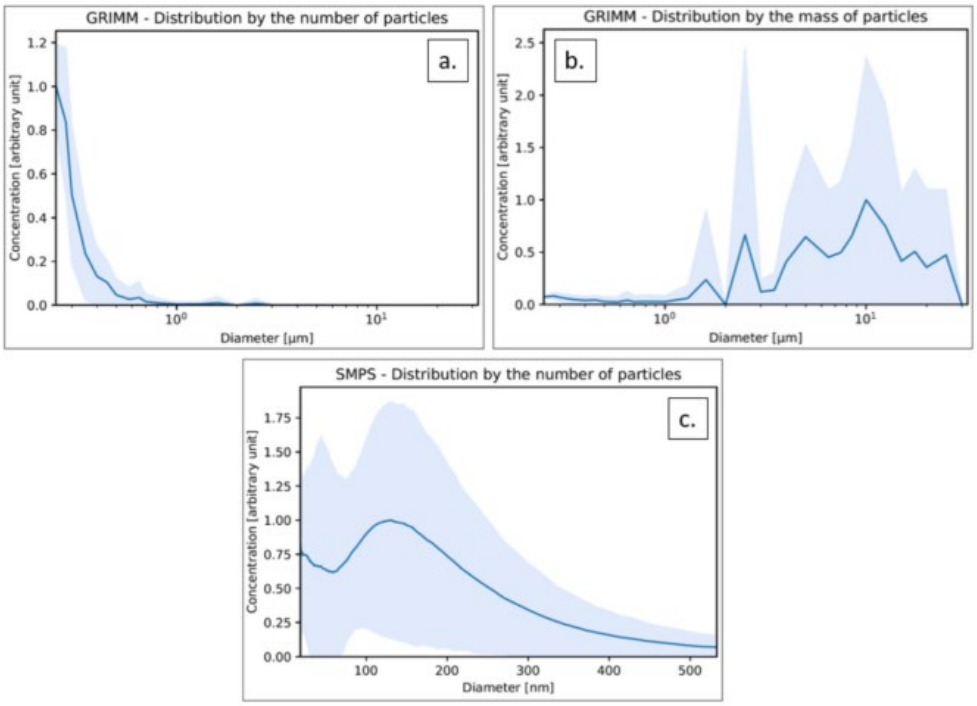


Figure 14: Particle size distribution released by heated NCA 18650 (37).

Premnath *et al.* (58) also detected solid particulate matter (PN) (5.6–560 nm) in a bimodal distribution during some tests on LFP modules regardless of the application of overcharge or nail penetration. For the total PN, however, no such bi-modal distribution was observed and a more pronounced quantity of PN was recorded for LFP modules triggered by a nail test compared to an overcharge case (58). This highlights that particle emission is also linked to the abuse method. The study also highlighted large particle production with PM2.5 emission higher than 375 g/h for NMC and LFP modules and a total PN emission of more than 2.10^{17} part/h (58).

Despite the wide variety of solid particle sizes analyzed, comparing the results from literature is not that trivial. Some conclusions could yet be drawn:

- Significant cell mass loss induces particle production (more than 10 percent), which produces large particles with large systems such as BESS
- Extensive study of the composition of particles has yet to be completed. Only elemental analysis has been done and has led to the detection of:
  - Metallic components coming from the electrodes (Ni, Cu, Co, Mn, Al, and Li)
  - Nonmetallic species such as C, Si, F, P, and S
- The risk of pollution to the environment and threat to human life cannot be ignored as:
  - Some aerosol particles are composed of toxic elements
  - Some aerosols can be inhaled due to their size

Aerosols are not only composed of particles but also of liquid droplets. Bordes *et al.* highlighted the presence of undecomposed solvents within wastewater obtained while spraying a NMC thermal runaway module (39). While this contamination could be due to direct electrolyte leakage and vaporized electrolyte condensation, potential contamination by electrolyte droplets within the aerosol cannot be ignored.

It should also be noted that the consequences of inhaling aerosols on human health remains unclear, additional research on this topic is needed.

The majority of the research has focused on identifying the expected components that can be released from battery electrodes and electrolyte composition. Additional focus on gases that are usually analyzed via combustion has also been proposed, and a large range of devices and methods can be used for further research, as shown in Table 5. Unfortunately, most of the available scientific knowledge is based on small-scale testing, as aforementioned.

It is interesting to compare the aerosol emission rates from Li-ion battery fires to other fuel fires. Some data were provided in a previous NFPA report on the environmental impact of fires (15) about particle emissions from fires involving plastic and wood. More specific analysis has shown that most of the particles released by those fires were smaller than 1 µm when considering a number-based distribution. The size distribution can then be compared between Li-ion batteries and more classic fuels. The typical particle emission rate for standard fuel fires is on the order of 10^{-2} g/g, see (15).

REFERENCE	ANALYZED PARAMETER	ANALYTICAL METHOD/INSTRUMENTATION
(39)	Gaseous emission	Gas Chromatography
	Water analysis	Inductively Couple Plasma Optical Emission Spectroscopy
		Inductively Couple Plasma Mass Spectrometry
		Ion Chromatography
		Liquid Chromatography
	Particle morphology	Centrifugal disc method (particle size distribution)
		Transmission Electron Microscopy (morphology)
(42)	Gaseous emission	GC-MS
		Quadrupole Mass Spectrometry
		Ion Chromatography (for HF analysis)
		Quartz-Enhanced Photoacoustic Spectroscopy QEPAS
(43)	Gaseous emission	FTIR
(44)	Gaseous emission	GC
		CO/CO2/O2/Halon 1301 analyzer
		THC analyzer
(45)	Gaseous emissions	Micro GC
(46)	Gaseous emissions	Two independent methods: FTIR + gas-washing bottle
(47)	Gaseous emissions	Paramagnetic analyzer (for O_2)
		NDIR (Non-Dispersive Infra-red) (for CO and CO_2)
		FTIR (for CO, CO_2, O_2, CH_2O, HCN, NOx, SO_2)
(49)	Gaseous emissions	FTIR and GC-MS
(37)	Gaseous emissions	Mass spectrometer
	Particle size	SMPS — GRIMM
(51)	Gaseous emissions	FTIR
(35)	Aerosol characterization	SEM and EDX analysis
(54)	Total suspended particle	ICP-MS
	Gaseous emissions	FTIR
(55)	Aerosol characterization	ICP-AES
(56)	Particles oxidation state	TG- DTA-FTIR
	Particle-specific surface area	Barrett-Joyner-Halenda (BJH) and Brunauer-Emmertt-Teller (BET) methods

	Particle microstructure and elemental distribution	Scanning electron microscope and electronic differential system (SEM-EDS)
(57)	Particle emission	Meshing, Malvern particle size analyzer ElementarAnalysensysteme (for C, S) Tester (Dionex, America) (for F) Inductively coupled plasma mass spectrometer (for P, Si, B, and non-radioactive element)
(58)	gaseous emission	FTIR
	Particle emission	Engine exhaust particle sizer (EEPS) Micro-soot sensor (MSS) Gravimetric PM2.5 filter measurement Carbon Aerosol Analyzer

Table 5: Characterization methods in cited papers.

2.4.2.3 Focus on water contamination

The previous section detailed the possible sources of pollutants and provided guidance on the relevant analyses that need to be carried out to characterize water pollution. Before any comparison, it should be noted that using large amounts of water is a standard method of firefighting operations, but the method of firefighter response can evolve depending on the fire scenario considered. Indeed, the quantity of water used is often unknown and can vary with respect to its availability and the fire profile. This means the concentration of water pollution in each fire scenario is different, making it difficult to evaluate the effects of water pollution. In addition, fire pollution needs to be carefully considered, as residual pollution can come from the original source of the water (e.g., a river).

In addition to the data available at Ineris, four water pollution studies have been chosen for further analysis: that of LCPP (France) on electric vehicles (EVs) (59), dated 2012; that of EMPA (Switzerland) on EV modules (60), dated August 2020; that of RIVM (Netherlands) on small batteries (51), dated 2021; and the Quant *et al.* study released in 2023 (40).

The substances polluting the water differ according to the intervention method chosen. Several firefighting operating modes that make use of water are broken down in Table 6 below.

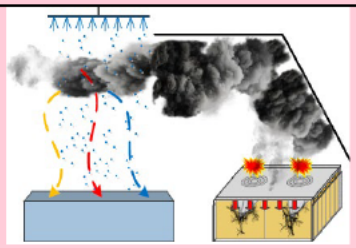
	Direct watering of batteries — when sprinklers or water hoses are applied directly to the faulty system and the water is in direct contact with the batteries.
	Smoke suppression — when water is not applied directly to the system, but the strategy is to spray the surrounding area to suppress smoke and prevent it from spreading to adjacent areas (a method used in the Geelong incident and sometimes at LMP vehicle fires). This scenario may also be of interest for a broader study of the environmental fallout in the event of rain on the day of the incident.
	Immersion water — when the battery is immersed in a large volume of water, either after an incident to cool the sample or during an incident to try to limit the fire (a method sometimes used for electric vehicles or to "deactivate" partially reacted samples). This solution is not considered in this report, as it appears difficult to apply to BESS.

Table 6: Illustration of possible water operation modes for LIBs.

Direct extinguishing water application

1.) LCPP study

Selected extracts from the report: "Fire-fighting water is alkaline water loaded with anions, cations, metallic elements and organic compounds. [...] Lithium, cobalt, nickel, manganese and fluorides were found in significant concentrations. [...] If we compare the concentrations obtained in the extinguishing water with those of the limit values for discharge into the environment for wastewater (decree of February 2, 1998), we can see that for eight parameters, the measured values do not comply. In fact [in some cases], the pH measured [...] is too basic [11 for one of the tests, and] the concentrations of fluoride, nickel and manganese, iron, copper, zinc and aluminum are above the thresholds defined as a monthly average. In the case of manganese and nickel, the concentrations measured [in one test were] well above the thresholds, with ratios between the values ranging from 10 to 20. What's more, these already very high values are undoubtedly underestimated due to the large volumes of fire extinguishing water used for this vehicle (dilution phenomenon).

“On the other hand, non-negligible levels were found for chlorides, barium, methanol, ethanol, cobalt and lithium. To date, we have no comparative values for these compounds in wastewater, enabling us to assess the impact of the concentrations found on the environment. Following a fire involving electric vehicles such as those tested during these trials, the extinguishing water likely to be discharged into the environment may have characteristics that enable it to be considered as a potential source of pollution. However, these sources remain point sources, and the measured values were compared with reference values given for emissions that [were] a function of discharge volumes and correspond to authorized monthly concentration averages. If recovery of fire-fighting water is feasible, then reprocessing by specialized companies would be the best solution. If this is not possible, it is important to rinse the area thoroughly with water to avoid any stagnation of polluted water, which could be potentially dangerous if ingested by living beings.”

This report proposing several tests on the same sample highlights the importance of the incident scenario. In the event of a fire affecting a battery to a great extent, resulting in significant damage to its outer casing, the water appears to be much more polluted than when the battery is found virtually intact. This underlines the importance of early intervention. Similarly, when a fire develops at the system level, other pollutants not specific to batteries can be found (chloride, sulfate, sodium, calcium, strontium, and zinc ions, for example).

The main limitation of this study is that the volumes of water used for extinguishing are not indicated, thus preventing comparison or the possibility of quantifying the amount of the pollutant or extrapolating the results according to the size of the incident.

2.) Ineris Data

A recent study was published by Ineris (39) about run-off water contamination in the case of a LIBs fire. Based on several fire tests with NMC batteries with a dedicated extinction system, this paper gives a detailed overview of run-off water pollution including metals, anions (F^- and Cl^-), and PAH and carbonates, as described in Table 7. A particle size analysis is also presented in this paper together with a transmission electronic microscopy analysis of those particles. An extrapolation to realistic field conditions concluded that some elements were present in concentrations higher than their respective PNEC (predicted non-effect concentration for the environment as defined by European directives), potentially affecting the nearby water ecosystem.

PAH (Polycyclic Aromatic Hydrocarbons)					
	QL	Reference	Test 1	Test 2	Test 3
			(Module A)	(Module A)	(Module B)
Naphtalene (ng/L)	10	<LQ	1279.2	2792.2	3114.6
Acenaphtylene (ng/L)	40	<LQ	2421.7	2405.1	1193.4
methyl-1.naphtalene (ng/L)	10	<LQ	26.8	459.4	667.1
methyl-2.naphtalene (ng/L)	10	<LQ	203.2	<LQ	2058.4
Acenaphtene (ng/L)	2	<LQ	34.1	110.6	275.7
Fluorene (ng/L)	2	<LQ	74.1	752.3	1055
Phenanthrene (ng/L)	4	5.7	360.9	3026.8	2581.6

Anthracene (ng/L)	2	<LQ	10.6	330.5	303.3
Fluoranthene (ng/L)	2	10.8	57.7	1280.9	349.8
Pyrene (ng/L)	2	7.2	45.1	1279.8	20.5
methyl-2.fluoranthene (ng/L)	4	<LQ	7.3	45.1	21.3
B(a)A (ng/L)	2	<LQ	24.8	185.7	131.8
Chrysene (ng/L)	2	<LQ	32.5	212.3	40.8
Retene (ng/L)	2	<LQ	104.9	170.7	19.8
B(e)P (ng/L)	2	<LQ	7.5	306.3	50.4
B(j)F (ng/L)	20	<LQ	<LQ	106.3	<LQ
B(b)F (ng/L)	2	<LQ	34.6	259.6	5.8
B(k)F (ng/L)	2	<LQ	8.3	81	8.2
B(a)P (ng/L)	2	<LQ	13	163.9	20.8
D(a.h)A (ng/L)	2	<LQ	<LQ	36.7	4.5
benzo(ghi)P (ng/L)	2	<LQ	13.3	169.6	4.1
Indèno (ng/L)	4	<LQ	35.2	162.1	11.8
Coronene (ng/L)	2	<LQ	4	54	<LQ

Species	QL	Reference	Test 1	Test 2	Test 3
			(Module A)	(Module A)	(Module B)
DMC (µg/mL)	8.8	n/a	n/a	n/a	n/a
EMC (µg/mL)	8.3	n/a	138	59	n/a
VC (µg/mL)	9.4	n/a	n/a	n/a	n/a
DEC (µg/mL)	8.1	n/a	n/a	n/a	n/a
FEC (µg/mL)	10.2	n/a	n/a	n/a	n/a
EC (µg/mL)	7.7	n/a	1082	461	n/a
PC (µg/mL)	10	n/a	n/a	n/a	n/a

Table 7: PAH content of wastewater after thermal runaway NMC battery sprayed with water (39).

This paper highlights, once more, the importance of considering the cell chemistry and geometry of a battery when dealing with emissions.

Smoke abatement water

3.) EMPA (Swiss Federal Laboratories for Materials Science and Technology)

During these tests carried out in 2020, the Swiss team did not want to spray the burning battery modules for fear of creating an explosive atmosphere, and so they only sprayed the smoke cloud that formed. The results obtained make it possible to study a scenario where intervention is limited to preventing propagation to neighbouring elements. They are also complementary to previous results, which did not distinguish between the proportion of pollutants attributable to the passage of smoke and that caused by direct contact with the battery debris.

The results of these water analyses are shown in Table 8. In this water, the concentration of ions in the solution seemed quite reasonable: the quantity of chlorides, sulfates, nitrates, and phosphates found did not exceed the permitted values for drinking water in Switzerland, while fluoride ions barely exceeded them (x5). PAH pollution was also moderate (x4). The main pollutants were the metals typically found in cathodes: Co, Mn, Ni, and Li. Concentrations of these compounds were 40 to 150 times higher than

authorized values for industrial effluents. Again, in terms of concentrations, the volume of extinguishing water used here was around 200 L for 4 kWh Li-ion NMC modules. The greater the volume of water used for extinguishing, the more likely that concentrations will decrease.

Criterion	Firefighting water	Drinking water limit value	Discharge limit values for industrial effluent
pH value	8.2	6.8–8.2	6.5–9.0
Chloride (mg/l)	2	250	Not specified
Sulphate (mg/l)	34	250	Not specified
Nitrate (mg/l)	2	40	Not specified
Phosphate (mg/l)	<1	1	Not specified
Fluoride (mg/l)	8	1.5	Not specified
PAH (µg/l)	0.001 0.36	0.1	Not specified
Benzo[a]pyrene (µg/l)	<0.001 0.07	0.01	Not specified
Cobalt (µg/l)	36,000 46,000	Not specified (≤70)	500
Manganese (µg/l)	36,000 44,000	50	Not specified
Nickel (µg/l)	36,000 48,400	20	2,000
Lithium (µg/l)	7,000 2,200	Not specified (≤40)	Not specified

Table 8: EMPA fume abatement test results. For PAHs and metals, the first line corresponds to dissolved compounds and the second to particulate compounds (60).

3 Building the emission factors for LIBs

As discussed in the previous chapter, some data exists for gaseous emissions in case of LIB thermal runaway, but measurements rarely enable building an emission factor (EF). Often, only concentrations are given (without the total emissions volume), while some papers do not provide enough details, and the methodologies used for gas analysis can vary. This, coupled with the variety of LIB chemistries and formats, makes building emission factors challenging.

Some papers, however, provide relevant data for building emission factors, but the results can be uncertain. This chapter presents, first, the method used, the specificity of LIBs when dealing with emission factors, and the available data that can be used for such systems.

Once more, it is important to remember that most of the available data was obtained from small-scale tests, making comparison to real situations highly complex. As a result, two specific data points must be considered. First, actual emissions should consider the real fire configuration, as ventilation can vary, and the presence of some other materials can trap certain species and lead to the production of others. Second, the emission factor should represent the emission of a given chemical for the combustion of a given mass of the substance. Determining the emission factor for a whole system would require measuring the real scale combustion velocity, which is a complex issue.

3.1 Methodology for measuring the EF for LIBs

While abuse testing of LIBs is common, the resulting mass loss is rarely reported. Even when measured, the lack of distinction between solid (not only particles but also large fragments) and gaseous emissions makes relevant measurements difficult. Also, potential damage to the weighing system cannot be disregarded and might impede or falsify the final estimation. Thus, having relevant emission factors expressed in grams of emitted gas by grams of fuel burnt, as in the classical combustion domain, is nearly impossible.

Because the objective of a LIB is to store energy, a simple approach is determining the emission factor based on the nominal Watt-hour (Wh) of stored energy. Unless the exact value is given in Wh/kg in the literature, all evaluations made hereafter are based on a generic capacity of LIBs of 160 Wh/kg for a full battery and 250 Wh/kg for a cell or a group of cells without external systems.

There are two ways to estimate the emission factor for LIBs currently. Ideally, the emission factor is included in the published paper that is used to build the database. In that case, the associated work consists only of a verification of the measurement methods used and the test conditions. This approach has been applied, for instance, to Rappsilber *et al.* (50), which analyzed emission factors for select gases and chemistries in 76 different papers. An important warning mentioned in this paper is the lack of data for building specific emission factors for each gas and for different LIBs chemistries. The second method consists of the integration of the emission curves, when available, to estimate the total amount produced for a given gas and then to normalize it to the potential available energy based on the mass of the sample.

Finally, some unpublished data from Ineris, already provided in the previous NFPA report (15), concerns PAH and VOC emissions that could be compared to existing data for electric vehicles (61). The available values in the air matrix should also be discussed in comparison to data obtained for water contamination, presented in paragraph 2.4.2.3 of this document. These products are key substances when dealing with environmental impact and a special focus on them is proposed in this chapter.

3.2 Data discrepancy for generic substances

As mentioned previously, one of the critical inputs for evaluating emission factors is the recent review paper published by Rappsilber *et al*. (50). In this paper, numerous sources were considered to propose a visual distribution of CO emission factors. The emission factor is calculated by normalizing the total amount of a given gas by the cell's energy storage capability. One of the main challenges of this approach is the variety of tests used to derive these values. Consequently, each emission factor may correspond to a different situation, making it difficult to standardize the results.

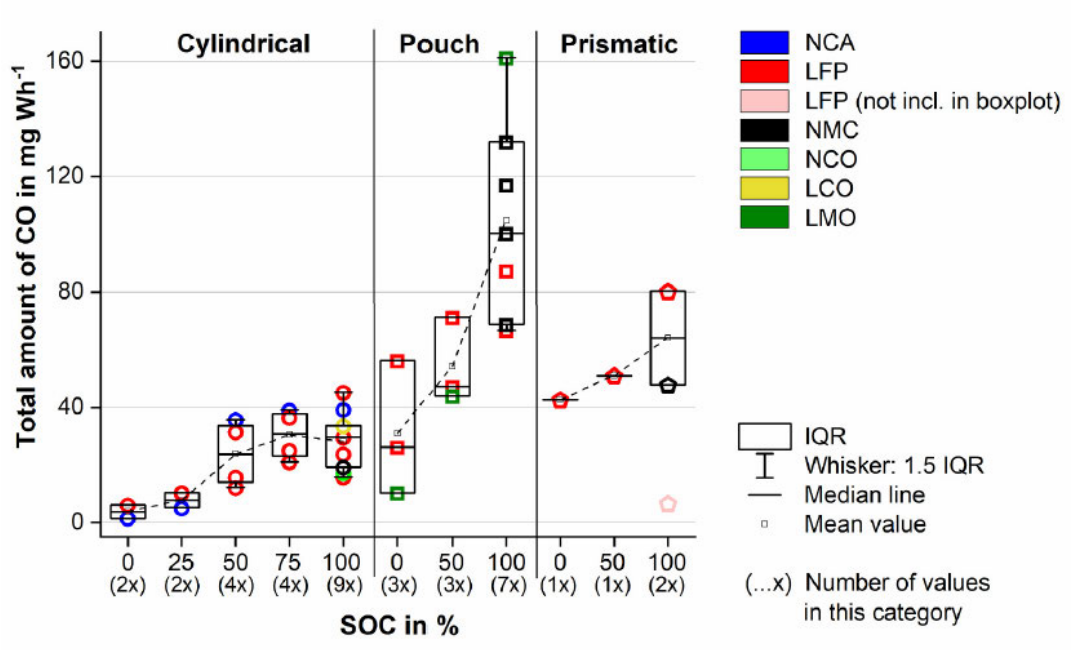


Figure 15: CO emission for different types of LIBs, different shapes and chemistries, and different SOCs, reproduced from (50).

Considering, for instance, the CO emission factors for prismatic cells with different chemistries, data were published by Liu *et al.* (62) for LFP chemistry and by Huang *et al.* (63) for NMC and LFP. In these experiments, a series of four cells was used, and thermal runaway was triggered using a heating plate placed on the outer edge of a stack of cells. Lecocq *et al.* (47) used a different approach, employing an FPA (fire propagation apparatus) calorimeter where batteries were heated by radiant panels. It is important to note that the experimental designs for triggering thermal runaway, as well as the methods for gas collection and measurement, are different. This variability should be considered when determining cell emission factors. However, this analysis only covers a selection of gases, mainly carbon oxides and some flammable products. These gases are not the most critical for assessing the environmental impact of a fire, where HF, PAH, VOC, or PCDD/DF are key issues.

Some emission factor data for HF were still provided in literature by Sturk *et al.*, which emphasized larger emissions in the case of LFP cells compared to NMC/LMO cells (49).

3.3 First steps toward an EF database for LIBs

3.3.1 Emission factors for carbon oxides, halogenated acids, and common gaseous substances

The first highlight of the literature review regarding LIB emissions is the wide range of emission factors. This variability arises due to several factors:

- The nature of the cell chemistry
- The form factor of the cell, which can influence decomposition and combustion processes
- The cell's state of charge
- The sequence of events during thermal runaway, particularly the delay between gas venting and vapor ignition, and whether ignition occurs immediately or not
- The thermal runaway triggering event, as the nature of the trigger can alter the thermal runaway sequence
- The ambient conditions, including the availability of free oxygen, whether the space is enclosed, hygrometry, temperature, cooling systems, and extinguishing method
- The battery's history, such as its state of charge, aging, and whether datasheet limitations have been followed

To illustrate this variability, a range of values is provided in the database rather than a single value.

Regarding emissions, as mentioned previously, only a limited number of gases, the most common ones, could be included in the database due to a lack of data for many critical chemicals that significantly impact the environment.

3.3.2 Emission factors for PAH, VOC, and other critical substances

As mentioned previously, little data is available regarding the emissions of PAH, VOC, or substances like PCDD/DF, despite their critical importance in assessing the environmental impact of fires.

A preliminary set of values was established during an Ineris test series for VOC and PAH in a recent project briefly presented in (15). An order of magnitude for the emission factor was determined: approximately 40 mg/kg for PAH and around 8,420 mg/kg for VOC. These values were obtained for 50 percent SOC cylindrical NMC cells. During these tests, it was also found that the predominant PAH is naphthalene, followed by 1-methylnaphtalene and anthracene, which is present in quantities four times lower. All other PAHs were an order of magnitude lower than these three. The predominance of naphthalene was also confirmed by Bordes *et al.* (39) through the analysis of water contaminated by PAH. This specific water analysis also highlighted the presence of 1-methylnaphtalene, but in lower quantities than in air measurements. Some other substances, such as phenanthrene or fluorene, which were not measured in the air during the first test series, were detected in the water (see Table 7, page 41 for more details).

The limited data concerning PAH emissions mostly correspond to emissions from EV fires. Recent analysis of emissions from internal combustion engine (ICE) vehicles (the most common combustion vehicle on the market) published by Willstrand *et al.* (61) provides a comparison between ICE vehicles and electric vehicles. This analysis shows a lower total emission of PAH for the first battery electric vehicle (BEV) compared to the ICE vehicle. However, it remains unclear how much the battery contributes to these emissions vs. other components of the vehicle, compounding the difficulty of considering LIB fire emissions. These emission factors for LIBs align with those published by Qiao *et al.* (64).

A visual representation of the emission factors in comparison to other fuels is plotted in Figure 16. These results come from a specific test campaign that managed to characterize the emissions from fires following the large Lubrizol-Normandie Logistic fire in France in 2019 (71). It should be mentioned that the quantity of hydrogen chloride (HCl) emissions mainly depends on the nature of the plastic used for the battery casing, so this specific graph does not provide a general average overview.

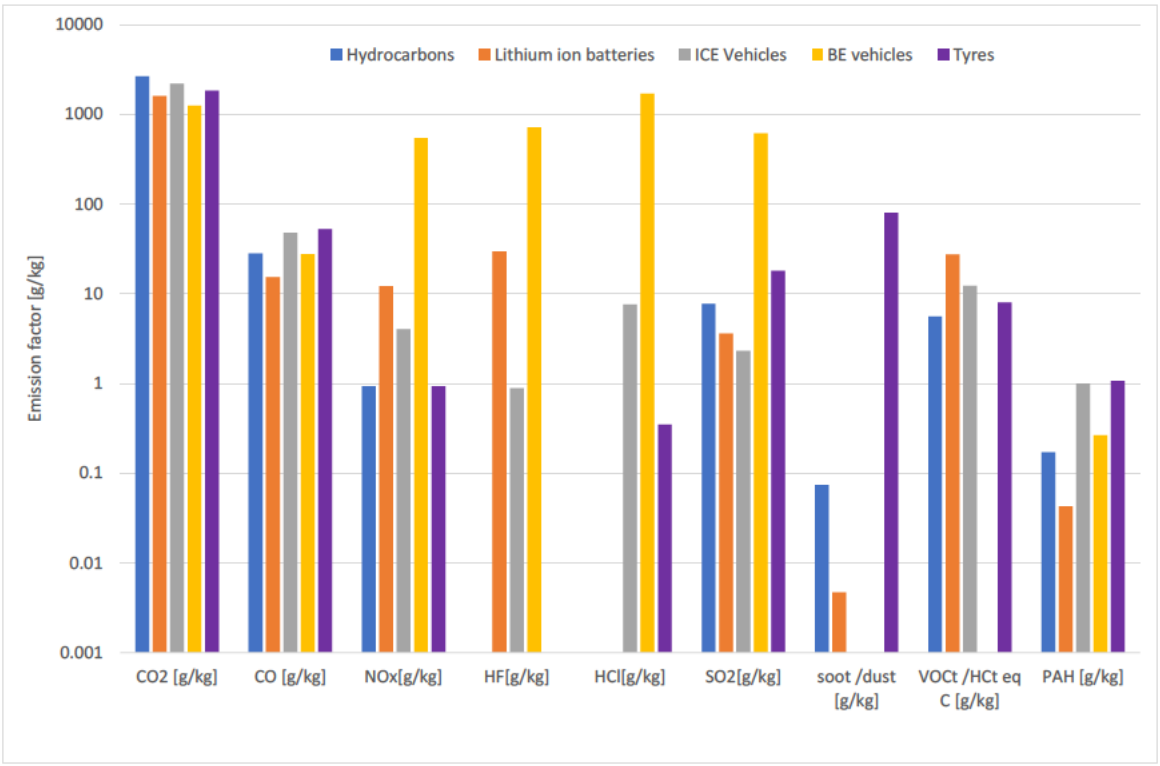


Figure 16: Emission factors for LIBs compared to other fuels.

An important aspect to consider regarding products that can cause long-term health effects is the strong dependence of their emission factors on combustion conditions. During a fire test with a classic fuel, the ratio of carbon monoxide to carbon dioxide, CO/CO_2, provides a good evaluation of the ventilation conditions. However, when dealing with LIBs, this ratio is less useful. While CO is produced by the combustion of the vented gases, the vented gases also contain a large amount of CO. Consequently, the CO/CO_2 ratio could be higher for LIBs even for well-ventilated fires.

Considering this, this visual comparison shows that emission factors for CO and CO_2 are not significantly different for LIBs compared to other fuels, such as hydrocarbons, or vehicles. However, nitrogen oxide emissions seem to have increased for LIBs. The reason for this increase requires further investigation. Regarding halogenated acids, as expected, the emission factor for HF is greater for batteries of BEVs than for hydrocarbons or ICE vehicles. Both halogenated acids and NOx are particularly concerning as they pollute the soil and water and destroy the ozone layer.

Particle matter production also appears to be less prominent with LIBs. Still, it is important to note that the composition of this particle matter, or more significantly, particles, likely differs between carboned-based fuels and LIBs, mainly due to the presence of metals in the particle mater from LIBs.

The emission factors for VOC and PAH are of the same order of magnitude as those observed for other fuels.

One of the key potential pollutants with long-term effect for LIBs might be metals; however, as detailed in the previous section, very little data has been published on metal emissions. Some measurements were conducted by Ineris but have not yet been published. These fire tests showed a significant emission factor for this type of fuel. The emission factor was much larger than other fuels, even tires, which are one of the classic fuels with the largest metal emission factor. Managed with NMC cells, these tests primarily identified the emission proportions of different metals. Figure 17 shows the proportion of metals that were quantitatively measured during this test campaign, while Figure 18 shows the same proportion distribution but with semi-quantitative metal measurements. Focusing on the quantitative measurements, nickel was identified as the dominant element in the metal emissions from NMC cells. Nickel has been identified (65) as a carcinogenic product, depending on the nature of the chemical nickel compounds. For the purpose of LIB fires, the most relevant compound identified as potentially carcinogenic is oxidic nickel. Nickel is also a short-term toxic product with an immediately dangerous to

life or health (IDLH) value of 10 mg/m^3 (66). The other main metallic compound in the smoke was Cobalt, which also has an IDLH threshold of 20 mg/m^3 but is not currently identified as a carcinogenic product. These two inorganic pollutants also have ecotoxicological consequences on various organisms, including fish, algae, and invertebrates.

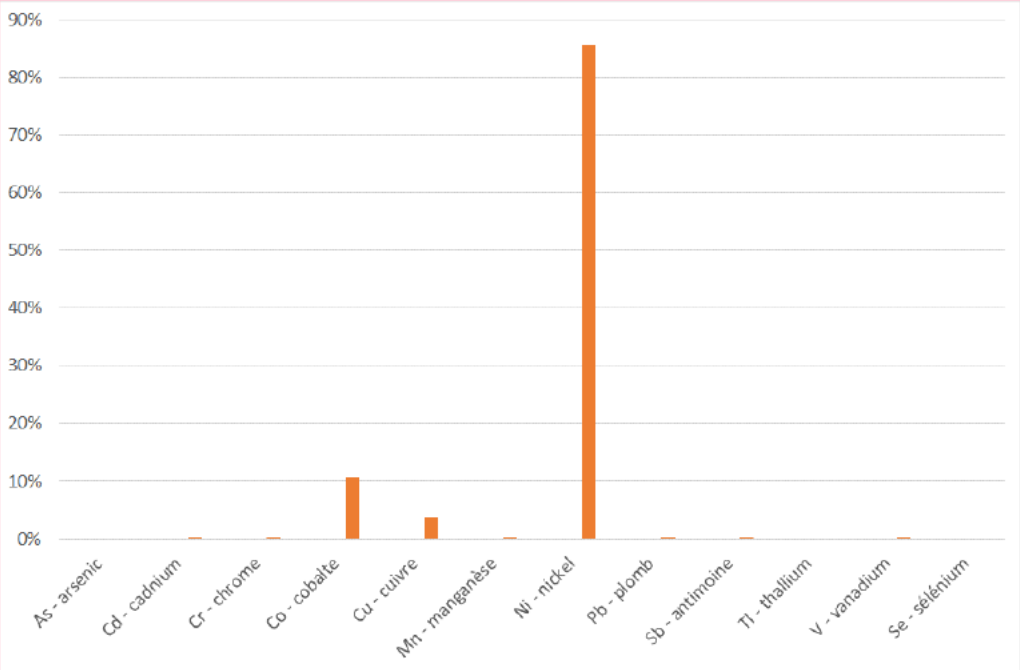


Figure 17: Proportion of quantitatively measured metals for an NMC LIB fire test.

Regarding quantitatively measured metals (Figure 18), they can also lead to an increase of potential environmental consequences, but more data must be produced on their emission factors to make any further conclusions.

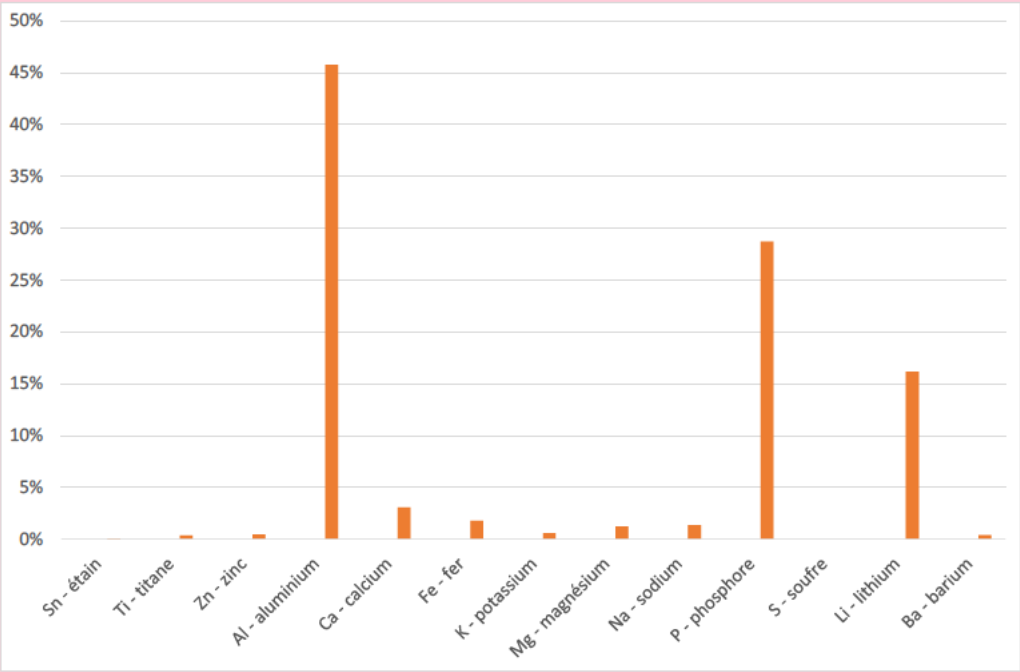


Figure 18: Proportion of semi-quantitatively measured metals for an NMC LIB fire test.

3.4 Synthesis of gaps for determining environmental impact of LIB fires

It is crucial to first understand that very little data is available for determining the environmental impact of LIB fires. While many papers have been published with pollutant measurements, evaluating the environmental impact of LIB fires is challenging due to a lack of relevant data.

Based on the current state of the art and using specific tests conducted by Ineris for one LIB technology, NMC, the following key issues have been identified as being necessary to improve the prediction of the environmental impact of LIB fires:

- Emission factors for acute toxic gaseous products need to be clarified for each chemical composition of LIBs
- PAH/VOC emission factors need to be confirmed to be of the same order of magnitude as those measured for other fuels
- Metal emission factors, which appear to be a critical pollutant series, should be determined, including specific tests to study the diversity of the environmental impact of each metal in both air and water

To meet these objectives, it is crucial to establish some generic rules for fire tests aiming to provide this kind of data and to identify the main parameters to be considered:

- Gas measurements should be taken continuously to enable the estimation of total emissions, not just peak concentrations
- The sample mass loss rate should be measured together with gas emissions because no emission factor can be estimated without the total mass loss. Specific attention should be given to LIBs regarding the projectiles that could induce error in mass loss measurements.
- The nature of the cell chemistry must be included in emission factor evaluations, along with the battery form factor (cylindrical, pouch, etc.)

Regarding the equivalence between test methods, it is not clear how the thermal runaway triggering method (over-charge, short-circuit, etc.) influences the emission factor. This should be clarified.

Furthermore, it should be mentioned that many factors govern the emission factor, including the cell chemistry, the BESS geometry and ventilation system, the fire propagation and resulting HRR, and the firefighting strategy, including automatic mitigation measures. These estimated emission factors should also be considered, as mentioned previously, as orders of magnitude. This conclusion is similar to those for more classic fuels.

4 Specificities of LIB environmental impact

Comparing the environmental consequences of BESS fires to other types of fires can be done several ways. Comparing environmental consequences remains a great challenge and making comparison possible requires the use of two fixed parameters:

- The mass of combustible product, varying the fuel itself
- The total size of the fire

Of course, a starting point for evaluating the environmental impact is the emission factor, which, as discussed in the previous section, is an uncertain parameter. To discuss the evolution of the environmental impact of fires with the development of BESS, some fires were chosen. Because the main focus of the present report is energy storage, comparisons were made with other types of energy sources, such as hydrocarbons. However, because the target is the environmental impact of fire, fuels that are known to cause significant environmental impact, such as PVC and tires, were also introduced for comparison purposes. Probability is not a parameter of this study but remains essential in the full analysis.

As a case study, the following three representative events were selected based on the events presented in section 2.3.1, as well as events representative of the evolution of BESS:

- The fire in a container in Surprise, AZ, that occurred in the US with significant human consequences.
- A domestic fire involving a large house with and without a BESS dedicated system.
- A large fire in a factory in Korea that involved lithium metal batteries and is representative in terms of the potential size of fires involving these products.

Obviously, the last event corresponds to a very large fire, representative of a potential event on a large factory. It was chosen more as a worst-case configuration than a representative situation.

Considering traditional fuels, the objective was to identify products with different potential environmental impacts using the major fires listed in (16). For each situation, the representative traditional fuel was adapted. Then, the following were considered for comparison purposes:

- For the container fire:
  - Hydrocarbons, as they are commonly used energy carriers
  - PVC as a plastic representative, as the chlorine in its comparison can lead to dioxin formation during a fire
  - Tires, as they are known to produce a large amount of particle matter and potentially induce a strong environmental impact even if such fires are rare
- For the domestic fire:
  - Consideration of the emission factors estimated for domestic fires
- For the worst-case large factory fire:
  - Hydrocarbons, as they are commonly used energy carriers
  - PVC as a plastic representative, as the chlorine in its comparison can lead to dioxin formation during a fire
  - Tires, as they are known to produce a large amount of particle matter and potentially induce a strong environmental impact even if such fires are rare

It should also be mentioned that the environmental impact comparison between electric vehicles and internal combustion engine vehicles was not considered here, as the emission differences between such vehicles are small because emissions of vehicles are mainly governed by the large amount of plastics and other hydrocarbon-based compounds they contain.

4.1 Comparison rationale

To assess the potential environmental impacts of the selected fires, the following aspects were analyzed:

1. Emission source term for battery fires – estimation of emission factors based on current state-of-the-art methods

2. Emission source term for equivalent fires – comparison with hydrocarbon, fertilizer, and wood fires of similar mass and surface area
3. Toxic compound deposition – calculation of potential deposits of select toxic compounds including PAH, particles, and metals
4. Firefighting strategy comparison – analysis of water contamination

The source term estimation used the Heskestad smoke plume model (67) and adaptations for dispersion modelling (68). Dispersion and deposition were computed using advanced distribution management system (ADMS) software.

Due to unknown water contamination coefficients (proportion of pollutants transferred to extinguishing water), the firefighting strategy comparison focuses on the required water quantity for firefighting based on existing standards (69).

All values provided here are rough estimates intended for comparison and discussion. Readers should note the uncertainties in the input data used.

4.2 The Surprise fire, a LIBs representative case

The Surprise, AZ, fire represents a BESS fire, reflecting installations worldwide. This reference configuration was chosen to compare the potential environmental impact of a BESS fire with fires involving other fuels. This case study uses BESS as a representative size and configuration and is not based on any observed contamination from the fire.

4.2.1 Fire characteristics

Based on the available information (70), the fire occurred on April 19th in a 2.16 MWh lithium-ion BESS. The system was housed in a steel structure with dimensions of about 15 m x 4.2 m x 4.2 m, representing a fire ground surface in the order of 60 m². Using an equivalence factor of 160 Wh/kg, the BESS represented a mass of approximately 13.5 tons of LIBs.

Considering the combustion rate of LIBs (20 g/m²/s) and a heat of combustion of 15 MJ/kg based on the Ineris database for those type of fuels, the fire's heat release rate was estimated at about 18 MW. The Heskestad fire plume measurements were used for atmospheric dispersion modelling, with the required data provided in Table 9. Similar evaluations were conducted for hydrocarbons and phytosanitary products, with fertilizers representing the latter category. Obviously, whatever the fuel is, the mass loss rate during a fire is not constant from one situation to another. In addition, the net heat of combustion, with the different inert material, is not the same. For comparison purposes, having in mind that mainly environmental consequences and associated potential distances for deposits were included, the upper value of the possible range was considered for those two values. Reducing those quantities, i.e., reducing the fire HRR, would increase the deposition rate close to the fire and reduce the deposition rate far from the fire.

Fuel	LIBs	Hydrocarbons	PVC	Tires
Mass loss rate	20 g/m²/s	60 g/m²/s	15 g/m²/s	40 g/m²/s
Heat of combustion	15 MJ/kg	40 MJ/kg	20 MJ/kg	30 MJ/kg
HRR	18 MW	144 MW	18 MW	72 MW
Emission height	7 m	16 m	7 m	15 m
Smoke mass flow rate	65 kg/s	520 kg/s	65 kg/s	260 kg/s

Table 9: Fire plume characteristics for dispersion modeling.

4.2.2 Emissions

For different modeling hypotheses, the corresponding total potential emissions were estimated (see Table 10). These quantities are based on the emission factors discussed in the previous section and those available in the literature (15). As discussed in section 3.3, these values have significant uncertainties and are presented only for comparison purposes. The total mass includes the mass of the fuel and the oxygen used during combustion.

Fuel nature	Mass [kg]	CO_2 [kg]	CO [kg]	HF [kg]	HCl [kg]	PAH [kg]	VOC [kg]	Metals [kg]
Lithium-ion batteries	13,500	21,000	200	400	0	0.6	380	6,000
Hydrocarbons	13,500	35,000	380	0	0	2.5	80	0
PVC	13,500	6,200	850	0	4,320	70	680	0
Tires	13,500	25,000	700	0	5	15	100	680

Table 10: Estimated total toxic product emission for the Surprise fire.

4.2.3 Acute toxicity

As mentioned in the environmental impact description, air toxicity includes the air transport of pollutants and the potential resulting toxicity in the area. Before considering deposits and their associated potential long-term impact, acute toxicity must be evaluated. To meet this objective, one should consider the main toxic species produced by the fire to build an equivalent toxic threshold, meaning the smoke concentration to be reached to induce toxic effect. This equivalent threshold, T_{eq}, can be written, while neglecting the different toxic mechanisms, as:

$$\frac{1}{T_{eq}} = \sum_{i=1}^{nb\_species} \frac{C_i}{T_i}$$

This equivalent threshold is based on the species concentration, C_i, and associated threshold, chosen here as the acute exposure guideline levels (AEGL) for 10 minutes of exposure.

4.2.4 Smoke deposition evaluation

To provide a comparison that considers all parameters, including the emission factors and fire characteristics, a deposition simulation was conducted. The wind properties mentioned in the accident analysis report (70) were used for this simulation. Due to the numerous uncertainties in these simulations, normalized values were used to facilitate the comparison between each fuel. The total deposition was normalized by the maximum deposition value for the LIB fire, and a standardized emission was set.

The first map of potential deposits was computed for particles with a 2.5 µm diameter, considered representative of PAH and fine particles. For this potential deposit, given that the emission factor is of a similar order of magnitude for both LIBs and hydrocarbon fires, the differences observed in Figure 19 were primarily due to the source term dynamic, i.e., the initial energy of the smoke that facilitates mixing with the atmosphere, which is typically higher for hydrocarbons. For PVC, because the heat release rate is similar to the LIB heat release rate, the main difference was the emission factor, with estimated PAH emissions being ten times lower for PVC than for batteries. For tires, both the heat release rate and emission factor were larger, and due to the large PAH emission factor for tires, this parameter predominated any other.

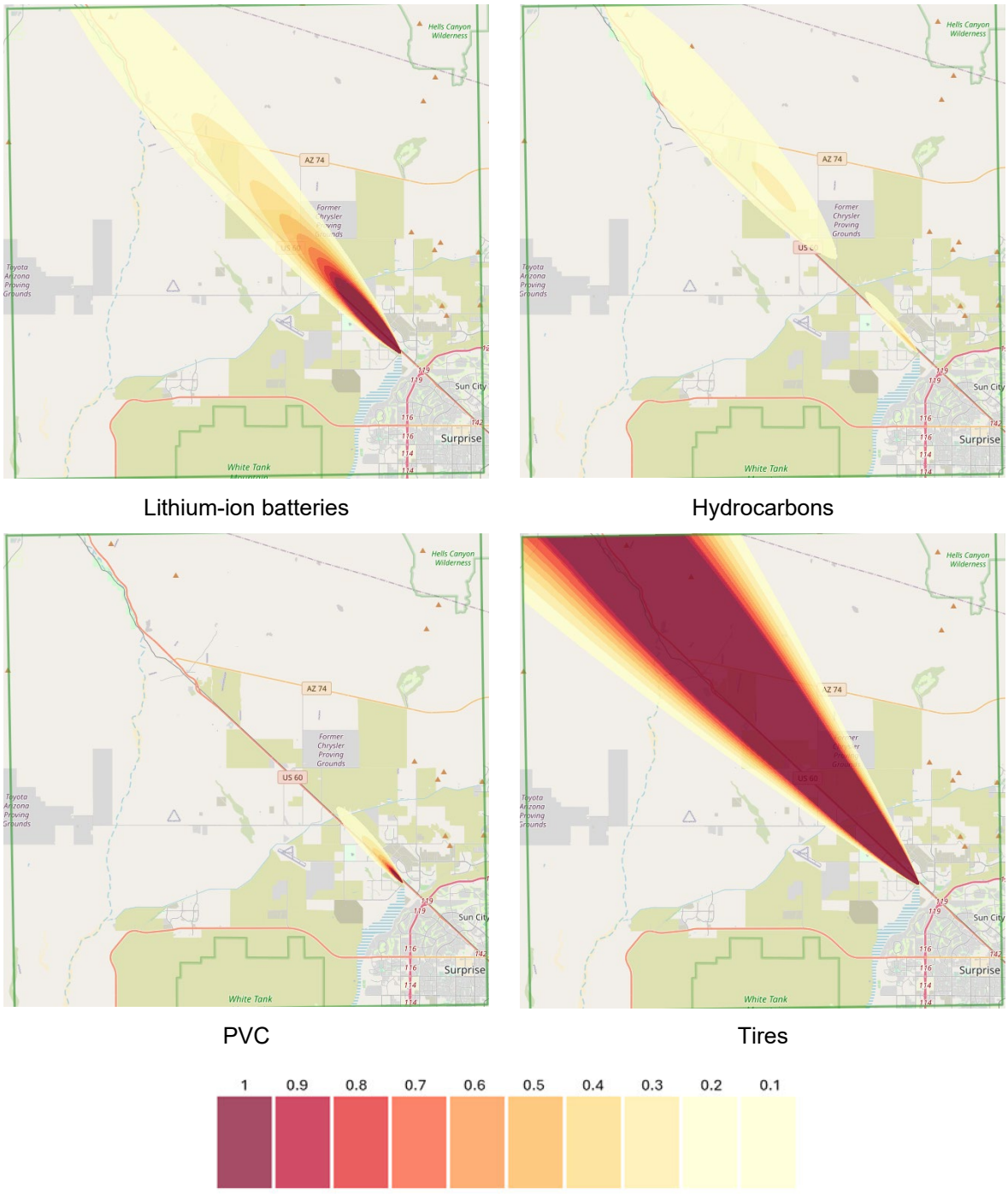


Figure 19: 2.5 µm particle deposition for different fuels with the main characteristics of the Surprise fire.

To address other toxic compounds, such as metal particles, an assumption was made and only particles with a 10 µm diameter were considered (see Figure 20). It is important to note that emission factors differ in this context. Only tires and LIBs were included in this analysis, as the other fuels considered do not produce metal emissions. As an assumption and due to limited data on metal emissions, the same emission factor was used for both LIBs and tires.

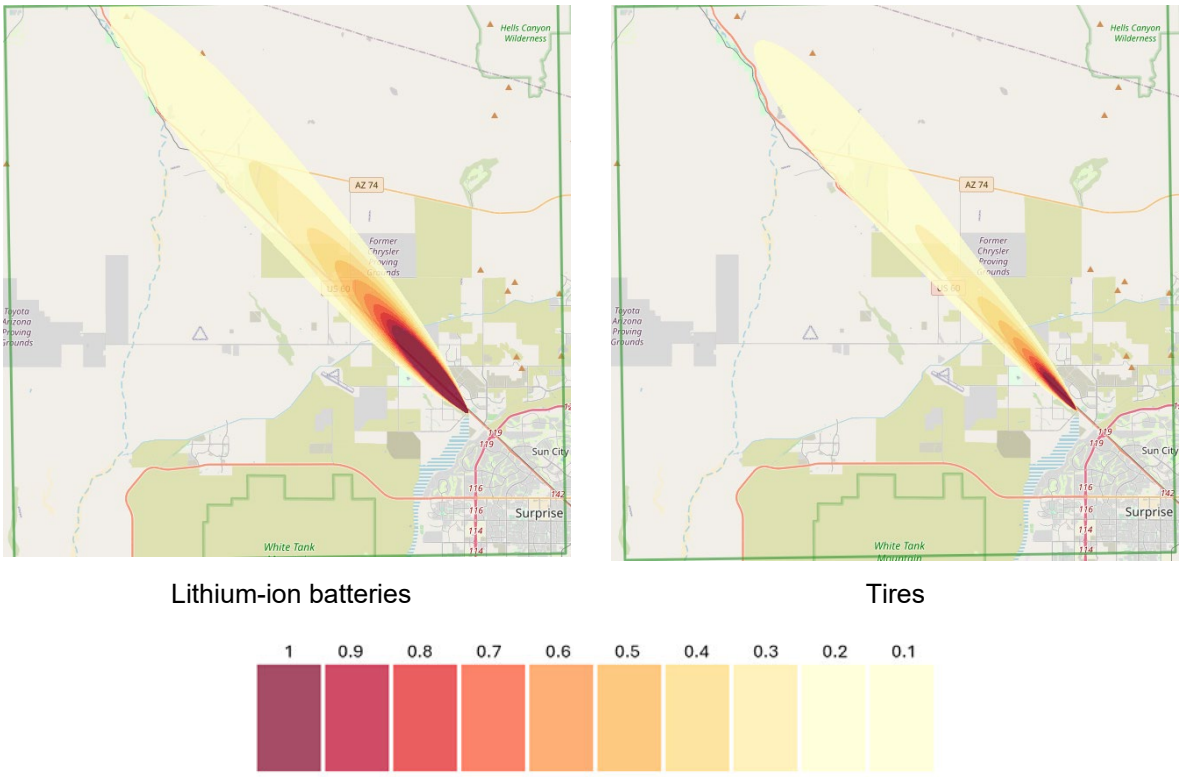


Figure 20: 10 µm particle deposition for different fuels with the main characteristics of the Surprise fire.

In Figure 19 and Figure 20, the deposit quantities are normalized by the maximum computed deposit quantity for all fuels, facilitating easier comparison. Normalized values were used instead of raw deposit quantities due to uncertainties in the emission factors. These maps are usually employed to determine the sampling area for more precise quantification of actual deposits.

4.2.5 Water contamination

To estimate the environmental impact of LIB fires through water contamination, the quantity of water used is a key factor. Data from multiple incidents indicated that the total amount of water used for such fires ranges from 500 to over 10,000 m^3, translating to 35 to 750 m^3 of water per ton of LIBs. This water then becomes contaminated with various products, including hydrogen fluoride, PAHs, metals, and base alkali, as observed in the Liverpool fire.

For the same amount of fuel, the maximum water quantity required for conventional fuels, based on the Sandoz method (69), is about 5 m^3 per ton, seven times lower than the minimum quantity used for LIBs. This water would also be contaminated with various products, including PAH, halogenated acids, and/or metals, depending on the fuel characteristics. For a scenario involving about 13.5 tons of product, this represents a need of less than 100 m^3 of water for hydrocarbon and plastic fires.

4.3 A domestic fire case

A typical application of BESS is their use as a power supply for domestic application, mainly in large buildings. In such a situation, the BESS emissions must be added to those produced by the building fire. Using the emission factors given for houses (14) and summarized in Table 11, it is clear that the environmental impact of a single domestic fire is quite negligible. As for other typical fires, not all pollutant emission factors are known and, consequently, the analysis was focused on the available values.

To evaluate the requested battery characteristics, the average annual electric consumption of an American customer, 10,791 kWh (about 30 kWh per day), was used as a reference. Considering an objective of 3 days of emergency supply, the battery capacity was fixed to 100 kWh. The corresponding emissions were based on this hypothesis and on the emissions factors for LIBs described in chapter 3. The measurements also considered a mass to electric capacity ratio of 160 Wh/kg, leading to 625 kg of LIBs in this scenario.

Fuel nature	Mass [kg]	CO_2 [kg]	CO [kg]	NOx [kg]	HCN [kg]	HF [kg]	HCl [kg]	VOC [kg]	Metals [kg]
Typical house emissions	11,000	11,200	445	10.4	263	—	112	82	—
Lithium-ion batteries	625	970	9	—	—	18	0	18	280

Table 11: Estimated total toxic product emission for the Surprise fire. The CO_2 emissions are estimated for the US configuration using the CO/CO_2 ratio available for Swedish fires in (14).

To evaluate the LIB influence on the environmental impact, not only the quantity but the toxic potential (i.e., the quantity compared to the specific threshold) must be considered. This objective can be met with the total smoke emission and corresponding equivalent toxicity as defined in section 4.2.3. To evaluate the corresponding threshold, one should estimate the fire characteristics, heat release rate, smoke total mass flow rate, and emission height to get the initial concentration. The mass loss rate was set at 30 g/m²/s and heat of combustion at 20 MJ/kg for the combustible part of the house, keeping in mind that the main constitutive material can affect those values. Based on the 120 m² house used as a reference (15), the resulting heat release rate is about 75 MW, representing about 230 kg/s of smoke.

Considering most emissions are produced during the peak HRR and this peak fire lasted about 1 hour, this leads to an equivalent threshold of about 22 ppm for the fire with BESS versus 23 ppm by considering the BESS. In such a situation, the Li-ion battery influence is negligible.

This conclusion is similar to the one observed when comparing electric vehicles to internal combustion engine vehicles (71).

4.4 The Iowa tire fire, representative of a major fire

Because a single case is insufficient for comparison, a similar analysis was done using a very large fire involving a more common fuel, specifically tires. The Iowa tire fire was used as a reference case. This fire occurred in 2012 in a large tire storage area of about 30,000 m² and involved about 1.3 million tires, with a total mass of 20,540 tons. The fire led to the formation of a dense smoke plume and led to significant polluting emissions (72).

The Iowa tire fire was selected for comparison as it represents a typical worst-case fire scenario. However, even larger tire fires have occurred, such as the one in 1983 in Winchester, VA, which lasted 9 months and resulted in 7 million burned tires (the pollution of the air and water was acknowledged as having impacted three surrounding states) (14).

4.4.1 Fire characteristics

The evaluation of this fire's characteristics is based on the available data (73), specifically the fire surface of 30,000 m². These characteristics led to a very large fire, which displayed an important initial ascension of energy for the fire plume, as shown in Table 12.

Fuel	Tires	Hydrocarbons	PVC	LIBs
Mass loss rate	40 g/m²/s	60 g/m²/s	15 g/m²/s	20 g/m²/s
Heat of combustion	30 MJ/kg	40 MJ/kg	20 MJ/kg	15 MJ/kg
HRR	36,000 MW	72,000 MW	9,000 MW	9,000 MW
Emission height	150 m	196 m	85 m	85 m
Smoke mass flow rate	130,000 kg/s	260,000 kg/s	30,000 kg/s	30,000 kg/s

Table 12: Fire plume characteristics for dispersion modeling.

4.4.2 Emissions

For the different modeling hypotheses for these fire configurations, the corresponding total potential emissions have been estimated, see Table 13.

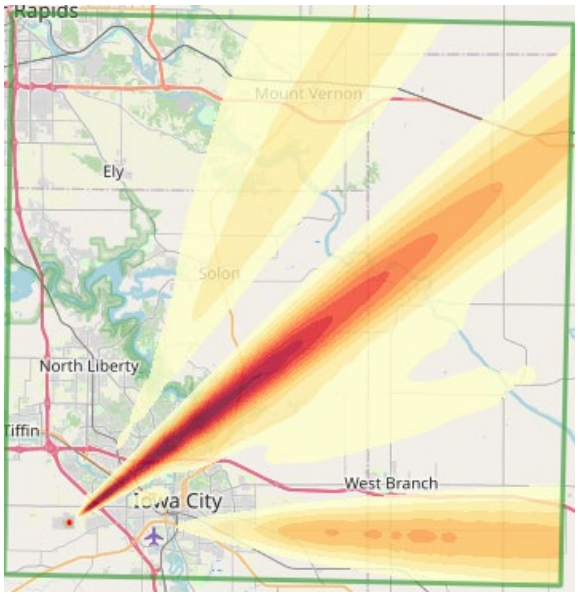
Fuel nature	Mass [t]	CO_2 [t]	CO [t]	HF [t]	HCl [t]	PAH [t]	VOC [t]	Metals [t]
Lithium-ion batteries	20,500	35,000	320	600	0	1	550	10,200
Hydrocarbons	20,500	54,000	600	0	0	3.5	120	0
PVC	20,500	9,500	1,200	0	6,500	100	1,000	0
Tires	20,500	40,000	1,000	0	8	20	160	1,000

Table 13: Total toxic product emission for the Iowa fire.

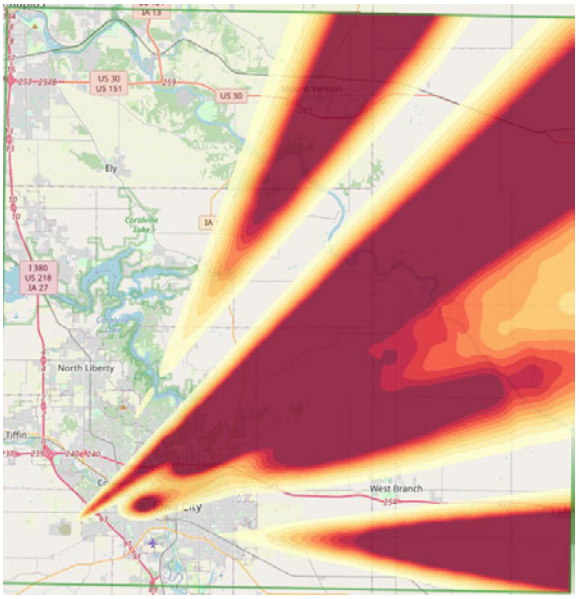
4.4.3 Smoke deposition evaluation

The dispersion modeling for the Iowa fire considered several wind directions and characteristics. Due to the prolonged duration of the fire, numerous atmospheric conditions were encountered, and the influence of these fluctuations is highlighted in Figure 20 and Figure 21.

The first set of graphs in Figure 21 shows the 2.5 µm diameter particle deposits for several fuels, all based on the Iowa fire characteristics. These results confirm the conclusions drawn from the Surprise, AZ, case. For hydrocarbon fires, with a hazardous air pollutant (HAP) emission factor similar to the one estimated for LIBs, ground deposition is reduced due to the high thermo-kinetic energy of the source and the resulting atmospheric dilution. However, for tire fires, where the HAP emission factor is 20 times larger, the increased atmospheric dilution induced by the fire source is insufficient to significantly limit particle deposits.

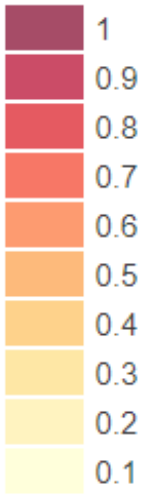


Lithium-ion battery fire



Tire fire

HC fire



Mean 2.5 µm particle deposition (µg/m²/s)

Figure 21: 2.5 µm particle deposition for different fuels with the main characteristics of the Iowa fire.

When considering larger particles, such as those with a 10 µm diameter typically representative of metal pollution, and assuming an identical emission factor for both LIBs and tires, the increased dilution induced by the fire cloud dynamics results in a reduced deposit level for tires compared to LIBs, as shown in Figure 22.

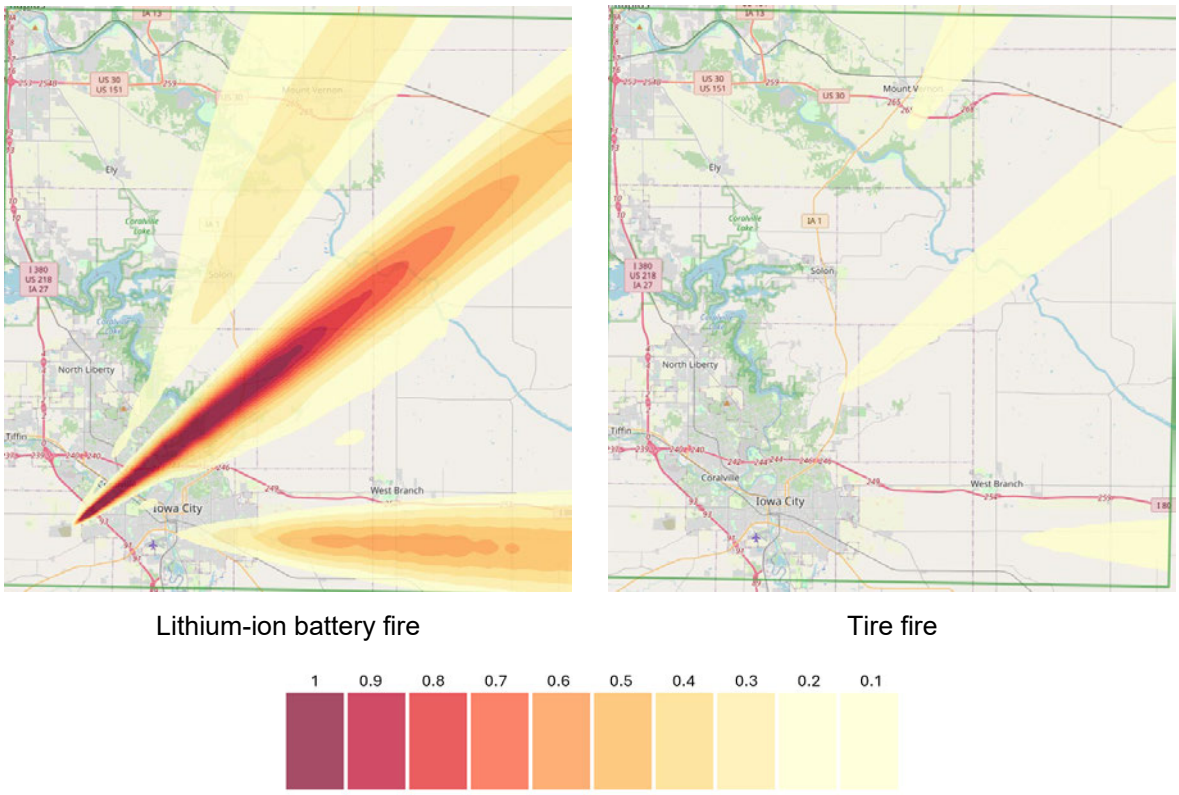


Figure 22: 10 µm particle deposition for different fuels with the main characteristics of the Iowa fire.

4.4.4 Water contamination

For a LIB fire, the required water quantities can be enormous. Using the lowest application rate of 35 m^3/t, nearly 1 million m^3 of water would be needed. In contrast, for the same mass of hydrocarbons, based on a 5 m^3/t factor, the water requirement would be 100,000 m^3.

4.5 Synthesis

The main learnings from the simulations presented in this chapter are:

- The dilution of the fire plume for battery fires can be reduced by the specific configuration of the fire
- PAH and similar product deposits might be higher for a LIB fire than for a classic fuel fire with the same emission factor magnitude, mainly due to lower atmospheric mixing
- Metals appear to be one of the most critical pollutants when dealing with potential deposits from a LIB fire

The results should be analyzed with consideration of the difficulty of defining robust emission for specific pollutants emitted by LIB fires, particularly metals, which remain a significant unknown parameter in assessing the environmental impact of these fires.

5 Conclusions

The use of LIBs is continuously increasing across numerous applications. This technological advancement introduces new risks, as evidenced by the various fires that have occurred over the last decade. Beyond the immediate fire consequences, such as exposure to high temperatures or thermal radiative flux, the environmental impacts of these fires have become a significant concern and should be considered. Many abusive tests on LIBs have been published in scientific literature providing information about potential emissions from such fires. However, these publications generally focus on acute toxicity, such as hydrogen fluoride emissions, and rarely consider other products that can have a significant environmental impact. Because water contamination from run-off water also contributes to the environmental impact, specific tests and analysis addressing this issue are necessary. However, these tests are not common.

Estimating the emission factor and environmental impact of LIB fires using the available data is challenging. This exercise highlights the need for future test series with this objective. Despite considerable uncertainty in emission factors evaluation, their magnitude can be estimated using several scientific publications and specific fire tests keeping in mind that many parameters influence these emission factors. The emission factors defined in this study are summarized in Table 14.

Contaminant	Emission factors (g/kg)				
	Lithium-ion battery fires	Hydrocarbon fires	ICE vehicle fires	Battery-electric vehicle fires	Tire fires
CO2	1,605	2,639	2,188	1,250	1,839.7
CO	15.4	28.0	47.8	27.7	52.7
NOx	12.1	0.9	4.0	544.5	0.9
HF	29.7	0	0.885	716	0.001
HCl	0	0	7.58	1695	0.35
SO2	3.6	7.8	2.3	610.0	18.0
Particle matter	0.0047	0.074	0	0	79.500
VOCt/HCt	27.5	5.6	12.2	0	8
PAH	0.043	0.171	1.000	0.265	1.068

Table 14: Emission factors based on the current study for Li-ion batteries with comparison to other types of fires.

Assuming this order of magnitude, rather than the exact value, these emission factors can be compared to those published for other fuels involved in significant fires, showing that:

- Carbon oxide emissions from LIB fires are comparable to those from classic fires
- Hydrogen fluoride is a potential marker of LIB fire emissions, though HF is highly reactive and may not always be easy to detect and measure
- The total emission of particle matter from LIB fires is lower than those from fires with high smoke production, such as hydrocarbon fires, but the particle chemical structure differs, as LIB fires contain a large amount of metals
- VOC emissions from LIB fires are similar to those from classic fuel fires
- PAH emissions from LIB fires seem lower than those observed for other fuels

However, the emission factor is not the only parameter governing the environmental impact of a fire. Dispersion to the environment is also strongly influenced by the fire plume, affecting the indirect contamination of soil and water. Considering all these parameters, current knowledge on emissions suggests that:

- The characteristics of LIB fires generally lead to limited thermo-kinetic energy of the fire plume, resulting in limited atmospheric dispersion
- Metal contamination may be an issue for LIB fires
- Emission factors for many substances, such as PAH, VOC, etc., need clarification

To improve the current knowledge of emission factors, specific precautions should be introduced for LIB tests, including continuous measurement of emissions while considering as many gases and substances as possible. Furthermore, a specific focus on mass loss rate is needed for those tests, as emission factor estimation is impossible without this value. In addition, one should highlight the lack of data regarding contamination by PFAS during LIB fires.

Finally, to provide a relevant evaluation of the environmental impact of such fires, water contamination should be analyzed using various application methods and different cell characteristics. Such water contamination knowledge improvement is a key to developing firefighting strategies keeping in mind that using large quantities of water or letting the fire burn could be valid approaches. The best strategies depend on many local parameters and the equilibrium between air and water contamination.

It is recommended that research programs intending to contribute emission factor information for battery fires report the following information at a minimum:

- The total energy (in kWh) and mass of the LIBs studied
- The final mass of any residual materials after destructive battery testing
- An assessment of potential contaminants, including PAH, VOC, and particulates

For a more comprehensive analysis, a complete study could include:

- A full quantitative evaluation of potential contaminants
- Quantification of particulate release
- Measurement of potential contamination to extinguishing water

Finally, an important factor when considering the available data concerning lithium-ion battery emissions is that the majority come from small-scale tests performed at the cell level. Obviously, transposing those measurements to real situations is highly challenging and should be considered with care. Developing large-scale tests that include the fire emissions should be considered for future evaluation of the environmental impact of such fires.

6 References

1. Abbas A. Akhil GH, Aileen B. Currier, Benjamin C. Kaun, Dan M. Rastler, Stella Bingqing Chen, Andrew L. Cotter, Dale T. Bradshaw, and William D. Gauntlett. DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA. SANDIA REPORT. 2013.
2. NFPA. NFPA 855: Standard for the Installation of Stationary Energy Storage Systems. 2023.
3. UL9540 : 2020 Standard for Energy Storage Systems and Equipment, UL9540 (Second Edition, 2020).
4. Accardo A, Dotelli G, Musa ML, Spessa E. Life Cycle Assessment of an NMC Battery for Application to Electric Light-Duty Commercial Vehicles and Comparison with a Sodium-Nickel-Chloride Battery. Applied Sciences. 2021;11(3):1160.
5. Bordes A, Danilov DL, Desprez P, Lecocq A, Marlair G, Truchot B, et al. A holistic contribution to fast innovation in electric vehicles: An overview of the DEMOBASE research project. eTransportation. 2022;11:100144.
6. Carvalho ML, Temporelli A, Girardi P. Life Cycle Assessment of Stationary Storage Systems within the Italian Electric Network. Energies. 2021;14(8):2047.
7. Center JR. BATTERIES FOR ENERGY STORAGE IN THE EUROPEAN UNION. EUR 31220 EN. 2022.
8. Sybil Pan, Li Z, Ju Y. https://www.fastmarkets.com/insights/lfp-batteries-extend-dominance-over-ncm-batteries-china/ July 19, 2023 [China's National Energy Administration banned the use of NCM batteries in medium-to-large energy storage plants in June 2022, while LFP is the dominant chemistry used in energy storage systems (ESS), another supportive factor for the LFP market that NCM does not enjoy.].
9. Sommerville R, Zhu P, Rajaeifar MA, Heidrich O, Goodship V, Kendrick E. A qualitative assessment of lithium ion battery recycling processes. Resources, Conservation and Recycling. 2021;165:105219.
10. Roe C, Feng X, White G, Li R, Wang H, Rui X, et al. Immersion cooling for lithium-ion batteries – A review. Journal of Power Sources. 2022;525:231094.
11. Gogolski JM, Rudisill TS. The Potential Interactions of Novec 1230 and Its Thermal Degradation Products with Actinide Metals and Oxides. Industrial & Engineering Chemistry Research. 2023;62(10):4466-9.
12. Mrozik W, Rajaeifar MA, Heidrich O, Christensen P. Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. Energy & Environmental Science. 2021;14(12):6099-121.
13. Bazyn T, Krier H, Glumac N. Evidence for the transition from the diffusion-limit in aluminum particle combustion. Proceedings of the Combustion Institute. 2007;31(2):2021-8.
14. Mich J, Braig D, Gustmann T, Hasse C, Scholtissek A. A comparison of mechanistic models for the combustion of iron microparticles and their application to polydisperse iron-air suspensions. 2023.
15. Margaret McNamee JÅ, Guy Marlair, Benjamin Truchot, and Brian Meacham. Environmental impact of fires in the built environment: emission factors. NFPA Research Fundation report. 2022.
16. Meacham BaMM. Handbook of Fire and the Environment. Springer 2023.
17. ISO 26367-1: Guidelines for assessing the adverse environmental impact of fire effluents –Part 1: General, (2019).
18. ISO 26367-3: Guidelines for assessing the adverse environmental impact of fire effluents – Part 3: Sampling and analysis, (2019).
19. ISO 26367-2: Guidelines for assessing the adverse environmental impact of fire effluents — Part 2: Methodology for compiling data on environmentally significant emissions from fires, (2017).
20. Guide Ineris, Guide sur la stratégie de prélèvements et d'analyses à réaliser suite à un accident technologique - cas de l'incendie. 2023.
21. Resource Conservation and Recovery Act (RCRA). EPA.
22. Conover D. Overview of the development and deployment of codes, standards and regulations affecting energy storage system safety in the United States. 2014(PNNL_23578).
23. Wang Q, Mao B, Stoliarov SI, Sun J. A review of lithium ion battery failure mechanisms and fire prevention strategies. Progress in Energy and Combustion Science. 2019;73:95-131.
24. Ojanen S, Lundström M, Santasalo-Aarnio A, Serna-Guerrero R. Challenging the concept of electrochemical discharge using salt solutions for lithium-ion batteries recycling. Waste management (New York, NY). 2018;76:242-9.
25. Torabian MM, Jafari M, Bazargan A. Discharge of lithium-ion batteries in salt solutions for safer storage, transport, and resource recovery. Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA. 2022;40(4):402-9.

26. Jafari M, Torabian MM, Bazargan A. A Facile Chemical-Free Cathode Powder Separation Method for Lithium Ion Battery Resource Recovery. Journal of Energy Storage. 2020;31:101564.
27. Insights from EPRI's Battery Energy Storage Systems Failure Incident Database: Analysis of Failure Root Cause. EPRI, Palo Alto, CA: 2024. 3002030360". 2024. Contract No.: accessed June 2024.
28. Service MFaR. Appendix 2 - Liverpool BESS Significant Investigation Report _ Incident: 018965 - 15092020. December 2021(1.2).
29. BEA-RI. Rapport d'Enquête Sur l'incendie d'un container de stockage de batteries au sein du poste de transformation RTE de Perles et Castelet (09) le 1er décembre 2020.
30. Morris Lithium Battery Fire [Available from: https://response.epa.gov/site/site_profile.aspx?site_id=15259#:~:text=Background,fire%20due%20to%20unknown%20causes.
31. Cartam sampling on Viviez fire 2024 [Available from: https://www.cartam.fr/Consultation/Table/SamplesSummary?AirMatrices=27.
32. Verzoni A. Fatal South Korea Factory Fire Highlights Need for Better Battery Regulation 24-Jun-2024 [Available from: https://www.nfpa.org/news-blogs-and-articles/blogs/2024/06/24/south-korea-battery-factory-fire-highlights-need-for-better-battery-regulation.
33. Wei D, Zhang M, Zhu L, Chen H, Huang W, Yao J, et al. Study on Thermal Runaway Behavior of Li-Ion Batteries Using Different Abuse Methods. Batteries. 2022;8(11):201.
34. Associated CE. BESS Quality Risks Report: A summary of the most common Battery Energy Storage Manufcaturing defects. February 2024.
35. Barone TL, Dubaniewicz TH, Friend SA, Zlochower IA, Bugarski AD, Rayyan NS. Lithium-ion battery explosion aerosols: Morphology and elemental composition. Aerosol Sci Technol. 2021;55(10):1183-201.
36. Premnath V, Parhizi M, Niemiec N, Smith I, Jeevarajan J. Characterization of Particulate Emissions from Thermal Runaway of Lithium-ion Cells. Journal of Electrochemical Energy Conversion and Storage. 2024:1-29.
37. Goupil V, Gaya C, Boisard A, Robert E. Effect of the heating rate on the degassing and combustion of cylindrical Li-Ion cells. Fire Safety Journal. 2022;133:103648.
38. Li W, Xue Y, Feng X, Rao S, Zhang T, Gao Z, et al. Characteristics of particle emissions from lithium-ion batteries during thermal runaway: A review. Journal of Energy Storage. 2024;78:109980.
39. Bordes A, Papin A, Marlair G, Claude T, El-Masri A, Durussel T, et al. Assessment of Run-Off Waters Resulting from Lithium-Ion Battery Fire-Fighting Operations. Batteries. 2024;10(4):118.
40. Quant M, Willstrand O, Mallin T, Hynynen J. Ecotoxicity Evaluation of Fire-Extinguishing Water from Large-Scale Battery and Battery Electric Vehicle Fire Tests. Environ Sci Technol. 2023;57(12):4821-30.
41. rgaret McNamee JÅ, Guy Marlair, Benjamin Truchot, and Brian Meacham. Environmental Impact of Fires in the Built Environment - NFPA. 2022.
42. Nedjalkov A, Meyer J, Köhring M, Doering A, Angelmahr M, Dahle S, et al. Toxic Gas Emissions from Damaged Lithium Ion Batteries—Analysis and Safety Enhancement Solution. Batteries. 2016;2(1):5.
43. Amano KOA, Hahn S-K, Tschirschwitz R, Rappsilber T, Krause U. An Experimental Investigation of Thermal Runaway and Gas Release of NMC Lithium-Ion Pouch Batteries Depending on the State of Charge Level. Batteries. 2022;8(5):41.
44. Maloney. Lithium Battery Thermal Runaway Vent Gas Analysis. DOT/FAA/TC-15/59. 2016.
45. Golubkov AW, Scheikl S, Planteu R, Voitic G, Wiltsche H, Stangl C, et al. Thermal runaway of commercial 18650 Li-ion batteries with LFP and NCA cathodes – impact of state of charge and overcharge. RSC Advances. 2015;5(70):57171-86.
46. Larsson F, Andersson P, Blomqvist P, Mellander BE. Toxic fluoride gas emissions from lithium-ion battery fires. Sci Rep. 2017;7(1):10018.
47. Lecocq A, Eshetu GG, Grugeon S, Martin N, Laruelle S, Marlair G. Scenario-based prediction of Li-ion batteries fire-induced toxicity. Journal of Power Sources. 2016;316:197-206.
48. Willstrand O, Pushp M, Andersson P, Brandell D. Impact of different Li-ion cell test conditions on thermal runaway characteristics and gas release measurements. Journal of Energy Storage. 2023;68:107785.
49. Sturk D, Rosell L, Blomqvist P, Ahlberg Tidblad A. Analysis of Li-Ion Battery Gases Vented in an Inert Atmosphere Thermal Test Chamber. Batteries. 2019;5(3):61.
50. Rappsilber T, Yusfi N, Krüger S, Hahn S-K, Fellinger T-P, Krug von Nidda J, et al. Meta-analysis of heat release and smoke gas emission during thermal runaway of lithium-ion batteries. Journal of Energy Storage. 2023;60:106579.
51. Veen NWV, Koppen A, Putten EMv. Risico's van rook door branden van Li-ion-batterijen. 2021.

52. Bugryniec PJ, Resendiz EG, Nwophoke SM, Khanna S, James C, Brown SF. Review of gas emissions from lithium-ion battery thermal runaway failure — Considering toxic and flammable compounds. Journal of Energy Storage. 2024;87:111288.
53. Rohr A. Lithium Ion Battery Thermal Runaway Propagation and Emissions Analysis. EPRI. 2021(3002021644).
54. Ulrika Bergström ÅG, Lars Hägglund, Christian Lejon, David Sturk, Tobias Tengel. Screening of Vented Gases and Aerosols from Li-Ion LFP & NMC Batteries under Nitrogen atmosphere. 2015.
55. Buston JEH, Gill J, Lisseman R, Morton J, Musgrove D, Williams RCE. Experimental determination of metals generated during the thermal failure of lithium ion batteries. Energy Advances. 2023;2(1):170-9.
56. Wang Y, Wang H, Zhang Y, Cheng L, Wu Y, Feng X, et al. Thermal oxidation characteristics for smoke particles from an abused prismatic Li(Ni0.6Co0.2Mn0.2)O2 battery. Journal of Energy Storage. 2021;39:102639.
57. Zhang Y, Wang H, Li W, Li C, Ouyang M. Size distribution and elemental composition of vent particles from abused prismatic Ni-rich automotive lithium-ion batteries. Journal of Energy Storage. 2019;26:100991.
58. Premnath V, Wang Y, Wright N, Khalek I, Uribe S. Detailed characterization of particle emissions from battery fires. Aerosol Science and Technology. 2022;56(4):337-54.
59. LCPP. Étude de l'impact de feux de véhicules électriques (RENAULT) sur les intervenants des services de secours. 2012.
60. EMPA. Minimisation des risques d'incendie de véhicules électriques dans les infrastructures de circulation souterraine. 2020.
61. Ola Willstrand, Roeland Bisschop, Per Blomqvist, Alastair Temple, Anderson J. Toxic Gases from Electric Vehicle Fires.
62. Liu P, Liu C, Yang K, Zhang M, Gao F, Mao B, et al. Thermal runaway and fire behaviors of lithium iron phosphate battery induced by over heating. Journal of Energy Storage. 2020;31:101714.
63. Huang Z, Li X, Wang Q, Duan Q, Li Y, Li L, et al. Experimental investigation on thermal runaway propagation of large format lithium ion battery modules with two cathodes. International Journal of Heat and Mass Transfer. 2021;172:121077.
64. Qiao Y, Wang S, Gao F, Li X, Fan M, Yang R. Toxicity analysis of second use lithium-ion battery separator and electrolyte. Polymer Testing. 2020;81:106175.
65. Copenhagen WHOROfE. Air Quality Guidelines for Europe. WHO Regional Publications, European Series, No 91. (Second Edition).
66. Ludwig HR, Cairelli SG, Whalen JJ. Documentation for Immediately Dangerous To Life or Health Concentrations (IDLHs). 1994.
67. HESKESTAD G. Engineering Relations for Fire Plumes. Fire Safety Journal. 1984;7.
68. Benjamin T, Lauris J, Karen P. Recensement des substances toxiques (ayant un impact potentiel à court, moyen et long terme) susceptibles d'être émises par un incendie - Ω 16. 2023(Ineris - 203887 - 2079442 - v4.0).
69. ISO/TR 26368: Environmental damage limitation from fire-fighting water run-off, (2012).
70. McKinnon MB, DeCrane S, Kerber S. Four Firefighters Injured In Lithium-Ion Battery Energy Storage System Explosion - Arizona. UL Firefighter Safety Research Institute. 2020.
71. Truchot B, Fouillen F, Collet S. An experimental evaluation of toxic gas emissions from vehicle fires. Fire Safety Journal. 2018;97:111-8.
72. Downard J, Singh A, Bullard R, Jayarathne T, Rathnayake C, Simmons DL, et al. Uncontrolled combustion of shredded tires in a landfill - Part 1: Characterization of gaseous and particulate emissions. Atmos Environ (1994). 2015;104:195-204.
73. Singh A, Spak SN, Stone EA, Downard J, Bullard R, Pooley M, et al. Uncontrolled combustion of shredded tires in a landfill -Part 2: Population exposure, public health response, and an air quality index for urban fires. Atmos Environ (1994). 2015;104:273-83.