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Review

A Thorough Investigation into the Current State of the Art in Safety Management on Battery Fire and Explosion Risks

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Abstract

Battery-powered applications are rapidly spreading in handheld, domestic, business and power storage appliances and in propelling a range of electric vehicles. Fast developments of new battery technology sparked an equally fast development of a new and wide range of applications, showing new safety problems at the same time. The acceptability of these new safety risks across the range has so far not been thoroughly assessed due to lack of statistical incident data. This study explores the wide range of new technology-based battery applications where people are exposed to these hazards, gathers credible incident scenarios and assesses currently available means for incident prevention and mitigation. Battery fire, explosion and toxic fume incidents are emerging as key safety issues in aerospace, shipping, transport and storage, waste handling, the high-risk chemical industry, domestic appliances, industrial power storage, road traffic and carparks. Incidents are causing severe injuries, death and considerable environmental impacts and financial losses. Implementation of both preventive and repressive safety measures is ongoing, yet complicated due to re-ignition and chemicals involved in battery fires. New firefighting strategies and techniques are needed. The authors present an indicative risk assessment based on the presence of risk factors, as derived from a triangulation of experiences reported from practice, scientific literature findings and expert interviews, thereby initiating a risk-based perspective. Several ways to move forward are recommended.

Keywords: battery fire; firefighting; electric vehicle; emergency services; accident; risk management; safety; thermal runaway; toxic gas release; prevention

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1. Introduction

Since Nicolas Cugnot's steam-powered artillery vehicle of 1769 became involved in the first automotive accident in 1771, safety became and remained an important aspect of automotive vehicles. After early electric cars and steam-powered cars had competed for a while, and experiments with gas powered cars had failed, petrol-fueled cars were considered to be the best way to move forward from 1911 onwards [1].

Hence, after the initial dangers of sparks and uncontrolled release or explosion of hot steam, mostly fuel fire and explosion of liquid fuel vapors, have determined the risk around road vehicles for over a century. Since 1960, usage of compressed and liquefied propane gas (LPG) in high-pressure tanks to power vehicles added the dangers of a Boiling Liquid Expanding Vapor Explosion (BLEVE) and a flame torch [2,3].

Today, energy transition from fossil fuels to sustainable energy sources is changing road vehicle design. Electric bicycles, scooters, motorbikes, cars, vans, buses and trucks appear in traffic in increasingly growing numbers. This introduced battery chemical leakage, runaway, fire, explosion and toxic and combustible fumes as new additional risks to be managed. Also, the emerging use of power cells will further increase the dangers—overheating and uncontrolled air intake—of hydrogen fire and explosion. These new risks cannot be controlled via prevention or mitigation with the existing traditional fuel-oriented strategies and firefighting means [4,5].

Both the emerging new generation of electric vehicles and the ongoing energy transition from fossil fuels to sun-, wind- and moving water-based sustainable power have boosted the need for batteries. This has led to the continuous introduction of new types of batteries in energy systems as well as various domestic and business-oriented power storage applications [6].

As sustainable energy sources supply power in an irregular or intermittent way both in time and place, the storage of energy must be designed to meet the—quite different—demand pattern of the grid power users [7]. Different approaches are being observed.

A battery-powered vehicle can be designed to exchange power with a house which generates its own electric power from photo-voltaic solar panels and wind generators. Although still connected to a 220 Volt power grid, residential homes are increasingly often equipped with battery systems to store daytime solar energy for night usage [7].

Rather than leaving power supply and demand management to millions of interacting companies, private households and cars, power storage functionality could—alternatively or simultaneously—be centralized on power grid level. Then batteries need to be bigger [7]. There are several issues here. New battery types are being developed to increase their size, to enlarge the scale of their production, to improve their performance, to allow integration of home and vehicle energy storage, to reduce costs, and at the same time to overcome global material availability challenges [8–10].

Besides in vehicle and home power storage, many other battery applications in home appliances, telephones and a range of small transport vehicles are bringing batteries closer to people than ever before. At the same time, the newly developed types of batteries have both known and new hazards. There is still much uncertainty about the actual risks of battery fire, explosion and toxic fumes over the full range of battery application areas [11]. Fast and ongoing development of battery technologies, their comparative performances in many applications and the lack of statistical incident data all underline the need for a practical form of risk assessment, preceding any future statistical evaluation. Risk management appears to be lagging behind in view of the currently observed battery fire and explosion incidents and fails to steer future risk-based research.

This is illustrated by electric car fires. Initial studies comparing the likelihood of electric car fire with internal combustion fuel car fires both gave widely varying and therefore indeterminate results and ignored the problems with extinguishing battery fires. Theoretical comparisons between fires of Internal Combustion Engine Vehicles (ICEVs) and electrically driven cars initially showed no significant differences [12,13]. Later, empirical studies changed this view on several aspects of car fire characteristics [14,15]. The probability of car fires remained indeterminate [16–19]. Recently, several countries started investigating EV accidents in the USA [20], UK [21], Australia [22], Germany [23,24], Norway [25], Finland [26], China [27] and in The Netherlands [28]. This leaves an uncertain and incomplete impression, due to a mix of both alarming and comforting case data and of both clear and unknown causes, originating from partly scientific or official sources and partly from other sources. Hence, for the time being, battery fires must be regarded as a new, emerging and potentially significant danger in a wide range of application areas [29–33]. Safety management systems following ISO-31000:2018 [34] of organizations using batteries would need to respond to this danger. Acknowledging it must be followed by appraisal of the associated risks and by taking countermeasures in support of prevention and mitigation of battery fire scenarios.

Existing battery-powered vehicle design, legal requirements, building code, safety standards and firefighting techniques appear not to sufficiently take into account the intricacies of battery fires [35].

It is yet unclear how to handle the dangers of battery fires over the full range of domestic and business battery applications. At the same time the energy transition leads to increasingly more battery energy storage, both in large-scale Battery Energy Supply System (BESS) facilities and in domestic power storage applications. In this study, the research question is as follows:

Which battery fire scenarios require urgent attention of safety management?

2. Materials and Methods

2.1. Study Design

Seeking a direction to move forward on the safe use of batteries in many applications, we explore the literature, investigate current practice and interview experts to investigate the state of affairs on battery safety risk management.

The overall design of this study follows the case study method. The latitudinal descriptive case study form we use requires a blueprint to provide a structure for data gathering [36]. To this end, we conduct a preliminary literature search and establish a shortlist of aspects [37,38] which are used to generate appropriate search terms for further literature search and a topic list for in-depth interviews [39].

For these in-depth interviews, experts were selected from relevant stakeholder groups involved in firefighting, commercial logistics, safety knowledge and regulation.

An initial multi-scenario 'bow-tie' theoretical model [40,41] and a preliminary compilation of claims, concerns and issues [42] are generated and gradually refined and expanded as results are gathered from the literature search process. Both the model and the compilation of initial findings were shown and discussed during the interviews to obtain valuable and critical input for further search and analysis.

The reliability of each of the literature findings is ensured by only admitting them if mentioned in multiple sources. We chose the time period for searching the literature in such a way that the findings are recent, actual and relevant.

The scientific literature sources originate from many countries and are considered representative for the situation in the battery application field in industrialized countries.

A meaningful result in this emerging field cannot be achieved if the systematic literature review is limited only to primary scientific sources. This is because much is reported in secondary sources, e.g., official governmental public information, Non-Governmental Organization (NGO) reports, in reports by national and international research institutes, and in tertiary sources, e.g., private company reports, news media and verifiable commercial technical information. The latter, so-called 'gray' literature [43,44] is included in this study.

The quality and validity of our findings are protected by using peer-reviewed primary scientific sources where available, by using dependable secondary sources from institutions as mentioned, by using trustworthy tertiary 'gray' sources where necessary [43] and by using interview data originating from different stakeholder groups via a representative group of experts in this particular field [45].

The findings in this study are thus derived and merged from three different information sources: scientific literature, 'gray' literature from practice and expert interviews. Hence, we protect the validity of the findings by mixed-method triangulation [46].

Based on these findings, we explore and analyze battery safety risks using a simple harm-to-people-based indicative risk assessment model approach. Utilizing this, we identify and describe critical cases with high-risk battery application safety scenarios.

We then position the emerging battery safety risks with regard to the six fundamental steps of safety management: awareness, acknowledgement, comprehension, risk assessment, countermeasures and learning from incidents [34,47,48]. Finally, in a critical reflection [49], we highlight the current state of affairs from a safety management perspective in several countries and application areas. We then discuss limitations of this study and future directions and conclude with recommendations for further work on safety management.

2.2. Literature Search Results

The shortlist of aspects is constructed by approaching the matter at hand from two different angles: the safety-related aspects and the battery technology and application aspects.

Firstly, a set of safety-related search terms was composed, reflecting the current use of words and concepts found in the literature. These are as follows: 'battery, safety, runaway, charge, fire, explosion, accident, investigation, firefighting, prevention, mitigation, testing'.

Secondly, a set of battery types and application-specific terms related to materials, production and usage was composed. These are listed in Table 1 in the description column.

Battery accident data originate from different battery types, different battery sizes, different manufacturing processes and different applications and situations. We conducted many consecutive and overlapping literature searches to gather data on battery accident causality, safety concerns and issues, fire situations, relevant conditions, prevention and repression activities.

Both sets of search terms are then used to find primary scientific, secondary and tertiary 'gray' information sources [43].

Since a wide range of subjects is involved, we explored the literature in a series of separate searches following the scoping review technique [50] using successive searches with different combinations of search terms from both the main set and the specific set of search terms.

Several inclusion and exclusion criteria were used to protect the quality of the sources:

- We included primary and secondary sources from direct internet search and from further searching in their reference listings.
- We used the following databases: Scopus, Medline, Google Scholar, Academia, Research Gate and associated proprietary databases.
- We included secondary sources [43] published by government organizations and international institutions.
- Tertiary 'gray' sources [44] were admitted, if necessary, only if particularly relevant to the subject matter and in absence of relevant primary and secondary sources.
- Since the emerging safety risk of today's frequently used lithium-based battery technology exists less than two decades, the default time period for searching was set to 2000–2024. Sources from this time period were included with a few exceptions for essential sources from before 2000. To ensure that results are actual and relevant, the search period was set to 2019–2024 for searches in areas where fast technological development is going on.
- We included publications available in English. Several exceptions had to be made, e.g., due to limited availability of English language incident reports in non-English countries.

- In total, 245 scientific, 157 secondary and 118 tertiary sources were selected on the basis of their contents, leading to a total of 506 admitted sources, as seen in Table 1.

Table 1. Literature searches and sources admitted.

NR	Search Description	Search Period	Hits	Cut-Off	Sources Admitted
1	Search 1 July 2020 (preliminary)	n/a	n/a	n/a	6
2	Search 8 January 2022 (preliminary)	n/a	n/a	n/a	10
3	Search 2020—2023 (preliminary)	n/a	n/a	n/a	32
4	Search 26 July 2023 Fremantle Highway fire information	n/a	n/a	n/a	2
5	Search 15 January 2024 Fire safety carparks	n/a	n/a	n/a	2
6	Search 2 November 2023 Battery explosions	Since 2019	16,000	1st 100	13
7	Search 6 November 2023 Hearing aid battery accidents	Since 2019	12,900	1st 50	4
8	Search 6 November 2023 Watch battery accident investigation	Since 2019	17,600	1st 50	19
9	Search 10 November 2023 Lithium battery accident investigation	n/a	n/a	n/a	11
10	Search 16 November 2023 Alkaline battery explosion accident investigation	since 2019	15,300	1st 100	4
11	Search 16 November 2023 Lead acid gel battery explosion	since 2019	17,100	1st 50	2
12	Search 16 November 2023 Lithium-ion battery explosion accident investigation	since 2019	17,500	1st 50	17
13	Search 29 November 2023 LFP (LiFePO4) battery explosion accident investigation	since 2019	3600	1st 50	3
14	Search 1 December 2023 NMC battery explosion accident investigation	since 2019	3670	1st 50	16
15	Search 1 December 2023 Silver oxide battery explosion accident investigation	since 2019	14,400	1st 50	3
16	Search 2 December 2023 Solid-state battery explosion accident investigation	since 2019	16,900	1st 50	7
17	Search 2 December 2023 Zinc–air battery explosion accident investigation	since 2019	1890	1st 50	3
18	Search 2 December 2023 BMS failure accident investigation	since 2019	16,800	1st 50	5
19	Search 3 December 2023 Battery thermal runaway testing standards	since 2019	16,800	1st 50	11
20	Search 4 December 2023 Safety rechargeable battery design	since 2019	17,400	1st 50	15
21	Search 4 December 2023 Battery fire and explosion firefighting	since 2019	5220	1st 50	20
22	Search 15 December 2023 Battery applications range and energy content	n/a	n/a	n/a	40
23	Search 16 December 2023 Battery types under development	n/a	n/a	n/a	12
24	Search 20 December 2023 Accidents per battery application	since 2019	n/a	n/a	65
25	Search 25 December 2023 Battery safety standards	n/a	n/a	n/a	7
26	Search 13 December 2023 NIPV information	n/a	n/a	n/a	24
27	Search 30 December 2023 Existing mitigation techniques	n/a	n/a	n/a	24
28	Search 22 January 2024 Full-scale testing, Lithium-ion battery fire	n/a	n/a	1st 50	14
29	Search 30 January 2024 Lithium battery production resource limitations	since 2020	15,700	1st 25	4
30	Search February–May 2024 Fire propagation	n/a	n/a	n/a	4
31	Method section references	n/a	n/a	n/a	(pm)
32	Search March 2024 Standards and Legislation	n/a	n/a	n/a	54
33	Search March 2024 Legislation	n/a	n/a	n/a	31
34	Search March 2024 NIPV CoP information	n/a	n/a	n/a	5
35	Search 2024 EV battery fire accident statistics	>2022	4600	50	17 +
	Total				506

(n/a is Not applicable).

3. Results

3.1. Theoretical Model

3.1.1. Construction of a Combined Model

Many current safety models present 'layers of protection' and are commonly used in the process industry and in other sectors, often adapted to fit the context [51]. Ideally, accident investigations deal with how an accident occurred and understanding why it happened [52]. Making accident circumstances also visible requires an accident investigation method that delves into underlying causation [53]. In order to obtain an overview of battery accident causality, we construct a model using two well-proven techniques:

- a timeline-based sequence of events model [54];
- a 'bow-tie' multiple scenario description [40,41];
- a 'fault-tree' analysis diagram applied to electric vehicle fire [55].

On this basis, a generic scenario model is built to describe the events associated with battery fire, explosion and toxic gas and fumes release.

In support of this combined model, we determine unwanted scenario events, a range of preventive and repressive countermeasures, also referred to as 'barriers', and a suite of supporting activities with each barrier. The way we go about this is by extracting text parts concerning battery safety issues and clustering these by means of a meta-synthesis process [43,56].

3.1.2. Timeline-Based Sequence of Events Model

As a start, a timeline-based sequence of events model [54] was constructed based on battery fire experience data [57]. Looking at the time elapsed between successive events, this model shows that very little opportunity exists to stop fire and explosion from happening once a [Lithium] battery-powered device becomes mechanically damaged and short circuit occurs. Sparking, heating up, fire and explosion can take place within a in second. These effects develop faster in smaller batteries. Prevention of damage is the only way to counteract the effects of small-battery-type scenarios. In runaway scenarios, a battery heats up due to, e.g., electric overload. For bigger batteries, this heating is slower. A scent of burning, visible smoke and temperature increase in the battery can be detected. Heating up may take a few minutes before sparking, fire and explosion occur.

Depending on the size of the battery, proximity to other batteries or flammable materials in the direct vicinity and of the fire characteristics (e.g., jet flame), initial spreading will take place, roughly within a 5–20 min period. This may not equate to the time it will normally take the firefighters to arrive, even if assuming they are warned shortly after the start of the fire.

In principle, solutions for the problem of fire spreading before firefighting starts can be found by either having an automatic mitigation action in place, or by having detection and firefighting equipment readily available on site. In practice, the first priority in any firefighting strategy is to save people from a fire. This may require the presence on site of a cooling system and/or fire screen, allowing a rescue team to do so.

3.1.3. Generic Battery Fire and Explosion Scenario Model

New causality is associated with the emerging usage of new battery technology, closed cells and package constructions and high energy density. Battery incidents can be initiated by production errors, abuse, lengthy charging, overheating, shock loads, mechanical damage and other causes. The ferocious fire, spreading of sparks, generated oxygen, combustible gases and toxic fumes all create new risks for direct emergency service intervention teams and victim rescue. New technology batteries can not only catch fire or explode spontaneously, but are also notoriously hard to extinguish. Spreading of such fires is difficult to stop [58–65].

By using these causality- and scenario-related literature findings, the timeline model was expanded into a 'bow-tie' multiple scenario description [40,41]. This generic scenario, an overview of battery fire and explosion causality, was refined with respect to both the above timeline model and the Electric Vehicle (EV) fire Fault Tree Analysis (FTA) model [55]. Figure 1 shows causality against time between root causes, via battery fire and explosion central events, towards the long-term effects: harm to people, damage to the environment and financial losses. With this overview, we compiled an event map showing events any battery fire and explosion scenario might encounter. For each unique scenario, a subset of these events is applicable.

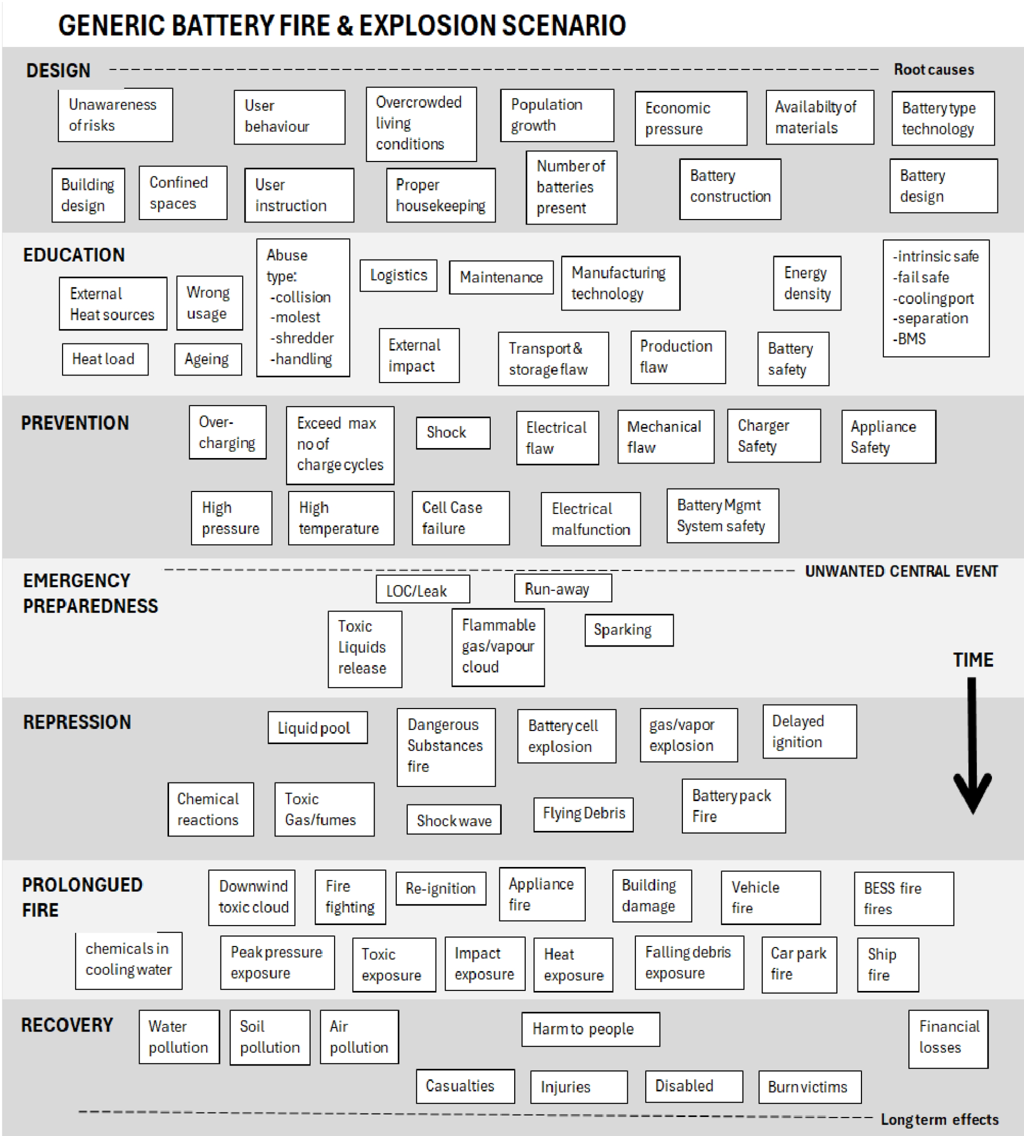

Figure 1. Causality of battery fire and explosion over time.

Over time, the causality—events and their logical sequential interconnections—can be allocated to seven phases. Causality in the model must begin from the ***design*** phase. Here, material properties, the technologies used, and safe design are key factors, ensured by the consistencies of production performance, and circumstances in which the materials are combined into battery cells, packs and larger units.

In the next phase, handling, storage and usage of batteries in a wide variety of applications are what it is all about. The key factor here is the ***education*** of the users. Causality in this phase is on mechanical, electrical, time and temperature factors as external factors affecting the battery performance and integrity.

The next phase responds to this by ***prevention***, via detection and support systems, allowing, postponing, suppressing or preventing unwanted battery malfunction, leakage, fire and explosion.

The next phase, as prevention might fail, is that of ***emergency preparedness***. Here, events are happening very fast, and therefore require automated actions to mitigate fire, toxic cloud and explosion of batteries and vent gases. Then a ***repression*** phase follows, which is about rescue of people and firefighting. ***Prolonged firefighting*** then avoids, e.g., re-ignition and minimizes long term effects on the environment. The final phase is ***recovery***, where—as far as possible—harm to people is healed and damage is compensated, repaired or undone and systems are made more resilient.

3.2. Expert Interviews

Four in-depth interviews [39] were held to verify the findings from the literature. The interviewees were experts, selected for their competence and experience and their affiliation with reputable Dutch institutions, stakeholders involved in battery safety. Together they cover knowledge, practical experience, prevention and repression aspects. The interviews were held as follows.

Project manager, government safety institution, regional office, 13 December 2023 (firefighting organization).

Dangerous goods expert, transport and storage knowledge center, national office, 26 January 2024 (logistics organization).

Expert energy and transport safety, public safety research institute, online meeting, 14 March 2024 (safety research/training/knowledge organization).

Specialist chemical and process safety, regulator knowledge center, off-site meeting room, 22 March 2024 (regulator, standards committee). The interviewees participated on a voluntary basis. Their anonymity is protected. The interviews were held face-to-face between interviewee and interviewer. The purpose of the study was explained in advance in a telephone conversation during the planning of the interviews and was briefly revisited at the beginning of each interview. Each interview lasted approximately one hour. The respondents were asked to freely express their views on the subject matter. A simple interview protocol was used. Research goal and preliminary literature findings (see Figure 1) were presented to initiate discussion. Further depth was achieved using 'open' questions. In this way, the interviewer ensured that the following subjects were addressed: the battery safety situation, applications, incidents, stakeholders, testing, future developments, critical issues. Notes were taken by the interviewer as the basis for a short interview summary written afterwards. Saturation was quickly reached and further interviews turned out to be not necessary. The following concerns and issues were mentioned by two or more of the experts:

Work safety

- Electro-Magnetic Cleanliness (EMC) related externally induced runaway causes not taken into account.
- Combination of Explosive Atmosphere (ATEX) zones and battery explosion risk are not satisfactorily investigated.
- Seveso III directive is not yet applicable to battery storage.
- Whether Lithium batteries are pressure-proof is doubted in ATEX zones, e.g., emergency power supplies.

- Handling procedures and criteria for suspect and damaged batteries are not regulated.
- Working procedures with (L)EV ((Light) Electric Vehicle) batteries in car maintenance and repair are not regulated.

Consumer safety

- Consumers and small-capacity applications are not (fully) addressed in safety legislation or standards although an average family may have some 100 batteries in their household.
- A lower capacity limit level for lethal accidents seems likely.
- A personal injury risk maximum in the center area of the range is likely.
- Home power batteries are not subject to safety regulations.
- Battery aging is not being monitored in many applications.

Transport and Storage safety

- Highest frequency of fires is at waste/recycling plants.
- Load percentage check is not practical.
- Cause of battery fire is often unknown.
- Standards for transport and storage of dangerous chemicals do not apply.
- Insurance companies are not in on this.
- Industry wants an increase in storage compartments from 2500 m^2 to over 10,000 m^2.

Fire safety

- Too little case info and records are available.
- Too little instructions on how to handle battery incidents are available.

Firefighters' safety

- Approaching battery fire needs a heat resistant + gas tight protective suit.
- Means to fight a battery fire still in testing stage.
- Cooling access port on EV would help a lot.
- Moving a burning EV to a safe location is difficult.

3.3. Concerns and Issues

Some 1403 concerns and issue [42] text parts were extracted from the admitted literature sources. Using a meta-synthesis process [56] these were clustered into theme groups. The resulting concerns and issues are listed in Table 2. We applied mixed-method triangulation [46] by merging extracted concerns and issue text parts from all admitted primary literature sources, gray literature sources and interview reports. This increases the validity of the findings. Frequency counts are included as an indicator of the current attention per theme.

From a safety management point of view, the main finding is that the likelihood aspect of battery fire and explosion risks is hardly mentioned in the literature. This makes a sound risk assessment impossible.

Table 2. Clusters of concerns and issues and their frequency counts.

Cluster	Concerns and Issues	Count	Frequencies
scenarios	Hazards	247	407
	Causality	64	
	Impact	39	
	Fumes	25	
	EV parking	19	
	Buildings	8	
	Scenarios	5	

Table 2. *Cont.*

Cluster	Concerns and Issues	Count	Frequencies
technology	Battery technology	194	312
	Testing	47	
	Design	36	
	sensors	19	
	Materials	12	
	Transition	4	
usage	Application	157	229
	Energy storage	46	
	User instructions	24	
	Other	2	
mitigation	Mitigation	77	132
	Firefighting techniques	34	
	Firefighting	21	
case history	Case history	113	123
	Statistics	10	
knowledge	Knowledge	56	89
	Future	18	
	Research	7	
	Mathematical models	8	
regulation	Regulation and Standards	58	58
logistics	Transport	44	53
	Storage	9	
			+
Total			1403

3.4. Battery Types

Batteries are commercially available in a wide variety of types and sizes. They all share the same construction principle: an *Anode* (negative electrode), a *Cathode* (positive electrode) and an interstitial *Medium* (electrolyte) allowing ions to move between the electrodes during discharge and/or charge [66,67]. A variety of battery chemicals are in use [11,68–73]. Frequently used battery types and their main characteristics are listed in Table 3 [74].

Current batteries are mostly Lithium-based because of their high electrical power storage capacity compared to their weight. New battery technology is under development in order to find less-flammable materials and better production methods [69,75–79].

Table 3. Frequently used battery types and their main characteristics [66,73–75,79].

Type	Chemicals	Energy	Runaway	Maximum
		Density kJ/kg	**Temperature Celsius *)**	**Charge Cycles**
	Alkaline	400–600	-	2000–6000
	Silver oxide	470	-	n/a
	Zinc–Air	400–1600	-	n/a
	Lead–Acid	140	-	500
NiCd	Nickel–Cadmium	140	-	500–2000
NiMH	Nickel–Metal hydride	250–400	-	180–2000
LTO	Lithium-titanate	50–80	dnya	3000–20,000
LFP	Lithium iron phosphate (LiFePO4)	90–120	220–270	2000–12,000
LMO	Lithium-manganese-oxide	100–150	210–250	300–700
	Lithium solid state	400	dnya	low
	Lithium–Sulfur	550	dnya	low
	Sodium-ion (Na-ion)	90	dnya	low
NMC	Lithium Nickel Manganese Cobalt oxide	150–220	160–210	1000–2000
LCO	Lithium Cobalt (Lithium-ion)	150–200	150–165	500–1000
NCA	Lithium Nickel Cobalt Aluminum oxide	200–260	140–150	500

*) dnya = data not yet available.

3.5. Battery Applications

The battery application range extends from watches and hearing aids, via domestic and business appliances, via electric road vehicles, to large-scale BESS. Batteries are available in a variety of energy capacities and shapes [2]. Currently, most battery applications make use of Lithium-based rechargeable battery technology. Table 4 lists commercially available examples of application types and their batteries in increasing size and energy content sequence; the smallest is for a watch [80], the biggest is for a BESS [81].

Table 4. Battery application, type and energy storage capacity range **).

	Type	Model	Range km	Speed km/hr	Power kW	Battery Type *)	Ah	V	Capacity kWh
1	Watch	Watch/Battery: VARTA V371 (Haga, Germany)	-	-	-	Silver oxide	0.042	1.55	0.00007
2	Hearing aid	/Zenipower.MF A675 (Zhuhai, China)	-	-	-	Zinc–air	0.60	1.4	0.00084
3	Remote	TV-Remote/Battery: AAA	-	-	-	Alkaline	1.0	1.55	0.0016
4	E-cigarette	Vape pen/Battery: Molicell 18650 (Taipei, Taiwan)	-	-	-	LCO (Lithium-ion)	2.8	3.7	0.0104
5	Smartphone	Samsung Galaxy S5/Battery: EB-BG900BBE (Suwon, Republic of Korea)	-	-	-	LCO (Lithium-ion)	2.8	3.85	0.0108
6	Toys	4DRC remote-controlled toy helicopter	-	-	-	Lithium-Polymer	1.50	7.4	0.01110
7	Camera	Nikon EN-EL3E (Tokyo, Japan)	-	-	-	LCO (Lithium-ion)	1.6	7.4	0.012
8	Laptop	Lenovo Thinkpad T470 (Beijing, China)	-	-	-	LCO (Lithium-ion)	2.08	11.55	0.024
9	Cordless drill	Bosch-easydrill-18v-40 (Gerlingen, Germany)	-	-	-	LCO (Lithium-ion)	2	18	0.036
10	Kids car	Teoayeah Anpabo G63 (Kangli, China)	4	5	0.07	LCO (Lithium-ion)	7	12	0.084
11	Vacuum cln. cleaner	Dyson V8 Handheld/Battery: Bonadget 4500 mAh (Singapore)	-	-	-	LCO (Lithium-ion)	4.5	21.6	0.097
12	Power bank	Generic Powerbank 20,000 mAh	-	-	-	LCO (Lithium-ion)	20	5	0.100
13	Kickscooter	Segway Ninebot Max G30D II (Beijing, China)	65	25	0.35	LCO (Lithium-ion)	15.3	36	0.55
14	One wheel	Onewheel PINT X (Santa Cruz, CA, USA)	25	29	0.75	NMC	-	-	0.75
15	Scootmobiel	Nipponia Pride 3 wiel scooter (Zwolle, The Netherlands)	50	25	0.65	Lead gel	-	-	1.38
16	E-Scooter	La Souris E-ID S6 Bosch—Delivery	60	45	2.00	LCO (Lithium-ion)	-	-	1.80
17	Unicycle	Inmotion V14 Adventure Electric Unicycle 50S (Munich, Germany)	120	25 (70)	4.00	LCO (Lithium-ion)	-	-	2.40
18	Three-wheel bike	2021 Cobra Trike 12″ El. 3 Wheel Citycoco Scooter (Xiamen, China)	100	45	0.35	LCO (Lithium-ion)	-	-	2.40
19	E-bike	E-Chopper 6.0 (Hamburg, Germany)	120	45	2.00	LCO (Lithium-ion)	45	60	2.70
20	Three-wheel scooter	Nipponia Pride 3 wiel scooter	40	25	0.65	Lithium	20	60	7.20
21	Power wall	Solarwatt/BMW Battery flex 14.4 kWh (Dresden, Germany)	-	-	-	LCO (Lithium-ion)	-	-	14.4
22	TucTuc	E-Tuk Factory (Utrecht, The Netherlands)	75	50	-	LCO (Lithium-ion)	1481.5	13.5	20.0
23	Small EV car	Nissan-Leaf (Yokohama, Japan)				LCO (Lithium-ion)			40.0
24	Medium EV Car	Tesla Model 3 Long Range/Battery: CATL China (Austin, TX, USA)	<438	<200	11	LFP (LiFePO4)	150	400	60.0
25	Tuktuk	Tuktuk/Replacement battery pack (Xuzhou, China)	-	-	-	LFP (LiFePO4)	1600.0	48	76.80
26	Future EV cars	Toyota EV/Mercedes EQXX/2028 (?) (Toyota, Japan)	1200	-	-	Solid-state (?)	-	-	100.0

Table 4. *Cont.*

	Type	Model	Range km	Speed km/hr	Power kW	Battery Type *)	Ah	V	Capacity kWh
27	E-bus	VDL Citea SLF-120/Battery: Akasol (Eindhoven, The Netherlands)	600	-	160	NMC	-	-	490.0
28	Future EV Trucks	Volvo FH Electric 44 Ton (Göteborg, Sweden)	300	-	490	LCO (Lithium-ion)	-	-	540.0
29	ESScontainer	DNV GL/TKI Systemintegration (2018) (Oslo, Norway)	-	-	10	LCO (Lithium-ion)	-	-	25,000.0
30	Giga Storage	Groningen, Delfzijl area (Groningen, The Netherlands)	-	-	-	(t.b.d.)	-	-	1.000.K
31	Vistra Energy Corp	BESS, Moss Landing, California/Batteries: LGES (Edison, NJ, USA)	-	-	400 K	LCO (Lithium-ion)	-	-	1.600.K

*) Battery LCO = Lithium-ion = Lithium cobalt; LiFePO4 = Lithium iron phosphate; NMC = Lithium nickel manganese cobalt oxide, **). Search on commercially available electric equipment and their (replacement) batteries, Google, time period 2023–2024.

From Table 4, it becomes clear that batteries cover a wide range of commercially available applications and come in a wide range of sizes and shapes, each fitting a particular group of applications. It is also clear that Lithium-based battery technology is used over most of the range. Currently, battery electric energy storage capacity ranges between 6.5×10^{-5} kWh [80] for a wristwatch and 1.6×10^{6} kWh for a large-scale BESS [81].

3.6. Standards and Legislation

Legislation addresses the safety of consumers and of workers in many countries. A list of 48 international standards relevant to battery safety is compiled from several sources, as seen in Table 5.

Table 5. International standards applicable to battery fire safety (not exhaustive) [29,57,72,82–87].

IEC 31010 2019	IEC 62933-5-1/-2:2020	EU 2008/98/EC/2023
IEC 60079-10-1: 2021	IEC 63056	EU 2016/425
IEC 60079-14:2014/2016	ISO 6469/-2/-3	EU 2019/1020/2023
IEC 60079-29-2:2015	ISO 12405-2	EU 2023/1542
IEC 60947-5-5:1998	ISO 13850:2015	JISC8715-28
IEC 60947-5-5:1998/2017	ISO 14001:2015	UL 1973
IEC 61508 series	ISO 17840 series	UL 9540A:2019 edition 4
IEC 61511 series	ISO 4126-1:2013	UN 118:2012
IEC 62281	ISO 4126-1:2013/2019	UN 38.3
IEC 62305-1:2011	ISO 7010:2012	NFPA 855:2023
IEC 62305-2:2012	ISO 26262-1:2018	PGS 37-1 2023
IEC 62485-5	ISO 26262-10:2018	PGS 37-2 2022
IEC 62305-3:2011	ISO-31000:2018	SAE J1766
IEC 62305-4:2011/2016	ISO 7010:2012 + addn	SAE J2929
IEC 62561 series	ISO 45000:2018	EN 50604-1
IEC 62619:2022	ISO/IEC 17020:2012	IEC 62133 series

On 14 June 2023, the European Commission issued EU 2008/98/EC [88] as an amendment to the existing Battery Directive and Regulation EU 2019/1020 [89] with control of the environmental impact of batteries and their construction materials. This new regulation is about the life cycle management of Light Electric Vehicles (LEVs), EV and industrial rechargeable batteries with power storage capacity above 2.0 kWh. In the future (by 2030), the feasibility of regulation EU 2023/1542 [90] of portable batteries with storage capacity < 2.0 kWh will be assessed. National legislation in EC countries, derived from this new regulation, is not yet implemented. Currently, European standards are not generally addressing battery fire

and explosion hazards over the entire storage capacity range. The international standard EU2023/1542 [90] and—if present—EC countries' national standards, e.g., the new 'pilot' standards PGS-37-1/-2 are recently introduced in the Netherlands to regulate storage facilities for large quantities of batteries on a basis similar to storage of dangerous chemical substances [82,83]. These are applicable to battery power supply systems with a stored capacity of more than 20 kWh. Hence, current battery power supply safety standards do not cover the entire battery capacity range (see Table 4) since these standards focus on high energy content.

There are several generally applicable requirements, e.g., on product quality, labeling and packing. Of special interest are standards addressing the management of battery power systems [85] and IEC 62619:2022 [91] specifically addressing Lithium batteries.

Independent from formal standards, there is a growing number of private company measures taken by users to avoid the presence of batteries in specific situations. This underlines the growing concern about battery safety. Examples of this are the limited size of power banks allowed onboard an aircraft and carparks not admitting electric vehicles.

3.7. Influencing Factors on Hazards of Battery Fire, Explosion and Toxic Fumes

On top of the existing safety risks of liquid and solid battery technology, new mainly Lithium-based battery types are associated with new hazards and therefore new risks:

- New battery types can be susceptible to thermal runaway reactions. These can lead to heat, release of electrolytes, high pressure, sparks and fumes containing oxygen, combustible gases, toxic pyrolysis reaction products and dissociated or evaporated battery construction materials and can spontaneously cause a 'primary' explosion and fire. This implies that a large stockpile of such batteries is hazardous [82,83].
- If the temperature increases by 10 °C/min or more in a Lithium battery, this is called a thermal runaway [25,92]. This underlines the importance of temperature-monitoring sensors on or in batteries. These can, e.g., be infra-red sensors, thermocouples, strain gauges, impedance measurement, ultrasonic/acoustic measurement, etcetera.
- 'Secondary' explosions can occur due to H_2 release associated with a thermal runaway. The H_2 gas can accumulate in a battery pack or under a ceiling and be ignited by the ongoing fire [77].
- New battery-type fires can start in any application at any time and at any place. This clearly implicates handheld, wearable and other applications in the direct vicinity of people to be potentially dangerous [93].
- Spontaneous fire or explosion can happen within a fraction of a second, depending on their cause [94].
- Causality extends from battery and battery pack construction, via Battery Management System (BMS), State of Charge (SOC) and temperature monitoring, sensor array, to system technical provisions, e.g., ventilation, and containment provisions, e.g., building design, compartments, distances and terrain layout [59,63]. Sensors allow early and fast intervention in case of a runaway, allow alarms and may support automatic actions such as shutdown, start a sprinkler or jettison a hot item toward a safe location.
- New types of batteries both have a larger energy content than previous generation batteries, and are more vulnerable to production flaws, mechanical shock, external impact, external heat, overcharging, shortcut and electro-magnetic irradiation [2].
- New types of batteries are flammable and, if on fire, they are notoriously hard to extinguish. This is mostly due to poor accessibility to cooling due to a closed construction [2], making fires last longer.

- Fire in a battery, if constructed of flammable materials, can also reignite until the electrical energy is fully dissipated [95]. This also makes the fire last longer.
- Rapid release of the large energy content and of flammable and toxic gases make it riskier for emergency services to approach [96].
- Fierce fire effects, toxic and combustible fumes and re-ignition increase the likelihood of fire spreading, e.g., in an EV transport ship [93] or in a carpark [97].
- Existing buildings, e.g., public carparks, are not specifically equipped for battery fire mitigation and recent building code changes address only newly built parking facilities [35].
- Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), using both a battery system and a combustion engine as a generator, have both liquid fuel and battery fire risks to consider. Such designs could lead to higher energy release by a fire than EV cars. Current hybrid cars have relatively small batteries [26].
- Rescue efforts in the presence of a battery fire and its toxic or combustible fumes are more complex to deal with and need special techniques [27].
- Accident victims, emergency medical service staff, firefighters, and the general public may be exposed to toxic fumes, e.g., HF [77,98,99], and may suffer from both short- and long-term consequences [100].

The aftermath of a battery fire presents an environmental impact due to large quantities of corrosive or toxic cooling and extinguishing water [27].

Causality of battery fires needs to be considered on cell, package, system and overall levels. Causality can also reside in the technical installation of which batteries are components. Last but not least, a range of environmental parameters and operational conditions contribute to the safety and security of a battery application. Prevention of battery fires can be performed by taking measures on all of these aspects.

3.8. Influencing Factors on Battery Fire and Explosion Effects

At first glance, there are three main categories to consider when it comes to battery fire, explosion and toxic fume hazards:

- Applications close to people (e.g., wearable, handheld, electric vehicle, domestic storage, operating table, EV). These battery fire/explosion incidents can cause personal injuries, disabilities or death. The harm to people and damage to their belongings might happen so quickly that emergency medical service is needed rather than firefighting. Here, a battery fire can cause not only personal injury and damage, but, also, e.g., to personal property and buildings.
- Applications involving gathering of large quantities of batteries (e.g., transport, storage, power generation, EV parking). Although injury and death are possible, these battery fire incidents develop over time, hence allowing people to use distancing to attempt escaping and to be rescued. Hence, these incidents mainly have environmental and financial impact. Firefighters can limit this damage considerably if suitable techniques are made available on site. Such battery fires can cause a toxic cloud and significant environmental air, water and soil pollution via contaminated water and electrolyte leakage. Also, there can be damage to installations and buildings.
- Battery recycling involves gathering end-of-life, ideally fully discharged batteries, processing these to regain electrolytes, electrodes and casing materials, and making these reclaimed materials available for new battery production. Practice shows there are frequent fires, toxic clouds and air, water and soil pollution risks. Causality is revolving around Lithium batteries being not fully discharged and becoming mechanically damaged during the recycling process. Direct physical harm to people is not reported in the literature but exposure to toxic fumes can have long-term health effects.

Several effects are unique to the new generation of batteries based on Lithium and Sodium. These are as follows:

- Release of combustible gases leading to secondary explosion
- Release of toxic gases or vapors
- Re-ignition by remaining electrical charge in a damaged battery
- Fire not put out by reduction in oxygen availability

The effects of battery fires need to be related to their likelihood of occurrence in order to evaluate the associated safety risks. Although case descriptions are available from both scientific and gray literature, statistical data are hard to find. New initiatives to gather such data have not yet produced results suitable for statistical risk analysis.

Therefore, in this study, an alternative way to assess the risks is used based on a range of situations around a battery fire and explosion event. These are derived from cases reported in both scientific and gray literature.

3.9. Typical Situations Around a Battery Fire

A battery fire can happen in a variety of domestic, public, transport and industrial situations.

This is best illustrated by a range of battery fire cases reported in the literature, as listed in Table 6.

Table 6. Typical battery fire and explosion situations.

Fire Situation	Case Description	References
Person, wearable, handheld	Phone, vape	[61,62,101–111]
Private home (inside, outdoor)	Home appliances	[112–116]
LEV Light Electric Vehicles	E-bike, scooter	[117–119]
EV Electric car	Traffic, parking	[25,60,120–126]
E-buses	E-bus in traffic	[127,128]
Tunnel (underground, traffic)	EV tunnel traffic	[58,129–135]
Carpark (multi-storey, underground)	Multi-storey bld.	[97,136–139]
Cargo ship (EV cars, batteries, fuel)	Cargo ship	[140–143]
Ferry (cars, trucks, passengers)	Ferry	-
Airplane (transport, passengers)	Battery fire	[64,144–148]
Battery storage (Storage unit)	Storage unit	-
Recycling site (battery waste)	Waste fire	[149–152]
Energy supply (ESS Container unit)	ESS container	[153,154]
Large-scale BESS	BESS site	[155–159]

In each situation, the possibilities for mitigation are different. Extinguishing, mitigating or controlling a battery fire is troublesome due to explosion hazard, fire re-ignition, toxic fumes, heat radiation and convection, buildings losing their structural strength [14] and poor access [77].

For situations involving people inside an EV, an E-bus, ship or airplane, there can be a delay before they can escape from a suddenly starting fire. This delay can be short if the vehicle is stationary but can be longer when traveling at high speed or because disembarking is not possible. Containing a fire and separating it from people is then the only viable way towards their rescue.

When it comes to battery fire and explosion incidents, firefighting requires dedicated techniques and equipment. For some of these mitigation tools it is realistic to have them readily available on site. For other tools this may not be feasible, e.g., for cost reasons. There will then be a delay time period before such tools can be brought in at the site of a fire. Furthermore, not all tools will be suitable for all battery fire situations.

3.10. Battery Fire Prevention

Prevention of battery fires starts from material choice, a safe and resilient design, reliable production, safe transport and storage and correct instructions for use of batteries [160–162].

The application design can minimize the exposure risk of damage or deformation and minimize fire propagation and spreading [31,161–166].

During battery use, the operating conditions must be within prescribed limits. The number of charging cycles, charge depth, charging speed, discharge speed, temperature level, thermal expansion, pressure, release of smoke, gas or vapor, shocks, vibration, electromagnetic interference and internal or external electrical shorts can all be indicators for battery problems leading to a thermal runaway.

There is a short period of time where such battery condition monitoring can make an important difference. The indicators can be used to counteract further heating up by taking automatic action, e.g., cooling, ejecting, isolating or remotely switching-off a battery, a battery pack or a unit in a larger system [121,167–172].

3.11. Battery Fire Mitigation Techniques and Strategy

Extinguishing a battery fire is notoriously difficult [2]. Hence, depending on the situation, firefighters need to decide how to go about victim rescue efforts and about fire mitigation [173]. At their disposal is a range of mitigation techniques (Table 7) in various stages of usage in practice. References are included as examples only. Firefighters need to be trained on how to use these techniques for different situations and organize ways to have suitable equipment available at the location of a fire.

Table 7. Mitigation techniques for battery fires (not exhaustive).

No	Mitigation Technique	Usage in Practice	References
1	Mobile sprinkler	Operational—Availability issues	[174]
2	Extinguishing blanket	Plastics that are not fire-resistant	[175]
3	Closed water container	Operational	[176]
4	Water battery cutting system	Operational—Availability issues	[177]
5	Water car baseplate cooler	Operational—Availability issues	[178]
6	Remote-controlled car mover	Design and Testing stage—Availability issues	[179]
7	Battery fire, mitigation, foil strain gauges	Design and Testing stage	[168]
8	Smoke control underground spaces	Operational	[169]
9	Permanent aerosol explosion inhibitor	Operational	[180]
10	EV Extinguishing blanket	Plastics that are not fire-resistant	[181]
11	Extinguishing robot	Design and Testing stage	[182]
12	Water container open	Operational	[183]
13	Software—car construction info	Operational	[184]
14	Battery water injection system	Operational—Availability issues	[185]
15	Pressure sensors	Design and Testing stage	[170]
16	Temperature, pressure sensors	Design and Testing stage	[171]
17	Water mist system	Operational—Availability issues	[186]
18	Car baseplate water injection system	Operational—Availability issues	[187]
19	Fast charging, review, temperature mapping	Design and Testing stage	[172]
20	Fire propagation limitation	Design stage	[188]
21	Salvage container	Operational	[189]
22	Car isolation water bag	Plastics that are not fire-resistant	[190]
23	Mobile water container foil kit	Plastics that are not fire-resistant	[191]
24	Mobile water container steel kit	Operational—Availability issues	[192]

Battery fires have long been treated like any other fire, as they were rare, certainly when battery types at the small-capacity end of the range are involved. Developments in firefighting practice are currently focused on EV fires in traffic and in carparks. The appearance of a growing variety of small battery-propelled LEVs with one, two, three or four wheels in traffic has extended the focus of firefighters towards LEV fires, predominantly in a domestic context [119].

Since 2020, recommendations stating that EV should be parked and charged near a carpark entrance were adopted. Several other technical measures should also be taken to accommodate new car designs: fire detection, H_2 gas release via vertical ducts and ceiling openings, EV charging equipment and cables to be of approved quality, collision protection of charging stations [77] and a remote emergency shut down switch. The people using the carpark facility should be instructed about safe conduct when an incident occurs. Recommendations about sprinklers, water mist systems and fume ventilation were issued as well [193].

Once an EV battery fire has started, the mitigation approach may consist of several interacting elements [2,77]. These are as follows:

1. Identify the vehicle type (via license plate and fire rescue centers) in order to assess the vehicle construction, localize access ports to the battery, localize jet flame or gas release points and choose the rescue approach accordingly [2,184].
2. Determine the firefighting plan [2].
3. Protect the people first [2].
   - Use cooling water via the water mist, drenching, sprinkler, base plate spraying or aerosol system to slow down the fire and stop re-ignition [2,14,77,174,178,180,186,187].
   - Use or make access ports for water injection in EV batteries [177,185].
   - Cover the fire with a blanket to reduce toxic gas release [14,175,181,194].
4. Control or extinguish the fire [77] and switch off the charging facility [2,182].
5. Vehicle is not to be moved immediately after the fire is extinguished [2].
   - Place burning EV in a pop-up water basin, container or bag for cooling [57,176,189–192].
   - Use a safety distance (e.g., 15 m) [77].
   - Let the fire burn out [12,77].
   - Use fire compartments to limit damage [83].
   - Move the burning vehicle battery to a safe place outdoor since re-ignition is possible [2,77,179,183].
6. On-site cleaning [2].
   - Collect cooling water contaminated with toxic chemicals [27].

3.12. *Analysis*

3.12.1. Indicative Risks

Using the range of fire situations (see Table 6), a qualitative yet indicative risk assessment for battery fires can be made. Both the effects and the likelihood of battery fires need to be addressed in order to establish a risk level for *harm to people*. Since statistical information about battery fires is non-existent or in its infancy at best, a simple risk assessment method has to be used. Its limitations are mentioned in the discussion section. Environmental impact and financial damage are not quantitatively assessed here but are qualitatively considered in the critical case descriptions section.

3.12.2. Conditions Influencing the Effects

The effects and conditions that directly affect human safety are assessed per fire situation.

Battery fires and explosions at the 'wearable' small-capacity area of the range of typical battery fire situations (see Table 6) happen quickly, are directly in contact with the body and make emergency medical service most needed rather than firefighting. Individual injuries and disfiguration stand out as the main potential effects. Lethal accidents are possible [94,108] but rare.

Battery fires in private homes can lead to injuries and significant financial loss. Battery-operated home appliances can set a house on fire. The number of residential battery fire incidents has been rapidly rising since 2020. A special situation is presented by solar power storage devices since these have a large energy content. Several measures, including a separate fire compartment, are now advised [116]. For battery fires in the central LEV and EV 'electric vehicles' area of the capacity range, both firefighting and emergency medical service are likely to be needed. For LEV incidents, injury and disfiguration of most likely a single person is possible, but also death, as a battery explosion and fire may happen during driving in traffic and a severe road accident may follow. LEVs do not have any crashworthiness requirement [87] which makes them susceptible to mechanical damage as an initiator of battery fire, e.g., after a collision.

The rescue of victims injured and/or trapped in close proximity of the fire in an EV is an additional risk factor [27]. Small numbers of people—either passengers in the burning car or passing by in, e.g., a carpark—may be exposed to toxic fumes, heat radiation or to a secondary explosion originating from the battery fire. Although EV fires may take some time to develop and people could have an opportunity of a few minutes to escape from entrapment, victims can also be unable to escape from a burning EV. Electrical functions may be interrupted, and deformation of the vehicle may keep doors and windows shut. When a large number of people are trapped inside, e.g., an E-bus, some may be injured and all others are probably trying to escape. Also, here the doors may not open. Escaping will take more time. Such time delay implies that the risk of death is higher due to people staying in an increasingly hazardous environment. People are exposed to dense and toxic smoke from burning interior materials. Leaving a bus is not possible when driving at high speed, e.g., in motorway traffic. Escaping from a fire onboard an airplane is not possible at all while traveling high in the air. They can only exit via slides after an emergency landing. Similarly, a fire in, e.g., a ferry or a cruise ship traveling on water will lead to a considerable time passing before people can exit into lifeboats.

For battery fires at the big-capacity 'storage' and 'power' end of the range, harm to people may not even occur since their presence would normally not be required inside the installation during normal operations. Thanks to electronic monitoring and sensing, workers would be aware of a fire before they approach a dangerous fire zone. Although harm to site-staff or firefighters is possible, it is likely that the number of victims on such sites will be small. Firefighters involved in mitigation of this industrial battery fire-type may face colossal challenges when attempting to rescue workers or reduce or avoid the battery fire propagation, spreading and domino effects. These attempts may lead to hazards during rescue operations and hazards during firefighting [15]. Emergency fire services may therefore have to settle for letting the fire burn out in a controlled way.

Financial damage, environmental pollution and long-term health effects of toxic fumes on site and in populated areas around the site would stand out in such industrial-size fires.

3.12.3. Likelihood of Harm to People

Although no statistical data is available on harm to people by battery fires over the range of applications and power storage capacities (see Table 4) the case descriptions found in both scientific and gray literature indicate that some situations (see Table 6) have higher frequencies than others. This indicates, e.g., that every day use by the general public implies a high probability. The probability in largely unmanned areas in cargo ships, storage facilities, Energy Supply System (ESS) containers and large-scale BESS is considered low. These notions are derived from expert opinion and literature findings.

3.12.4. Indicative Risk Assessment Approach

We have built a fully transparent indicative risk assessment model in Table 8 for the appraisal of possible harm to people exposed to battery fire and explosion scenarios. This model is both new and necessary because classic risk assessment methods cannot be used due to lack of statistical data.

Table 8. Battery fire indicative risk assessment for harm to people.

		Conditions Influencing the Effects Per Fire Situation																					
Number of People	**Harm Severity *)**	**Happens Quickly**	**Contact with Body**	**Driving in Traffic**	**Close Proximity**	**Toxic Fumes**	**Heat Radiation**	**Secondary Explosion Hazard**	**Dense and Toxic Smoke from Interior**	**Entrapment**	**Unable to Escape**	**Larger Number of People**	**Time Delay**	**High Speed**	**On Water**	**High in the Air**	**Hazards during Rescue Operations**	**Hazards During Firefighting**	**Potential Impact Low High**		**Likelihood of Occurrence Low High**		**Indicative Risk Level**
Person, wearable, handheld—Phone, vape																							
1	4	1	1		1														7			10	70
Private home (inside, outdoor)—Home appliances																							
1	4	1	1		1														7			10	70
LEV Light electric vehicles—E-bike, scooter																							
1	4	1		1	1									1					8			10	80
EV Electric car—Traffic, parking																							
5	4			1	1	1	1	1	1	1	1			1			1			30		10	300
E-buses—E-bus in traffic																							
50	4			1		1	1	1	1	1	1	1	1	1			1			211		10	2110
Tunnel (underground, traffic, train)—EV tunnel traffic																							
50	4			1		1	1	1		1	1	1	1	1			1	1		211		10	2110
Carpark (multi-storey, underground)—Multi storey bld.																							
5	4						1	1									1	1		24		10	240
Cargo ship (EV cars, batteries, fuel)—Cargo ship																							
10	4					1	1	1			1		1		1		1	1		48	1		48
Ferry (cars, trucks, chemicals, people)—Ferry fire																							
50	4					1	1	1		1	1	1	1		1		1	1		210		10	2100
Airplane (transport, passengers)—Airplane fire																							
50	4					1		1	1	1	1	1	1	1		1	1	1		211		10	2110
Battery storage (Storage unit)—Storage unit																							
2	3					1	1	1										1	10		1		10
Recycling site (battery waste)—Waste fire																							
2	3					1	1											1	9			10	90
Energy supply (ESS Container unit)—ESS container																							
2	3					1	1	1										1	10		1		10
Large scale BESS—BESS site																							
5	3					1	1	1										1	19		1		19

*) Harm severity: 1 = small, 2 = injury, 3 = disability, 4 = death.

<u>Range of battery fire cases</u>

For a range of typical battery fire case situations, ranked in increasing battery size order in the left-hand column, we gather risk factors and then calculate an indicative numerical value for the case risk. These typical case situations are derived from the literature. Together, they cover the full range of battery applications in Table 4.

<u>Risk formula</u>

The model requires a *Likelihood of occurrence* of a battery fire and explosion and a *Potential impact* if it happens. The *Indicative risk levels* are then calculated with the following formula:

$$\text{Indicative risk level} = \text{Likelihood of occurrence} \times \text{Potential impact}$$

<u>Likelihood of occurrence</u>

The *likelihood of occurrence* is set on 1 for low probability (technical situation) and on 10 for high probability (human action situation). It is generally accepted that human action is notoriously less reliable than technical action.

Conditions influencing the effects

- A condition is either allowing, causing or increasing the effects (value set on 1) or has no bearing on it (value set on 0).
- Multiple conditions are included by adding the values for all individual influencing conditions per case situation to calculate the *sum* (*influencing conditions*).
- The *number of people* in a single-case situation is proportional to the magnitude of effect. The estimated number of people in each fire situation is derived from the literature.
- The *harm severity* for an individual is modeled by a number (1 = small injury, 2 = injury, 3 = disabled, 4 = death) in line with maximum harm observed in the literature.

Potential impact

A simple formula is then used to calculate *potential impact*:

$$\text{Potential impact} = \text{number of people} \times \text{harm severity} + \text{sum (influencing conditions)}$$

For visualization purposes, we use the criterion for 'Low' and 'High' *potential impact*. If the calculated case value is more than 10 times less than the highest potential impact level found for all battery fire case situations, then it is 'Low'. In all other cases, it is 'High'.

Results found

Looking at *harm to people*, this indicative and qualitative risk assessment points at E-bus, tunnel, ferry and airplane settings as a group of highest-risk situations. Here, a group of people are inside a larger vehicle together with a battery on fire. Quickly escaping is not possible because of speed, water or altitude. A further group of situations with major risk is found in EV-related traffic and carpark settings. Here, several people are situated in an EV car with its battery on fire and possibly having other damage. Escaping from the vehicle may take considerable time, adding to the danger. In a carpark situation, fire propagation can make financial and environmental impacts large as well.

Moderate risks are indicated for the low-capacity end of the battery application range. Here, the individual in a setting of direct contact to or in close proximity of a battery which suddenly explodes and catches fire is the key situation. This happens so fast that escaping is not feasible and medical emergency and firefighting services will come too late to make a difference.

Minor risk for people is indicated in industrial settings at the high-capacity end of the battery application range. In EV cargo ships, battery storage facilities and battery power plants, a large quantity of batteries is concentrated. In case of a possibly large fire, financial and environmental impacts are to be considered.

3.13. Critical Case Descriptions

The above indicative risk assessment makes it possible to derive a set of *critical case descriptions*, backed up by both the findings and the analysis. This set of cases indicates which battery incident scenarios require urgent attention of safety management. The cases are concerning personal injury risk, environmental impact and financial impact.

3.13.1. Highest Personal Injury Risk Case

The indicative risk assessment shown in Table 8 leads to three candidate cases here:

1—Wearable/hand-held appliance battery explosion and fire

The number of batteries in a private household is roughly estimated to be up to 100, spread over various sizes. Hearing aid, smartphone and vape battery explosion and fire incidents stand out in the (mostly 'gray') literature information in the wearable application group [94]. An explosion very close to the human body is known to cause severe injury or death [61,62,104,105,108–110,147].

2—E-bus accident

The high indicative risk suggests that getting involved in an E-bus accident as a passenger can be a major threat to individual safety. If the high-power battery in the bus catches fire, either after sudden failure while driving or after mechanical damage by a collision, it is likely that electrical functions are interrupted. If the bus is no longer under control, a disaster scenario may unfold. Not only the entrapment, delay, injury and chaos conditions caused by the battery fire and/or collision in this setting but also the exacerbated exposure to toxic fumes from combustible materials in bus interiors play an important role here [23,127,128,194,195].

3—Domestic fire

The increasing numbers of a wide range of battery-powered domestic appliances bring new and more causes of fires in private homes. Currently, systematic statistical information gathering on small appliances and on home battery power supply systems causing domestic fires is not being conducted. However, this is necessary, as suggested by the recent recommendation to install a home battery power supply in a separate fireproof enclosure [116].

3.13.2. Highest Environmental Impact Case

Battery fires leading to the largest environmental impact must be those in settings with a large quantity of batteries: transport ships, recycling plants, battery storage facilities and battery electric power plants. Four types of accidents could qualify for the highest environmental impact case [196–198]. The contribution to air, water and soil pollution of each situation is not easily quantifiable. Therefore, the combined energy storage capacity per situation is used as a proxy. Lithium batteries have a stored energy density of about 250 Wh/kg (see Table 3). This property is of practical use in a comparison to the dangerous substance quantity between different situations (and must not be confused with the heat of combustion per kilogram).

1—Battery storage fire

The maximum quantity of Lithium-containing batteries allowed in a fire compartment in the Netherlands currently is 3000 tonnes. In the largest single-battery storage compartment, currently limited to 2500 m^2 in size, the total energy stored in the batteries would add up to 750,000 kWh [83]. Very few people are present in such storage facilities. Their personal safety risks are not determined.

2—EV transport ship fire

In a car transport ship, like the *Fremantle Highway* [143], *the Felicity Age* [199] or the *Hoegh Xiamen* [141,200] some 4000 cars can be transported. If each of these has a battery of approximately 60 kWh, this would add up to a total of 240,000 kWh. The ship's crew faces a serious personal safety predicament as soon as an onboard battery fire starts. Limited experience thus far shows that poor accessibility and little time to stop fire spreading in a densely packed cargo vessel complicate effective firefighting [14,93,140,141,143,201].

3—BESS fire

The largest quantity of batteries in a single system is found in a BESS plant. At the largest BESS at Moss Landing near Los Angeles, a total of 1,600,000 kWh capacity is installed [202]. It would seem realistic to assume that not the entire plant will be consumed by a fire. Separation between modules in fire compartments could maximize the burning quantity of batteries to less than, e.g., 100,000 kWh per fire compartment. This would bring the fire spreading potential back to a manageable level. Although few cases with injuries of firefighters involved in a BESS fire are reported [96,155,173,203,204], their personal safety risk is a serious concern.

4—Waste handling recycling plant fire

Although hundreds of Lithium-ion battery-ignited waste fires happen each year, the total burning battery weight causing toxic fumes is a fraction of the burnt material [149,151]. For example, a waste pile containing 10,000 smartphones burnt each day of the year would add up to a burnt battery capacity of 40,000 kWh per year. Although this rough estimate suggests that the magnitude of battery waste fires is likely smaller than the above three categories, this needs to be further investigated since internationally, only little quantitative data on such small battery-type waste fires is available [151,152,198]. Also 'zombie battery'-initiated waste fires occur prior to arrival on a waste-handling site, when sitting inside waste-handling trucks. This exposes both the driver and the general public to an undetermined safety risk [150].

3.13.3. Highest Financial Impact Case

Cars, including EV cars, can catch on fire for many reasons. The causes of carpark fires are often not known, however [205].

Bigger carparks and bigger cars, containing more combustible plastics in their construction, also increase fire propagation in settings with many cars close together, which makes early detection and short response time important for mitigation [25,205]. Many potential causes for car fires are being mentioned, e.g., poor quality of EV charging equipment and cables, collision, arson, fireworks and lightning [205].

A multi-storey carpark fire in Cork, 2019, led to severe damage of the building. It could not be saved, and its replacement cost was 30 million Euros. The number of cars involved in a carpark fire increases over time. The fire spreading rate is dependent on the layout of a carpark building and how close cars are to each other. This carpark fire led to 1200 lost cars [25]. For an average of replacement cost of 10,000 Euros per car, this would add a further 12 million Euros to the financial damage. Temperatures as high as 1000 degrees Celsius were observed in this fire, resulting in steel beams buckling and loss of the entire building. An important observation in a Liverpool, 2017, carpark fire was that the elapsed time between the first sign of a fire—smoke recorded by a security camera—and the start of firefighting was 27 min [25].

Multi-storey carpark buildings can start to show floor and ceiling holes when local concrete temperatures exceed 375 °C. The fire can spread through such openings. Structural collapse of the building is possible for temperatures over 540 °C because the concrete material strength is then reduced by some 50% [194]. In a carpark fire in Stavanger, 2020, it was observed that the fire took 35 min to spread vertically to the next higher floor level after it started. Building collapse was observed after 2 h [25]. Structural collapse is unlikely if the fire cannot spread to more than four EV cars [2].

The rate of fire spreading is an important factor for mitigation. It may take up to 10 min before a first burning car sets a second car on fire [194]. Studies in the USA show that fire spreading between cars in a carpark may occur within 5 min. Once several cars are on fire, the spreading rate increases rapidly, however. This underlines the need for fast intervention by firefighters [15]. Carpark fire cases show a trend toward more cars being set on fire before firefighters can stop fire spreading, in some cases leading to over a thousand cars lost in the fire. A horizontal fire spreading rate increasing to about one more car set on fire per 30 s was observed in Liverpool in 2017. Testing suggests that fire spreading takes place via heat radiation and hot fumes convection and gets hold first on soft rubber window trim. The failure of fuel tanks with petrol, diesel, LPG or H_2 may cause jet flames or pool fires which speed up fire spreading considerably [25].

In current carpark settings, a fire would include a mix of ICEV, hybrid and EV cars. An EV car with a battery on fire would need a firefighting strategy that differs from that for ICEV cars. Immediately cooling the burning EV car battery with water, screening off the other cars from the fire and moving the burning EV car to a safe place is currently seen as the most desirable course of action [205]. An EV car with damage or with an otherwise suspect battery, e.g., malfunction indicated via its BMS, would require the same action [77].

There are major obstacles to overcome before this course of action can be realized in existing carparks, however. Cooling requires a large quantity of water and an entry port to inject cooling water in the EV battery. Used cooling water needs to be collected via ducts in a special basin since it may contain toxic chemicals [15,27]. Screening off other cars, either in a static situation or during removal of a burning car, requires equipment. Water mist and sprinkler systems may reduce fire spread rate [15]. Also, a safe place must be available for burning out and/or prolonged cooling [77]. Today, however, neither current 'safe-zone', 'high strength cabin' and 'impact absorbing body' EV car designs [2,87] nor existing carpark buildings and fire mitigation installations provide all that are necessary.

3.14. State of Affairs in Battery Safety Management

3.14.1. Lacking Statistical Data

Ideally, statistical records and regular reporting by public institutions about battery fires would be a valuable source of information. Currently, this is not available, however. Statistical information is not gathered over the whole battery application range. At present, the main focus is on EV car battery fires. A few special application areas are prioritized: battery transport and storage, large power plants, aviation and waste handling. Recently, LEV accidents have also caught the attention of researchers and governmental institutions. Only a few other applications have been subject of scientific study. Other very small or big battery capacity application incidents only reach the news headlines as a rare incident or they are investigated, e.g., as medical case studies. Generally applicable statistical information is presented below per application.

3.14.2. Risk Research and Incident Reporting by Application

Internationally, specific battery application fire and explosion data are being gathered about the following:

- *Aviation* [32,33,64,102,144–148,206–208].
- *LEV accidents* [87,117–119,209].
- *Small battery applications* [61,68,103,107–111,210–213].
- *Children's toys* [112–115,214–217].
- *Large battery applications, BESS, transport and storage* [82,83,155,158,159,202,218–224].
- *Battery waste handling and recycling* [149–151,157,198,225,226].
- *EV battery fires:* Sun et al., 2020 [2] compare EV, hybrid and ICEV battery fire risks. They test and analyze the release of toxic gas, fire, jet flames and explosion, analyze peak heat release rates and discuss mitigation challenges such as cooling and re-ignition. Based on analysis of 16 selected EV battery fires reported worldwide in 2018, the Lithium battery runaway and re-ignition behavior make EV fires different from and more difficult to extinguish than ICEV fires. EV battery fires caused by abuse are linked to hot environment, overcharging or external short circuit in the EV electric system. EV battery self-ignition incidents are linked to poor manufacturing, poor design and inadequate BMS functionality. Explosions, release of black smoke, hot sparks, jet flames, combustible and toxic gases, hydrogen (H_2), methane (CH_4), carbon

monoxide (CO) and hydrogen fluoride (HF) are a safety threat to people involved. Peak HRR of up to 10 Mw within 10 min from the start of the fire was observed in full-scale tests on different EV cars.

3.14.3. Statistical Information Gathering by Country

In the USA, long-term trending from 1980 to 2020 shows that the number of road vehicle crashes remains more or less constant around 7 million per year while road vehicle fires reduced by some 60% from 0.45 million to some 0.18 million per year. A similar trend is observed in Sweden and the UK [25]. Battery fires were identified and acknowledged as a new risk for firefighters a decade ago [204]. Victor Chombo et al., 2021 [87], underline the safety risks of both passengers and rescue teams after an EV car crash and point out that high speed and fast acceleration crashes are often fatal due to immediate explosion and fire. The use of batteries in classic car construction designs is not accommodating the release of electrical energy stored in the battery of an EV after an EV car crash. Battery casings still allow deformation for observed crash speeds; an additional crush zone may reduce the importance of crash-related mechanical damage as a battery fire-initiating factor.

Liu Xu et al., 2023 [173] investigated how well some 1000 emergency first responders are trained and prepared to handle EV accidents and battery fires in traffic. They flag up 'Electric shock', coming from 400- or 800-Volt car power systems, which can seriously injure or kill a person touching a damaged car. The other dangers from explosion, fire, heat, multiple re-ignition and fumes also require responders' risk awareness. The survey showed that some 40% did not receive training specifically addressing EV risks. The importance of such training is emphasized by the expected 2/3rd share of EVs on the road in the USA by the year 2050. Aalund et al., 2021 [227], flag the problem of DIY activities with car batteries and warn for battery and BMS interchangeability problems on the replacement market.

In Finland, some 44 EV or hybrid vehicle fire incidents were found over the period 2015–2023. This includes four bus fires. EV fire incident rates of approximately 0.9 per 10,000 vehicles per year were derived for 2023. The cause of the fire was technical failure in some 2/3rd of all 44 cases. Cooling water quantities were recorded of up to 4.1 m^3 per case, increasing to some 10 m^3 for prolonged cooling [26].

In Norway, the share of EV and hybrid cars in car fires increased to 27% in 2022 [25]. A study on EV crashes in Norway in the period 2011–2018 resulted in 342 EV crashes which were found to be about equal in severity of harm to people, when compared to 35,441 ICEV crashes during the same period. A significant difference was found for EV cars hitting pedestrians and cyclists more often than ICEV cars due to their lower noise level. Higher vulnerability for motorcyclists and impact on emergency first responders' victim rescue efforts for EV accidents are flagged as an important issue [124,173].

In Sweden, research shows that in 2023 some 23 EV fires happened in a fleet of 610,716 EV cars on the road. Some three E-bus fires in a fleet of 1062 E-buses on the road were recorded. Fire cause was not related to the battery in two of the three cases. The third case was caused by mechanical damage to the battery during maintenance work [15].

Research shows that the peak HRR of an EV car can be as high as 3–10 mega Watt and the Total Heat Release (THR) of a burning EV battery is in the order of 0.8 giga Joule per 50 kWh battery capacity [15]. An E-bus can have some 5 to 10 times higher release rates than an EV car.

In Germany, bus fires are not uniformly recorded for statistical evaluation although a history of some 200 bus fires were identified via internet search of which 68 took place in the engine compartment. No battery fire was mentioned. In several cases, fire progressed to the interior within minutes, showing that materials used there—supposedly satisfying the requirements of the UN-R-118 (2012) [228] standard applicable to bus fire safety—constitute an additional hazard [23]. The problem is for a part also caused by flame retardants and dense smoke [195].

In China, risk analysis of EV traffic accidents resulted in several recommended actions on how to go about high-voltage circuits, toxic fumes and heat release of an EV car fire. A temperature rise to 1200 °C within 210 s after the first spark was reported for a Lithium battery catching fire. Experiments showed that jet flames coming from such battery fires can reach a length of some 5 m, easily igniting combustible material, gases and fumes in its vicinity. Rescuers should wear appropriate personal protection and cut off the power as a first priority. Water is preferred over most other coolants since fire retardants and CO_2 are found to have less re-ignition suppression capability. Large quantities of water are required for cooling and suppression of re-ignition. Toxic substances, e.g., electrolyte liquid, organic chemicals and HF and CO gases are released into the cooling water, air and surrounding environment. The associated hazards can affect both rescuers and trapped passengers; water spray to screen-off the heat is recommended. White smoke which suddenly appears can announce a secondary explosion [27,173].

Tohir et al., 2023 [55] compare results from Denmark, Korea, The Netherlands, Norway, Sweden and Finland and calculate an indicative overall weighted average EV fire rate of 2.44×10^{-4} per registered EV per year for all causes. Among these initiating causes, 'unknown' (42%) and 'vehicle faults' (29%) are the most frequently reported. For EV battery fires there are insufficient data to establish robust likelihoods of occurrence for battery fire or its causality.

In The Netherlands, Hessels, 2023 [28], compiled EV and LEV data over 2021. Some 243 alternative fuel vehicle incidents (94% were EVs) were analyzed, showing that 25% of the EV accidents is associated with a fire and that some 2.5% of all EV accidents concerns a multi-passenger coach, bus or minivan. The fires concern batteries in approximately half of these cases, most of them started from a thermal runaway, initiated by a range of different causes, an important cause being that the battery is damaged by the accident. Over 2022 some 135 fires in 515,838 EVs; 31 fires in 1505 LEVs and 3 fires in 13,835 E-buses were reported. In over 50% of the EV fire cases, the cause is reported to be 'unknown' [15].

4. Discussion

4.1. The Six Phases of Safety Management

In this study, critical reflection [49] is used as a way to evaluate the findings and their robustness in support of assessing the situation for each of the six phases of risk management [34,47,48]. These six phases describe dealing with risks in a sequential way. Looking at battery fire and explosion hazard as a single case of risk control, the six phases of risk management provide a suitable reference frame:

7. *Awareness*—discover and become aware of hazards;
8. *Acknowledge*—acknowledge the presence of the hazards;
9. *Comprehension*—learn about the hazards and understand their nature;
10. *Risk magnitude*—determine credible adverse effects, likelihood of occurrence and assess risks;
11. *Countermeasures*—choose and implement appropriate countermeasures;
12. *Learning from incidents*—learn from incidents via records, reports, investigations and improve.

4.2. Main Findings

The findings in this study from the literature, expert opinion and analysis by the authors show that not all of the six phases have reached a satisfactory state of completeness, as seen in Table 9. This leads to several key observations, constituting an answer to the research question.

- Scientific research progress currently addresses the stage awareness, acknowledgement and comprehension. The general public is slowly being increasingly more confronted with a variety of new battery fire and explosion incidents. New battery types allow new fast and fashionable application types and generate booming business while the associated risks have yet to be discovered.
- Not covered is the stage risk magnitude. As a new type of accident, 'battery fire and explosion' is not separately mentioned and therefore not visible in accident statistics. This means that no probability can be allocated and hence—for the time being—it is not clear whether battery fire and explosion is an acceptable risk in specific application areas or a risk that needs to be further investigated.
- The stage countermeasures is being studied while new ideas are being generated and tested. In the meantime, it is clear that EV firefighting currently receives most of the attention. EV design needs to evolve toward facilitated fire mitigation access and toward new techniques, e.g., to quickly separate the EV passengers from the battery fire. Fire compartments are needed in more applications.

Table 9. State of affairs on battery fire and explosion per safety management phase.

Phase	Literature	Expert Opinion	Analysis
1—Awareness	The literature on hazards is available.	Transport, storage, BESS and recycling have serious problems. Large incidents in BESS, carparks and shipping.	Battery explosion is not being considered as a risk by the general public.
2—Acknowledgement	The literature on safe battery design is available.	Storage and BESS are regulated.	User instructions impose unrealistic requirements on users. Users ignore instructions.
3—Comprehension	The literature on battery fire causality is available.	Safe storage is still in the design stage. Close to zero EV fires in traffic.	Users of wearables and (light) EV are not aware of battery hazards.
4—Risk magnitude	No risk level estimates are readily available. No battery incident statistics are available.	Expectation is that in 10 years Li-batteries will be phased out. Trusting that safer batteries will be developed soon.	No risk level estimate could be made from existing data.
5—Countermeasures	Battery Design and Production are key factors. Other ways of prevention are scarce. No intrinsic safety in Li-battery designs. No standard requirements for BMS performance.	Limitations to power banks onboard aircraft. EV not allowed in existing carparks. No measures in shipping. No measures in wearable applications. Very few e-vehicle design measures. Still setting up monitoring in other areas.	Battery fire is hard to extinguish. New and sophisticated equipment is needed. Firefighting equipment development and testing are ongoing. Huge investment costs for buildings expected.
6—Learning from incidents	Few incident reports and superficial gray sources constitute the available info. The literature on what can go wrong and on test results is available.	Firefighting is the primary response.	Little learning from incidents. EV car design is not accommodating the need for fast cooling in case of battery fire.

Learning about risks from battery fire incidents is, at this time, only possible from a limited number of indicative case descriptions and not from systematic accident investigation, reporting and statistics.

4.3. Research Limitations

Using the large volume of literature originating from both scientific and societal sources and expert interviews ensures consistency and robustness of the findings. However, there are several limitations to consider.

- The first is about the way we gathered the literature.

We used English language as an admission criterion for internationally accessible scientific and 'gray' sources. We did make a few exceptions for relevant sources from Dutch firefighting practice and research points of view. Reports about local data on battery safety and battery-related incidents in 'gray' literature in many countries are often available in the local language only, may be not reported on the internet or may be not reported at all. We explicitly gathered the literature from a range of non-English-speaking countries and analyzed this in a separate section, Section 3.14.3. This minimizes lack of information and supports representativeness. We used well-known, credible and verifiable sources for admission as 'gray' literature.

- The second is about the simple risk assessment method used.

Since systematic battery accident investigation, battery incident recording and statistical reporting on a national and international level are non-existent or in their infancy at best, a simple and practical risk assessment method had to be used. Though still incomplete and inaccurate, this allows making an indicative risk assessment. This points out where the focus for further safety research needs to be.

- The third is about the sample size for in-depth interviews.

The four respondents chosen, although small in number, are representative for the different perspectives, the knowledge and practical experience on the subject of battery fire and explosion about both prevention and repression. Out to find concerns and issues, we reached saturation quickly; we consider it unlikely that interview data gathering from other stakeholder groups would have a significant impact on the outcome of this study.

- The fourth is about reliability and validity.

Possibilities to achieve a representative overview of the state of affairs in an emerging field are limited. By using triangulation with scientific literature, 'gray' sources and expert interviews we obtained indicative, yet valid and reliable results.

4.4. Future Research Directions

In this emerging field of battery fire and explosion safety, we recommend proceeding with the following:

- Policy and risk management perspective

Looking at the six phases of risk management, the first priority must now be to record battery fire and explosion incidents over the full range of battery applications. In due course, this will support a traditional quantitative assessment of safety risks associated with battery types and applications. Then it will become clear to policymakers whether the current safety focus on large industrial and automotive battery use and neglecting the high indicative '*harm to people*' risk applications we identified in this study, and the range of smaller domestic and wearable battery applications, are still justifiable.

- Set up records to support evidence-based improvement

Decision-making on preventive and repressive countermeasures can then become evidence-based rather than precaution-based. The immediacy of increasing numbers of fire and explosion incidents on the one hand, and the colossal economic pressure on the other, necessitate the creation of a reliable and independent system for statistical battery fire and explosion incidents recording and reporting in many countries.

- Future research involving more international experts is recommended

This widens the scope for risk assessment beyond the current indicative model, limited selection of experts and the few countries performing research as mentioned in this study. Over time, statistical evaluation may gradually refine the indicative risk assessment presented in this study. Over time, comparisons between battery technology performances, materials required, manufacturing processes, waste handling, suitability for a variety of applications and the environmental impact can be involved in an overall assessment.

- Safer battery and BMS technologies

Battery technology is under development towards safer designs and safer production. Meanwhile the achievements demonstrate significant differences in fire- and explosion-related battery and BMS characteristics. For their applications, a similar observation is made: some applications do not have a safe and reliable battery, or a suitable BMS or the design allows uncontrolled battery and BMS combinations. Battery and BMS need to be coupled in a safe way, adequate instructions for use are to be provided. Early 'runaway' warning and battery aging need to be included in BMS functionality.

- Implement early warning techniques

Either instrumentation on or in batteries or more distant observation by, e.g., cameras or smoke and heat detectors currently support early warning systems. Different directions are being explored in industry. Battery sensors may be based on monitoring the status of a single cell, a cell pack or bigger quantities of batteries in various applications. Many possibilities exist to do this, both by battery instrumentation and observation and via the BMS. The possibilities of artificial intelligence in early risk warning and prevention and control need to be further explored as sensor arrays become larger and battery applications become more versatile.

- Develop fast or automated response techniques

An early detection of battery runaway or overheating allows a quick response, thus potentially enabling the minimization of the damage caused by the anticipated fire and explosion. This can be the response of emergency services, user response or the fastest automated response. In large applications, the latter may require the equivalents of process technology plant safety provisions, e.g., 'sprinkler', 'safe location', 'emergency shut down' and 'alarm'. These concepts are valuable in smaller battery applications also. A few examples are as follows: a fireproof bin aboard an airplane or an alarm and safety switch-off in an electric vehicle. Moving a hot battery towards a safe location could be performed by jettisoning or a robot. In carparks, a transport device can move a hot vehicle outside or drop it in a cooling basin.

5. Conclusions

Batteries of various construction type and size, in a wide range of applications, generate an increasing number of safety incidents. Reports from practice show that their hazard fire, explosion and toxic fumes constitute a new emerging safety threat.

These incidents cause harm to people, damage to the environment and lead to considerable financial losses.

In spite of this, battery safety management is lagging behind on risk assessment. This leads to indecision about appropriate countermeasures, both in prevention and mitigation. Battery fires are notoriously hard to extinguish due to re-ignition and poor accessibility.

Firefighting struggles to adequately respond to battery fires occurring in a wide range of application areas and requires new strategies and techniques. At the same time the development of safer battery and BMS technology and production methods is ongoing, opening both new design solutions and safety hazards.

A major obstacle is the lack of incident investigation, records and statistics, making evaluation of the likelihood over the entire range of applications near to impossible.

The indicative 'harm to people'-oriented risk assessment in this study initiates a risk-based perspective, leading to new ways to move forward by industry, researchers and policymakers. Further work is recommended on adopting battery safety policy, setting up records in support of evidence-based improvement and further developing safe battery and BMS technologies including early warning and fast or automated runaway response techniques.

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