A Review of Safety Measures in Battery Electric Buses

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Review

A Review of Safety Measures in Battery Electric Buses

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Abstract: Battery electric buses (BEBs) are widely regarded as a safe and sustainable alternative to internal combustion vehicles. However, the lithium-ion batteries that power them present safety risks. This paper provides a comprehensive overview of the safety of battery electric buses, highlighting current challenges, relevant regulations and proposed solutions to enhance safety. There are significant shortcomings in the fire safety regulations for buses, especially concerning qualification methods for bus interiors. Enclosed spaces and structures represent the most critical risks for these transport systems. The presence of large vehicles, such as BEBs, in tunnels could increase the risk of transitioning from deflagration to detonation. Fires involving such vehicles produce more soot than fires from internal combustion engine buses (ICEBs) and have slightly higher toxicity levels. High-pressure water spraying systems are not yet an effective solution, as not all the heat is removed if the thermal runaway has already been triggered for several minutes, and their action remains largely limited to the outside of the battery pack. Another critical issue is cybersecurity. Managing and protecting BEBs from cyber threats is complex and requires robust strategies.

Keywords: NEC; BEV; BEB; Battery electric vehicles; safety; fire; thermal runaway

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1. Introduction

With the rise in electric technology in the automotive industry and the increasing focus on environmental sustainability, electric buses are becoming more common on our roads [1]. Transport is a major contributor to greenhouse gas (GHG) emissions, accounting for about a quarter of global anthropogenic pollution [2]. Cars are responsible for 60.4% of total CO_2 emissions from road transport, while heavy trucks and buses are the second-largest source, contributing 26.4% [3]. Therefore, the decarbonization of road transport is essential to meet future CO_2 emission targets. According to a report by the insurance company AutoinsuranceEZ, electric cars have a probability of ignition of 0.03%, compared to 1.5% for ICVs [4]. Studies show that between 0.5% and 1% of all registered bus accidents are caused by battery malfunction each year [5]. Incident experiences show that the primary cause of fires in BEBs is battery malfunction, which leads to thermal runaway. Depending on the data set used (from different countries), the fire rate of these vehicles was calculated in a range from $4.96 \times 10^{-0.5}$ to $6.52 \times 10^{-0.4}$ [6]. However, risk analysis tools usually use the rate of fires per km traveled instead of fires/vehicles registered. These data suggest that although electric vehicle fires may occur, the frequency is relatively low, mainly due to their different distribution in the road network compared to conventional vehicles. Vehicle electrification is an attractive alternative to fossil fuel dependency, offering the opportunity for a more sustainable future without requiring immediate changes in human behavior [7]. However, a clean energy mix is needed to effectively reduce emissions. Although public transport produces significantly less greenhouse gas emissions per passenger than private vehicles, it is still a significant source of pollution [8,9]. Battery electric buses (BEBs) are particularly well-suited for urban traffic, especially considering anticipated advancements in battery technology and the growing shift towards renewable energy sources [10]. The literature highlights several advantages of adopting BEBs, particularly their higher efficiency compared to internal combustion vehicles (ICVs). These benefits include reduced oil dependency, decreased local air pollution, and minimized vibration and noise [11,12]. Furthermore, electric motors are preferred over both ICVs and fuel cell electric vehicles (FCEVs) due to their substantially higher energy conversion efficiency, which ranges from 80% to 95% [13,14]. A comprehensive analysis of FCEVs was carried out by Pramuanjaroenkij et al. [15]. Safety aspects were also considered, with three main issues assessed: safety in hydrogen usage (flammability, etc.), safety in refueling, including hydrogen storage systems, and quantitative risk assessment [16]. Luo et al. reported that the operating cost of FC buses is about 30-40% lower than that of conventional buses. However, market penetration faces several challenges, including the high cost of FC stack production and maintenance, insufficient hydrogen supply facilities, insufficient reliability, slow cold start, safety issues, and immaturity of pack technology [16–18]. In 2020, there were nearly 600,000 electric buses globally, representing 16% of the total fleet [19]. The Netherlands ranks first in Europe in electric bus adoption. Starting in 2025, only battery-electric or fuel-cell hybrid-electric buses will be preferred for all new public transport purchases to achieve zero greenhouse gas emissions. In line with carbon neutrality targets, Austria aims to reach this in 2040 [20], while Cape Verde has set 2035 as its target year for transitioning to 100% zero emissions. In South America, Chile, like Colombia, has stated that beginning in 2021, it would transition to a 100% electric or zero-emission approach for new bus purchases, aiming for full implementation by 2035. The US state of California has announced that the transition to zero-emission public transport buses will be phased in, with full implementation by 2029. In the European Union, the share of zero-emission buses increased from 4% in 2019 to approximately 6% in 2020. In line with the zero-emission approach, EU member states set minimum targets for public transport bus purchases in 2019. These targets range from 24% to 45% in 2025 and from 33% to 65% in 2030 [21]. Since 2010, 27 high-voltage battery fires have been recorded globally in a fleet of over 250,000 electric buses [22]. Two fires occurred within a month involving Bluebus electric buses operated by RATP. The French public agency concluded that the fires were likely caused by an internal short circuit triggered by thermal runaway in the high-voltage batteries. This issue was traced to a manufacturing defect, leading to a recall of the affected batteries [23]. Thermal runaway in electric vehicles (EVs) is a critical safety concern, particularly as battery sizes increase with advancements in electric mobility. Recent studies highlight that thermal runaway is primarily caused by internal factors, such as battery overcharging or system malfunctions, although external conditions like fires or accidents can also trigger it. A key finding from recent research by Sturm et al. [24] suggests that the heat release rate (HRR) in battery electric vehicles (BEVs) can be slightly higher than in conventional internal combustion engine vehicles (ICEVs), especially in models equipped with large batteries (up to 80 kWh). This reaction is triggered by the decomposition of the solid electrolyte interphase (SEI) film in the battery, which primarily occurs during overcharging. Once this protective layer breaks down, the battery's anode is exposed, setting off a chain reaction of heat generation that accelerates thermal runaway. Yao et al. [25] present a comprehensive study using a Fire Dynamics Simulator to analyze the effects of various ventilation conditions on electric bus fires. Caliendo et al. [26] use numerical modeling to examine temperature variations and CO concentration in electric bus fires under different ventilation scenarios. Their findings indicate that optimal ventilation, such as fully opened windows and controlled wind speeds, reduce fire risk and enhance firefighting and evacuation strategies [26]. Currently, the large-scale adoption of BEBs faces several challenges, including battery costs, effective charging strategies, charging stations interoperability, and the impact of e-bus integration on the power grid [27]. Despite the promises of sustainability and efficiency, safety concerns surrounding these innovations are also emerging. Moreover, as high-capacity lithium-ion batteries become more prevalent in road vehicles, safety risks are likely to escalate over time [28]. Therefore, the transition to electric buses raises crucial safety issues, including battery safety, fire risk management, charging infrastructure and more. This paper highlights the rising adoption of battery electric buses (BEBs) and the associated safety challenges, particularly fire risks linked to battery malfunctions and thermal runaway. While existing literature emphasizes environmental benefits and efficiency, this study focuses on the evolving safety concerns as BEB battery sizes increase. It is crucial to underline the absence of a strong experimental campaign to validate the proposed models [28].

2. Safety Tests

Safety tests for electric buses are essential to ensure the safety of passengers, drivers, and the public. Ruiz et al. [29] and Tidblad [30] conducted a comprehensive review of the various standards required for electric vehicle safety testing. In addition, they summarized lithium-ion battery safety tests in automotive applications under various stress conditions.

Electric vehicle safety tests include the following:

- crash tests: frontal collision, side collision, and rear collision tests
- fire tests
- vibration tests
- safety tests for REESS (rechargeable energy storage systems) and battery packs
- rollover tests

In general, safety testing is governed by ISO, IEC, SAE, and especially UN/ECE standards. Many of these standards are undergoing revision or are nearing the release of new editions due to the rapid technological advancements in automotive propulsion batteries in recent years [30]. Additional safety testing standards include the Federal Motor Vehicle Safety Standards (FMVSS). Primarily used in the United States, these standards are issued by the National Highway Traffic Safety Administration (NHTSA), a division of the US Department of Transportation.

2.1. Safety Tests for REESS and Battery Pack

The design of the vehicle's battery must be carefully analyzed considering all potential stress factors that impact safety. One of the first comprehensive manuals covering stress tests for BEV and HEV applications was published by Doughty and Crafts for the FreedomCAR program [31]. This manual was revised and published in 2022 [32]. The initial tests of an EESS (energy storage system) project should be conducted at the lowest assembly level (unit, module, or package), as shown in Figure 1, where the most relevant data can be collected [33]. Subsequently, test results obtained at a lower level (e.g., unit level) can be correlated with the overall response of the entire REESS (i.e., at a higher level). The result can be analyzed using the Fault Tree Analysis (FTA) [34,35], or Failure Mode and Effects Analysis (FMEA) [2,6].

Figure 1. The three main assembly levels of the battery pack (cell, module, pack) of an electric bus [36].

In most cases, the recommended assembly level depends on the EESS technology, design, and specific test profile, with the required minimum assembly level specified in each test profile [31]. Abuse tests for REES can be listed as follows:

- Mechanical stress: crash tests, impact tests, drop tests, nail penetration tests, and others [37].
- Thermal stress: high-temperature hazard battery test, thermal stability test, thermal shock cycling, and others [33].
- Electrical stresses: overcharge, over discharge, external short-circuit, forced discharge, and others [38].

The standard tests required for an electric bus battery pack depend on the specific regulations and standards of the country where the bus will be used [39]. However, the safety of a BEB's battery follows the United Nations Economic Commission for Europe (UN/ECE) Regulation No. 100. The response of the REESS can be classified according to the eight hazard levels established by the European Council for Automotive Research and Development EUCAR [40]. Hence, manufacturers may find useful information when evaluating the response to a certain stress of the EESS [31], see Tables 1 and 2.

Table 1. Activities related to REESS of electric buses.

Reference	Researcher/Research Organization	Publication Date	Investigation Method	Summary
[41]	Spirka, Kepkaa	2015	Finite element analysis	A simulation was conducted to evaluate a REESS as part of the development of an electric ŠKODA bus. The impact of load dynamics was assessed by comparing calculation results based on UN/ECE 100.2 [41].
[42]	Kunakron-ong, Ruangjirakit, Jongpradist	2017	Finite element analysis	Mechanical analysis, modal constraint analysis, and frequency response analysis were conducted using finite element model simulations and vibration testing under various conditions for the battery compartment. This research serves as a foundation and reference for the structural design of the battery compartment in the REESS quick-change electric bus, aiming to enhance the safety and reliability of BEBs [42].
[43]	Spirk, Kepka	2016	Finite element analysis	The study simulates the behavior of the front REESS during impact involving a battery electric bus. The effects of dynamic impact on the load are analyzed, taking into account the material behavior at higher strain rates [43].

Table 2. Fire experiments related to BEB batteries.

Reference	Researcher/Research Organization	Publication Date	Investigation Method	Summary
[44]	Yu, Li, Zhang, Dong, Han, Xian	2019	Experiments	A fire test model for the lithium-ion battery of an electric bus was developed. A test was conducted to extinguish a lithium-ion battery using a perfluorohexanone-based extinguishing agent, verifying its effectiveness [44].
[45]	Un, Aydin	2021	Experiments	This study focuses on the thermal escape mechanism and fire-fighting applications of LIB batteries. Ten experiments were carried out. In the first, a manual water-based fire extinguishing system was used, while in the second, an automatic boron-based fire extinguishing system was used. The LIB cells used in the experiments were selected from models currently used in BEBs and the electric vehicle industry [45].
[46]	P. Andersson, J. Brandt, O. Willstrand	2016	Experiments	A full-scale fire test was conducted on an electric–diesel hybrid bus at the rescue-service training facility Guttasjön outside of Borås. The fire was started in the engine compartment and allowed to spread and grow until the entire bus was consumed in the fire.

2.2. Roll-Over Simulation

A specific test conducted on electric buses is the rollover test. Unlike small electric vehicles, where the battery pack is usually placed at the bottom of the chassis, in electric buses, it can also be positioned at the top [47], leading to issues such as stability, maneuverability, and center of gravity shifts [48] (see Figure 2). These issues are being addressed by many manufacturers, who have rebalanced bus structures, taking into account the presence of battery packs installed at the top of the buses. Some manufacturers have also placed the battery pack at the bottom of the bus.

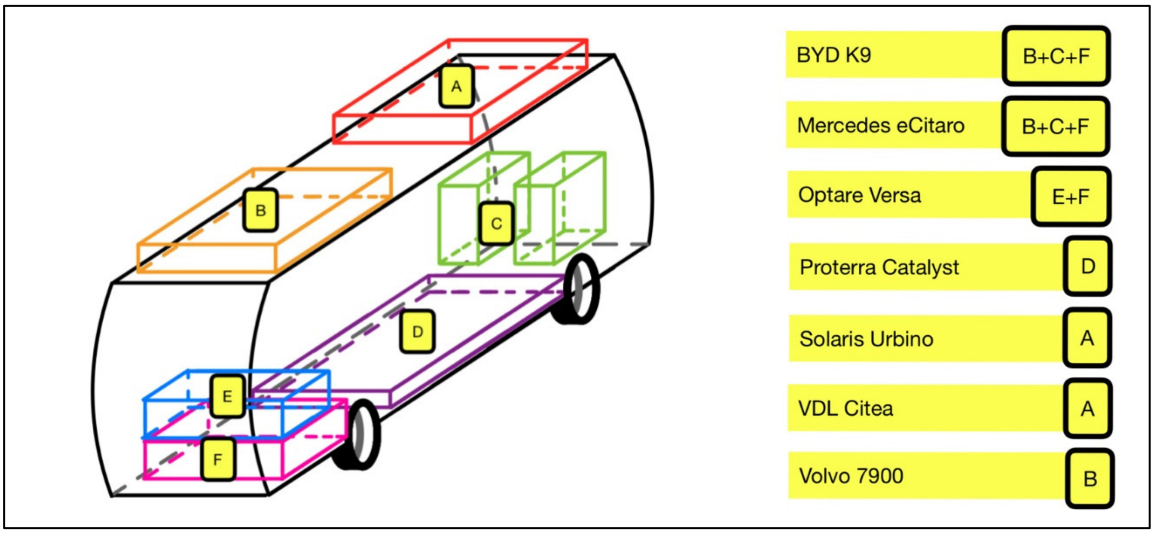

Figure 2. Main battery pack positions in electric buses [47].

The globally recognized safety standard for bus structural integrity in rollover accidents is the United Nations Economic Commission for Europe (UNECE), Regulation 66 [49,50]. Additionally, the US National Highway Traffic Safety Administration (NHTSA) has introduced FMVSS Standard No. 227, titled ‘Bus rollover structural integrity’. This standard is designed to improve structural integrity in the case of bus rollovers [51] (see Table 3).

Table 3. Roll-over activities/analysis.

Reference	Researcher/Research Organization	Publication Date	Investigation Method	Summary
[52]	China SAE	2020	Finite element analysis	A simulation based on the GB 17578-2013 standard was conducted to analyze rollover safety, leading to improvements in the electric bus chassis to reduce weight [52].
[53]	Mihradi, Dhaniswara, Wicaksono, Mahyuddin	2022	Finite element analysis	A numerical simulation of the rollover of an Indonesian-manufactured electric bus was conducted, identifying structural improvements based on deformation and stress analysis results [53].
[54]	Satrijo, Kurdi, Haryanto, Yob, Riyantiarno, Taufiqurrahman	2020	Finite element analysis	The rollover performance of an electric bus chassis made from three different materials was simulated. Simulation results were compared to identify the material with the best structural performance. Based on the comparison results, aluminum 6061 T6 was proposed as the material for the electric bus chassis [54].
[55]	Alpar, Savran, Karpat	2024	Finite element analysis	A numerical optimization study was conducted on an anti-roll bar for a BEB, defining its diameter and comparing different materials to identify the best solution in terms of weight and stability [55].
[56]	Nguyen, TT., Nguyen, CT., Nguyen, VS., Nguyen, DN.	2022	Finite element analysis	This study optimized the BEB's structural design to comply with the ECE R66 standard. The simulation process examined different steel-tube thicknesses to reduce weight while ensuring compliance with ECE R66 [56].

2.3. Frontal Collision Test

The frontal collision test of an electric bus simulates a controlled frontal impact, where the vehicle crashes into a fixed barrier (see Table 4). This test evaluates the structural integrity of the vehicle, the effectiveness of passenger restraint systems, and overall occupant safety [15,19]. Standards for occupant safety in heavy vehicle frontal collisions include pendulum impact tests based on UNECE Regulation No. 29 and frontal impact against a rigid barrier according to Federal Motor Vehicle Safety Standard (FMVSS) No. 208. Most passive vehicle safety analyses focus on metal structures, while studies on composite sandwich bus structures remain limited due to their complex damage behavior during impact [57].

Table 4. Frontal collision activities/analysis.

Reference	Researcher/ Research Organization	Publication Date	Investigation Method	Summary
[57]	Jongpradist, Saingam, Tangthamsathit, Jariyavadee, Aimmanee	2022	Finite element analysis	A LS-DYNA simulation was conducted on a BEB. This study concerns the analysis and design of the impact resistance of a sandwich composite microbus, especially to improve the efficient transfer of energy from the point of impact to the other structural elements [57].

Table 4. *Cont.*

Reference	Researcher/ Research Organization	Publication Date	Investigation Method	Summary
[58]	Jongpradist, Limpanawisut, Siritana, Saardying, Saingam, Tangthamsathit, Chanpaibool	2021	Finite element analysis	The optimized design of a lightweight composite microbus with a one-piece sandwich structure was analyzed. There are constraints on torsional and bending stiffness and natural frequency under frontal impact conditions [58].
[59]	Yang, Fan, Zhou, Zhang	2023	Finite element analysis	The frontal structure of a BEB was optimized for weight reduction and impact resistance [59].

In addition, ref. [60] analyzes the impact behavior of an electric bus's rear structure during a rear collision. The study also developed energy-absorbing mechanisms to protect battery integrity during impact [60].

2.4. Side Collision Test

The side collision test simulates a controlled impact between the vehicle and a side obstacle (see Table 5). This test assesses the bus's ability to protect passengers during a side collision [61]. The relevant ECE safety standard is Regulation R.95. This European standard deals with safety requirements for the protection of occupants in the event of a side collision [62]. The Federal Motor Vehicle Safety Standard (FMVSS) No. 214 is the regulation covering side impact protection that applies to all vehicles [63].

Table 5. Side collision activities/analysis.

Reference	Researcher/Research Organization	Publication Date	Investigation Method	Summary
[64]	SAE	2021	Finite element analysis	To optimize the electric bus chassis for reduced weight and improved side-impact resistance, the surrogate model method based on Least Squares Regression (LSR) and Radial Basis Function Neural Network (RBFNN) was used [64].
[65]	Wang, Liu, Li, Zhang	2015	Finite element analysis	The BK612EV electric bus was used in the simulation study. A side-impact safety control strategy was developed for a BEB to mitigate risks associated with battery system failures, including high-voltage hazards [65].
[66]	Kurdi, Haryanto, Yulianti, Satrijo, Suprihanto, Taufiqurrahman	2019	Finite element analysis	An analysis of side collision effects on an electric bus chassis conducted based on ECE R95 was presented. A side collision simulation was performed on a medium-sized electric bus chassis with a 48-passenger capacity [66].
[67]	Wang Z., Wang Y.	2013	Finite element analysis	A side collision simulation was conducted on the BK6122EV electric bus. The model includes the frame, body panels, power battery, and moving barrier. The side collision test was conducted at the rear hull section in accordance with collision regulations [67].
[68]	Wang, Cui, Luo	2014	Finite element analysis	To enhance collision safety, finite element models of the entire BK6122EV electric bus, its power battery system, and the movable deformable barrier were developed. The study included equivalent stress analysis of the battery module and deformation analysis of the battery pack and rear panel of the battery box [68].

2.5. Fire Tests

Data on full-scale fire tests for electric buses are even scarcer than for electric vehicles. Currently, most data on fire prevention, fire tactics, and incident response for electric buses come from real accident reports [69,70], including some reported in [39]. Fire simulation models are commonly used as a cost-effective and sustainable alternative for these tests [10]. Despite their importance, research on full-scale fire tests remains scarce, with few published studies on the topic. Furthermore, detailed information on fire tests for this type of vehicle may be limited due to intellectual property issues. Regulatory reference FMVSS 302 has been criticized as outdated for vehicle fire safety. According to [71], standards should be improved based on objective fire performance criteria, similar to crashworthiness standards. UNECE has also conducted studies on the fire safety of buses. These studies have led to proposals for the improvement of ECE 118, including the introduction of a flame spread test as specified in ISO 56581 [72]. ISO 3795 is widely used to assess the fire resistance of interior bus materials but has been criticized as inadequate for representing real-world bus fire scenarios [73]. This complication will be further analyzed in the 'Thermal Runaway' section of the article.

2.6. Vibration Tests

Vibration testing is a crucial part of electric bus design and production. This test assesses the structural integrity and durability of the vehicle under varying conditions, such as road irregularities and dynamic loads (see Table 6). These tests help identify and mitigate potential issues affecting vehicle performance, safety, and passenger comfort. Standards such as ISO 16750-3:2012 and AIS-153 provide guidelines for conducting these tests. Despite their significance, comprehensive research and standardization in vibration testing for electric buses remain limited. Therefore, further research and development are needed to establish solid test protocols for electric buses [74,75]. AIS-153, an Automotive Industry Standards (AIS) regulation in India, specifies additional requirements for bus construction. AIS-153 outlines vibration test specifications for buses, with clause 2.3.1 of AIS-153:2018 focusing on evaluating the lowest natural frequency. This vibration test is essential to ensure structural integrity and minimize vibrations affecting passengers and crew. The simulation methodology for whole-body bus vibration testing according to AIS-153:2018 is described in a technical document published on the website of the Ministry of Road Transport and Highways of the Government of India [76]. The document details a finite element modeling methodology to represent the worst-case bus structure in terms of global modal stiffness and gross vehicle weight [77].

Table 6. Vibration tests/analysis.

Reference	Researcher/Research Organization	Publication Date	Investigation Method	Summary
[77]	SAE	2024	Finite element analysis	Numerical simulation—vibration test of a complete bus (normna AIS-153:2018, clause 2.3.1)—assessment of the minimum natural frequency of the bus. This simulation framework helps the bus industry assess the natural frequency of the entire vehicle body [77].
[78]	SAE	2020	Finite element analysis	The use of eco-friendly materials like aluminum in bus manufacturing is under evaluation. Lightweight aluminum bus prototypes meet Indian regulatory standards, including AIS:052, AIS:153, and city bus strength requirements. The added weight of battery packs can be offset by lightweight aluminum technology [78].

Table 6. *Cont.*

Reference	Researcher/Research Organization	Publication Date	Investigation Method	Summary
[79]	Lei, Hu, Fu, Liu, Yana	2019	Finite element analysis/experiments	Modal and acoustic analyses using FEM and BEM methods were conducted on a three-axle, four-speed automated mechanical transmission (AMT) model for all-electric buses [79].
[80]	Tajanowskij, Kruglenya, Tanaś, Szymanek	2022	Mathematical model, two-mass and four-mass models of the human body according to ISO	Passenger vibration levels in a mobile machine were assessed according to ISO standards. A computational experiment was conducted for parametric optimization of the 6K2 electric bus suspension. These considerations enable structural optimization of the electric bus layout [80].
[81]	Zeng, Tan, Ding, Zhang, Zhou, Chen	2019	Finite element analysis	The proposed approach effectively addresses vibration problems, offering an efficient strategy to identify resonance sources and vibration transmission in all-electric buses [81].

2.7. Standards and Regulation

Currently, BEB safety regulations vary significantly across countries, making it challenging to establish uniform safety criteria. The document in [82] provides guidelines for transit agencies on identifying the specific risks associated with motor vehicle fleets and recommends best practices for safety certification. One of the key findings highlights the need for collaboration between regulators, electric bus manufacturers, and transit agencies to develop harmonized safety standards [82]. Most existing standards and regulations impose testing requirements based on regulatory documents originally intended for conventional vehicles. More analysis and evaluation of data specific to electric and high-speed vehicles are highly desirable to address the particularities of electrified technologies. For example, the comparability of component tests on the level of cells, modules, and packs needs to be assessed. Furthermore, the variability of test conditions (e.g., state of charge and temperature) is rather wide for most tests. The inconsistency of data obtained using different standards significantly impacts their comparability, highlighting the need for uniform criteria to accurately assess fire safety standards [29]. Accidents in real-world scenarios are dynamic events. However, component-level tests are performed using static assemblies where an impact mechanically penetrates the battery. Investigations have revealed discrepancies in mechanical loads between current standards, regulations, and dynamic crash tests, indicating the need for appropriate modifications to the regulatory framework [29]. It is also essential that future regulatory and standardization developments include harmonized guidelines and test protocols to ensure the accurate assessment of automotive battery fire safety standards. This will help to ensure that toxic products from potential fires are properly assessed, thus safeguarding vehicle occupants and people in the vicinity [29]. In the United States, the Federal Motor Vehicle Safety Standards (FMVSS) cover fire safety aspects, although they do not specifically address BEBs. Key regulations include FMVSS 305, which pertains to battery system integrity and protection against fire risk, and FMVSS 302, which deals with the flammability of interior materials. Additionally, the National Fire Protection Association (NFPA) sets more specific guidelines, such as NFPA 70 (National Electrical Code) for safe electrical installations and NFPA 855 for energy storage systems, including BEBs [83,84]. In the European Union, Regulation No. 100 (ECE R100) regulates the approval of electric vehicles and covers several safety features, including fire safety. This regulation emphasizes thermal management systems to prevent overheating, the integrity of the battery compartment to prevent short circuits or fires, and fire prevention measures such as ensuring that batteries are housed in fireproof enclosures [85]. European standard EN 1839 also deals with fire safety in public transport vehicles, requiring the installation of automatic fire suppression and fire alarm systems to warn passengers and drivers of potential fire hazards. China follows its own set of standards, such as GB/T 27930, which includes specific requirements for battery system protection, fire prevention and accident preparedness [86]. In Australia, the Australian Design Rules (ADR) cover the safety of BEBs, with a focus on electrical safety and fire-resistant vehicle structures. Australian Standard AS 3786 regulates fire alarm systems, ensuring that BEBs are equipped with smoke and heat detectors [87]. In Japan, fire safety standards for BEBs are regulated by the Japanese Industrial Standards (JIS) and the Japanese Electric Vehicle Standards (JEVS) [88].

3. Charging Safety of E-Bus

Ensuring the safety of electric buses (e-buses) during charging is crucial due to the high voltages involved and the potential risks associated with battery technology. Several standards, including IEC, ISO, SAE, and UL, regulate electric bus charging. All these standards are continuously being updated to reflect the increased DC charging capabilities currently being introduced [89]. In addition, European bus manufacturers (Irizar, Solaris, VDL, and Volvo) and charging system suppliers (ABB, Heliox and Siemens) have agreed to establish common charging interfaces [90]. The key components of the Conductive Charging Station (CCS) are illustrated in Figure 3, with further details provided below.

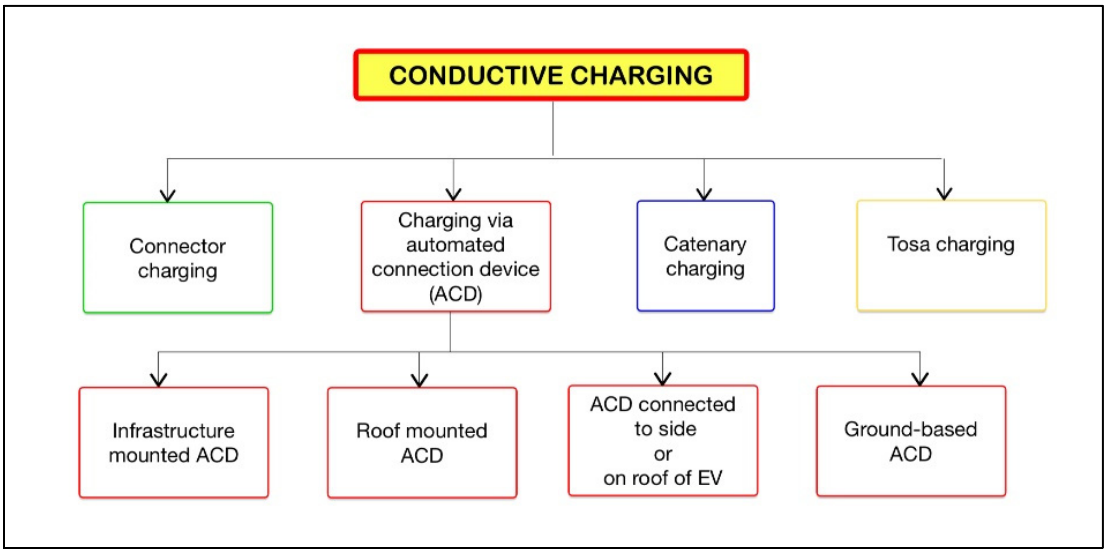

Figure 3. Different charging options for a BEB [91].

According to [89], manual connection is usually used for charging vehicles in depots. This charging process is regulated by IEC 61851-23, IEC 61851-24, and IEC 61851-1, along with their derivate EN standards. High-level communication occurs via the PLC (Power Line Communication) in conformity with EN ISO 15118-3 for cabling, using the CP contact pin as specified in IEC 61851-23 (for vehicles) and IEC 61851-24 (for chargers) [89]. According to the ASSURED design, the CCS manual plug connector must support power levels between 50 and 250 kW [91]. The infrastructure-embedded ACD features four distinct mechanical contact points and utilizes Wi-Fi/WLAN technology compliant with ISO 15118-8 throughout the charging process. The CCS charging process has been adapted to accommodate infrastructure-installed ACD. These adaptations are described in ISO 15118-2 Ed2.0 (ACD use case) and IEC 61851-23-1 (in particular Annex CC). Related working groups can be found in IEC TC 69, ISO TC 22/SC 31, and IEC TC 23 H WG 5 [89]. Automatic connections must support a power range of 150 to 600 kW [91]. The ACD installed on the roof of the electric vehicle is equipped with four separate mechanical contact points, similar to the CCS manual connector, and IEC 61851-23-1 (Annex CC) and IEC 61851-1 are applied, using power line communication (PLC) following EN ISO 15118-2:2014 and EN ISO 15118-3:2016 for the charging sequence. Related working groups can be found in IEC TC 69 and IEC TC 23H WG5 [89]. If the ACD is installed beneath the BEB, the vehicle establishes contact with the charging infrastructure from its underside. The ACD installed under the floor has three separate mechanical contact points, and IEC 61851-23-1 and IEC 61851-1 are applied, while the communication method uses WIFI/WLAN according to ISO 15118-8_Ed 1 and prEN ISO 15118-2 Ed 2. Furthermore, related working groups can be found in IEC/TC 69 and IEC/TC 23H WG5 [89]. Concerning inductive charging and battery swapping for a BEB, the standards have been summarized by ASSURED in the following Table 7 [91].

Table 7. Standards for inductive charging and battery swapping [91].

Inductive Charging	
IEC 61980	This is a set of standards and specifications for equipment required for the wireless transfer of electrical energy from the power grid to electric road vehicles (IEC-2020b, IEC-2019b, IEC-2019c)
ISO 19363	Safety and interoperability requirements for on-board equipment enabling wireless transfer of magnetic field energy for charging electric vehicles (ISO-2020c)
SAE J1773	Recommended practices on electric-vehicle inductively coupled charging (SAE international, 2009b)
SAE J2954	Safety, interoperability, and electromagnetic compatibility with wireless energy specifications for plug-in light electric vehicles (SAE international, 2020b)
Battery Swapping	
IEC 62840	Set of standards for battery exchange systems for electric vehicles (IEC-2016A, IEC-2019a)

Energy and power quality are regulated by the European standard EN 5016 [90]. Additionally, most charging points are equipped with temperature sensors. If the measured temperature exceeds a certain threshold, the charging process is interrupted [92]. Lastly, the ZEUS Project, in collaboration with VDV and UITP, recently developed two documents entitled “Use cases and requirements concerning the opportunity charging” and “Use cases and requirements concerning the charging of buses in depots”. These guidelines have been developed to describe the processes and requirements of operators and are intended to be used as a basis for European standardization activities. The group is committed to contributing to European standardization efforts and sharing its expertise with CEN/CENELEC and ISO/IEC to establish a unified European standard for electric bus systems [93,94]. There are no standards specifically dedicated to BEBs.

Fast Charging Stations

Fast charging technology has been integrated into BEB systems to allow electric buses to operate continuously without requiring a large battery. Fast charging is often perceived as increasing electrical system costs, potentially compromising the competitiveness of electric public transport vehicles. However, an appropriate and efficient distribution of charging stations could significantly reduce both the battery cost of BEB vehicles and the overall system cost [95–97]. DC charging stations overcome the main problems of high-power AC charging stations [98], such as harmonics, voltage fluctuations, and stability [99–101]. However, using a DC charging station may pose a greater risk of electrical injuries if safety measures are not carefully followed. In addition, high-power DC charging stations increase the risk of overheating and fire if they are not properly cooled or managed. The ASSURED project, co-funded by the EU commission, highlighted the need for consolidated data from the point of view of DSOs (Distribution System Operators) regarding the potential risks to distribution networks from superfast charging [102]. Reference [12] analyzed the safety implications of electromagnetic emissions from two fast-charging stations (350 kW and 300 kW) developed under the ASSURED project for BEB charging. High-power charging during the charging process could pose health risks to individuals and electronic devices both inside and outside the bus [12]. The test was performed with a Volvo 7900 Electric with a battery capacity of 196 kWh. The results showed that the magnetic and electrical emissions are far below the limits of the safety standards defined by the EU [12]. Simulations conducted under the ASSURED project suggest connecting high-power chargers to medium-voltage transformers rather than low-voltage transformers to maintain voltage stability. To ensure grid stability, it is recommended that grid operators be allowed to reduce charging points in the event of an emergency. Further mitigation strategies could include more careful planning of infrastructure location and power limitation, e.g., through smart charging. In the future, e-buses could be equipped with larger batteries, reducing the need for intermediate recharging and increasing reliance on depot charging, thereby mitigating such impacts [103]. In addition, the work carried out in the ASSURED project showed that there are gaps in the definition of mitigation measures for the negative impacts of high-power charging of electric buses:

- There is no comprehensive assessment of the potential negative impacts of high-power BEB charging on the electricity distribution network.
- There is no consolidated view by European DSOs on mitigation measures [103].

4. Thermal Runaway and Prevention

Thermal runaway can be triggered by several events, including overload, a severe malfunction of the battery or control system, an external fire, or, most commonly, a collision. Recent tests conducted by Sturm et al. suggest that the heat release rate (HRR) of BEVs may be slightly higher than that of ICEVs of similar size. The tested vehicles had battery capacities of up to 80 kWh [104]. The results indicate that the decomposition of the solid electrolyte interphase (SEI) film in the battery is the main cause of thermal runaway, which is most severe in an overcharged state [105]. Once the film has decomposed, the anode is no longer protected, and the battery's thermal runaway becomes unrecoverable. The mechanism of thermal runaway can be interpreted as a series of chain reactions, as illustrated in the following figure (Figure 4) [106].

A sequence of chemical reactions occurs, and when the temperature rises abnormally under hazardous conditions, chain reactions are initiated. The heat-temperature-reaction (HTR) cycle is the main cause of chain reactions. Specifically, heat generation increases the temperature of the cell and initiates side reactions, such as the decomposition of the interphase film of the solid electrolyte mentioned above. The side reactions release more heat, resulting in the heat-temperature-reaction (HTR) cycle. The cycle is triggered at extremely high temperatures, leading to thermal runaway of the cell [106,107]. In general, a BEB fire results in a higher production of toxic substances than an ICEB fire, but the products released are mostly the same in composition due to the similar materials used to produce the vehicles [108]. The following table (Table 8) gives examples of the composition of the exhaust gases that are released from the battery cells in the event of overheating [109]. Some compounds may lead to jet fires, flash fires, etc., while others are toxic. Their impact depends on the specific scenario in which they develop. The concentration of these compounds is certainly influenced by various system and battery parameters. The main parameters influencing their concentration are [110] as follows:

- State of charge (SOC) (0–100%)
- Electrodes material (LCO, NCA, LFP, NMC, . . .)

- Battery capacity (0.5–80 Ah)
- State of health (SOH)
- Type of configuration (coin cells, prismatic cells, pouch cells . . .)

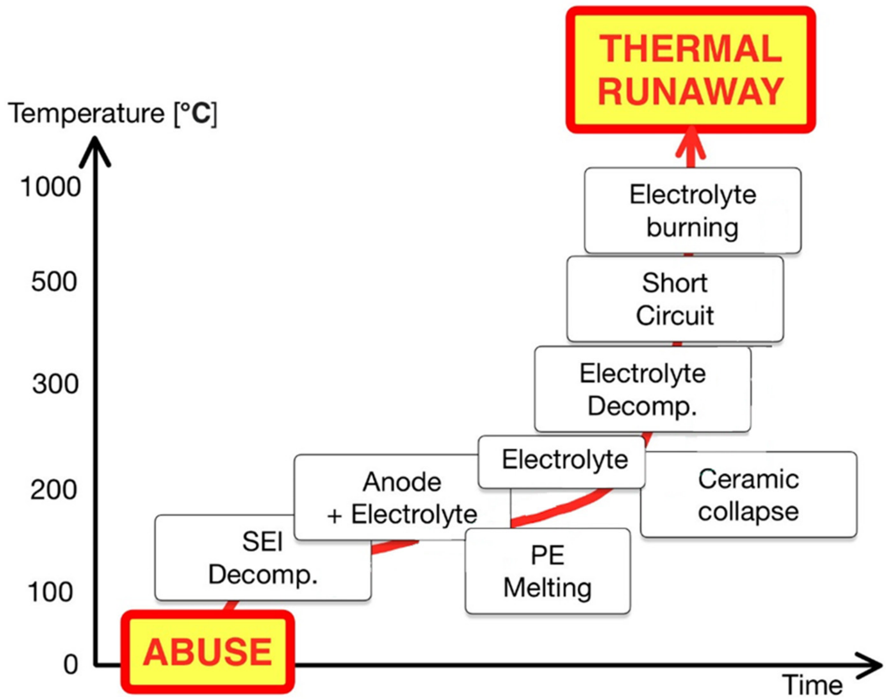

Figure 4. Qualitative interpretation of chain reactions during thermal runaway [106].

Table 8. Exhaust gas composition of lithium-ion batteries (mass percentages, estimated from volumetric ratios derived from the literature) [109].

Type of Gas	NMC 18650 Cells [111]	LCO/NMC 18650 Cell [111]	LFP 18650 Cell [111]	Li-ion Batteries—Review Article [110]
	%	%	%	%
H_2	2.4	2.6	2.2	2–50
CO	14.1	33.3	4.8	27–29
CO_2	70.4	47.3	83.4	35–37
CH_4	4.2	5.9	2.3	4–5
C_2H_4	8.9	9.3	6.8	-
C_2H_6	-	1.6	0.3	0.5–1
C_3H_6	-	-	-	0–0.5
HF	-	-	-	0.003

For a full-scale comparison, the studies by Lecocq et al. from INERIS, which assessed fires in electric and conventional (diesel-powered) cars, were analyzed [112–114]. In [115], fire tests were conducted on two full battery packs for an electric vehicle (EV), and an analogous internal combustion engine (ICE) vehicle [115]. The results showed that the production of thermal power between the two types of vehicles is similar, while the production of toxic compounds is different. The dynamics of production are different, and for electric vehicles, compounds such as HF and other toxic gases show a higher concentration. The results are in agreement with the table above, especially considering the type of substance emitted.

In [116], a critical review was made that envisions the development trends of battery chemistry technologies. At the moment, the most stable and safest battery chemistries for electric vehicles include the following:

- Lithium Iron Phosphate (LFP): This chemistry is known for its thermal and chemical stability, reducing the risk of fires and explosions.
- Lithium Nickel Manganese Cobalt Oxide (NMC): Although this chemistry has a high energy density, it is generally considered safe and stable.
- Lithium Nickel Cobalt Aluminum Oxide (NCA): Mainly used by Tesla, this chemistry offers a good balance between energy density and stability.
- Lithium Manganese Oxide (LMO): This chemistry is known for its stability at high temperatures [117].

In the event of a battery-electric vehicle accident, fire propagation between cells and modules takes time, depending on the battery pack configuration and type [109]. The reduction in hazards caused by thermal runaway can be realized through three levels, as in Figure 5 and as explained in [106]:

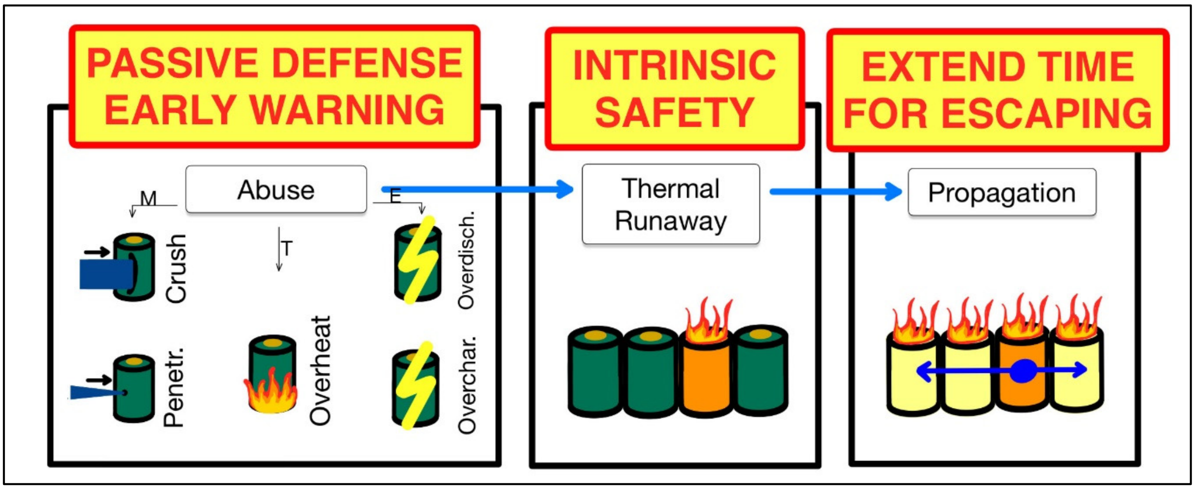

Figure 5. Three levels of protection to reduce the hazard caused by thermal runaway.

Kim et al. [118], developed a numerical model to investigate gas venting behavior, considering internal pressure and the dynamics of gases inside a Li-ion cell. Batteries with a high state of charge (SOC) show faster temperature growth than tests with batteries with a low state of charge. In addition, high SOC values reveal higher internal pressure, increasing the probability of side-wall rupture and potential explosion. To enhance internal safety, efforts have been made to modify the materials used in lithium-ion batteries [119]. In particular, modifying the cathode, anode, separator, and electrolyte can be effective [120], as the thermal stability of the electrode materials largely determines the thermal safety of the entire cell [106,121]. Regarding research on the application of new phase change materials, several studies have consistently demonstrated the cooling capabilities of phase change material (PCM) systems through experiments and simulations [122,123]. For example, aluminum nitride has been incorporated into phase change composites to enhance heat transfer performance, temperature regulation, and battery pack sealing performance. This material provides cooling performance to the battery system and also solves some engineering problems, such as the possible influence of fluid leakage on the battery's thermal management system using phase change materials and also the high stiffness and low thermal conductivity of the materials [124]. In high-power application scenarios, a PCM-assisted secondary cooling system, such as air, liquid, and heat pipe cooling, has emerged as a viable and effective solution [122]. Regarding the inherent safety measures of the battery pack, there are several safety measures already taken by manufacturers:

- Battery cooling system designed to maintain BEV batteries at a safe and optimal temperature during both operation and charging.
- Battery Management System (BMS), which has the function of constantly keeping track of the temperature, charge level, and other factors of the battery. The purpose of the BMS is to prevent the battery from overcharging, over-discharging, or overheating, all of which can trigger fires [125]. Specifically, the BMS constantly monitors the individual cells and shuts them down if they are not operating within the aspired range of parameters. The cells operate within strings; if an anomaly occurs, each string can be switched off, but the vehicle can continue to run to a safe location [126].
- Thermal management system, to keep the battery at a safe temperature and avoid thermal runaway reactions that can cause fires, this system uses cooling and heating.
- Fire walls, which prevent flames from spreading to other interior compartments. They are usually constructed of heat-resistant materials. Fire walls can tolerate extreme temperatures.
- Fuses and circuit breakers are designed to protect the electrical system of electric vehicles from overloads and short circuits, both of which can lead to fires. Fuses are strategically placed along the circuit and are designed to melt and interrupt the flow of current in the event of an overload or short circuit, avoiding more serious damage to the system [127]. Circuit breakers, on the other hand, are used to regulate the current flow within the module pack [128].
- Emergency shutdown is a crucial function of battery management systems (BMS) to prevent future damage or fire; this mechanism shuts down the electrical system and disconnects the battery.
- The incorporation of a pressure release valve is a common practice in the lower section of the battery pack. When the pressure within the battery pack exceeds a specified threshold, the valve opens, resets, and then closes again after the thermal runaway of individual cells and subsequent pressure release. This mechanism prevents external air from entering the battery pack, thereby slowing down the propagation of thermal leakage risk within the pack [124].

Early identification of problems and timely warning of safety hazards before accidents occur, combined with proactive battery system maintenance, are key factors in improving the safety management of electric battery systems. These elements have become the focus of research into the safe applications of high-power batteries such as those used in BEBs. Active safety measures for high-power batteries can be divided into two categories: the first involves diagnosing battery system issues, while the second focuses on the early prediction of thermal runaway risks [124,129,130]. Concerning the diagnosis of power battery system failures, researchers assessed the operational status of vehicles by analyzing data on electric vehicle speed and battery current [124]. However, once thermal runaway has been triggered, countermeasures must be implemented to mitigate the secondary hazards associated with this event. The occurrence of a fire during thermal runaway increases the probability of damage. Components designed to protect the battery pack from extreme conditions are likely to break and fail once exposed to fire. Fire extinguishing must be carefully considered [131], as the heat released during a fire can be substantial [39,106]. Several studies have been conducted on the research and development of CF_3CHFCF_3 (heptafluoropropane) fire extinguishing systems for electric vehicles, aiming to encourage the adoption of fire suppression devices for electric buses equipped with lithium-ion batteries. The heptafluoropropane fire suppression system offers several advantages over traditional systems, including low toxicity, non-damaging properties for electrical equipment, and minimal environmental impact [132–134]. Specifically, in study [135], the fire protection system was designed for BEBs with an intervention temperature of 80 °C. Test results show that the battery's performance does not change significantly before and after the fire is extinguished, and that the extinguishing system can provide safety guarantees [135]. Thanks to its excellent fire suppression performance, enhanced environmental compatibility, and good thermal stability, R1216 (1,1,2,3,3-hexafluoro-1-propene) has demonstrated potential as a halon substitute, warranting further research for its practical application in fire suppression [136]. Currently, several studies have explored new mixed working fluids containing R1216 and other low Global Warming Potential (GWP) flammable gases, aiming to optimize the environmental and safety characteristics of the mixtures [137]. At present, fire safety standards for buses exhibit significant shortcomings, especially concerning the methods used to assess the fire resistance of materials inside the buses [5]. These deficiencies could severely impact the evacuation conditions in such transport systems. The preliminary study in [5] suggests the necessity of an approach similar to the EN 45545-2 fire safety standard, which applies to materials used in railway vehicles. This recommendation is based on extensive pre-normative research conducted over more than a decade, advocating for an expanded and revised version of bus fire regulations, with buses classified into operational categories and materials categorized by product type [5]. In study [70], materials used for bus interiors that meet the updated fire safety requirements were experimentally analyzed. However, the updated regulations do not consider smoke production or its toxicity. During the thermal decomposition of materials, the composition of emitted fumes was continuously analyzed using FT-IR spectroscopy. Excessive smoke production can rapidly create unbearable conditions inside a bus due to the confined space in the cabin. Reduced visibility may hinder passengers from evacuating in time [70]. Guidelines for the future development of regulations regarding BEB interior materials can be found in study [5]. Regulation 107, introduced by the United Nations Economic Commission, mandates that all combustion engine vehicles in the industry must be equipped with an automatic fire suppression system in the engine compartment. However, this regulation has been only superficially extended to electric buses, which, being powered by lithium-ion batteries, introduce additional fire hazards that existing regulations fail to adequately address [70]. The UNECE Regulation 100 (Construction and Safety of Electric Powertrains) includes a new proposal requiring a mandatory fire alarm system in case of battery and/or REESS failure. According to this regulation, in the event of a thermal runaway risk, the vehicle system or REESS must issue early warning signals to detect potential battery failure as soon as possible, preventing fire escalation. In line with this requirement, fire suppression systems could be implemented as retrofit devices to release cooling agents and mitigate related risks [70,138].

5. Safety of E-Buses in Tunnels and Enclosed Spaces

The risk of major incidents, such as fires in road tunnels, requires increased attention. Special consideration must be given to fire behavior, toxic emissions, and their impact on tunnel occupants, as well as emergency response strategies [104]. In certain conditions, pollutants released during a fire can accumulate in the indoor air more quickly than in open spaces and disperse more efficiently, potentially exceeding critical thresholds for human health. Mao et al. [138] evaluated the toxicity of the gases (CO and CO_2) emitted by a 10-cell battery pack in an electric bus garage and found that fire-induced toxicity levels were extremely high, significantly exceeding the limits considered safe for humans [138]. Because of the specific properties of battery emissions, these gases can spread both during and after the fire, contaminating areas that were not initially affected by the incident [28]. In most cases, fires involving BEVs follow a conventional fire pattern (without a 'pool fire' or 'fireball'), accompanied by a small 'jet fire' if the vented gases ignite immediately or shortly after release [109]. Conversely, the most common explosion scenario involving a BEV is a gas cloud explosion, primarily triggered by the fact that hydrogen is the main exhaust gas from the battery pack. In particular, the explosion can occur as either a deflagration or a detonation. Without a significant ignition source, the gas cloud undergoes deflagration, characterized by a relatively low flame velocity. In certain situations, the flame velocity of a deflagration can gradually increase until it reaches supersonic speed, leading to a sudden transition into detonation. The transition from deflagration to detonation is rare in open environments but more likely to occur in enclosed spaces such as tunnels. Furthermore, the presence of large vehicles, such as a BEB, can significantly enhance the likelihood of this transition [109]. A 2023 study by H. Raza and S. Li used a fire dynamics simulator to model a BEB fire in a tunnel and compare its behavior with that of an ICEB fire. The simulation results indicate that, in a BEB fire scenario, occupants take longer to evacuate the tunnel. This delay is because BEB fires produce more soot compared to ICEB fires and exhibit slightly higher toxicity levels [108].

Mechanical Ventilation System

A mechanical ventilation system is essential to facilitate the evacuation process in a tunnel [108]. Poor ventilation increases flammability and makes the transition from deflagration to detonation more likely [109]. Additionally, mechanical ventilation is essential to prevent adverse events, including the phenomenon of 'backlayering', which is influenced by various factors such as the 'blockage ratio' due to obstacles, fire geometry, tunnel slope, and heat release rate [139–144], in particular by analyzing variables such as the height and shape of the vehicular block, the configuration of the vehicular block, etc. It has been confirmed that the presence of large vehicles can contribute to reducing the backlayering length [145,146]. Furthermore, an electric bus may have an even greater impact on this phenomenon due to its higher smoke emissions compared to an ICEB [108]. Ventilation capacity is a key area of research that will be explored in detail by PIARC researchers and members of WG4 TC4.4 [141,147].

6. E-Buses in E-Bus Depots

This section provides a comprehensive overview of the safety challenges and solutions for electric bus (e-bus) depots. The risk of electric buses catching fire while in operation or during charging remains an open research topic [148]. These issues can cause high-voltage electrical discharges or arc flashes, which may ignite a fire [39,149]. Furthermore, the presence of multiple BEBs in depots exacerbates the situation, as a fire involving a single battery pack can rapidly escalate due to thermal runaway, resulting in chain fires [150,151]. This underscores the need for specialized fire safety strategies in zero-emission bus depots, as these challenges do not exist in conventional ICE bus depots [92]. Even a single battery pack involved in a fire can create a highly critical situation [39]. Therefore, battery fires pose a significant challenge for zero-emission bus depots, an issue that does not affect conventional depots with only ICEBs. In electric buses, thermal runaway that leads to depot fires begins inside the battery pack and becomes visible only after the pack ruptures. At this point, the fire spreads rapidly, making early intervention extremely difficult. However, fire progression in a ZEB is similar to that in a diesel bus, as fire loads are comparable. Therefore, some aspects of a fire in a diesel bus depot also apply to ZEB depots [92].

6.1. The Netherlands—The Westraven E-Bus Depot

The case study of the Westraven e-bus depot in the Netherlands provides real-world examples of compartmentalization, fire barriers, and quarantine areas, demonstrating how design and operational measures can mitigate fire risks. In the e-bus depot in Utrecht, the charging area for these vehicles is divided into compartments. In each compartment, a maximum of 40 BEBs out of a total of 160 are grouped [152], and all compartments are separated by a containment wall and a fire barrier [148] to limit the fire for a predetermined period, such as 60 min [70]. In addition, there is at least 4 m of space between two compartments. The space can be used as a lane for fire trucks that must be able to encircle the burning buses [152]. The total of 40 buses per compartment is specific to this bus depot and must be customized to meet local circumstances and safety issues [152]. In this context, the figure of 40 electric buses per compartment is based on the consideration that these buses, if they were to be destroyed, could be replaced in a relatively short time without causing major disruptions to the public transport service [148,152]. In addition, to limit the spread of a potential fire, there is a quarantine area [70]. This is an area separated from the bus depot, equipped with fire-fighting systems, where suspect buses can be parked. The objective of the quarantine area is not to prevent the fire but to prevent it from spreading [153]. For example, buses that have been involved in a minor collision are parked in this area [70]. The bus depot features an innovative fire detection system (see Table 9). This is a system created by the US military, based on radar images, which reacts to heat. In Utrecht, practical experience with this system is still limited [148].

Table 9. Fire risks and potential safety solutions in e-bus depots.

Focus Area	Description	Implemented Solutions (Westraven E-Bus Depot)
Fire risk from thermal runaway	A fire can start inside the battery pack and quickly spread to other buses.	Depot compartmentalization with fire-resistant walls between groups of max 40 buses.
Minimizing impact on operational buses	A fire can compromise the fleet and disrupt public transportation services.	The 40-bus-per-compartment limit allows for quick replacement in case of damage.
Fire propagation	Fire can rapidly spread between nearby buses, causing chain fires.	Fire barriers between compartments and a 4 m-wide space between them for firefighter access.
Challenges in rapid intervention	Thermal runaway becomes visible only after battery rupture, making timely action difficult.	Installation of an innovative radar-based thermal detection system to identify overheating early.
Management of suspect buses	Buses involved in minor accidents may pose a latent fire risk.	Creation of a separate quarantine area to isolate potentially hazardous buses.

6.2. High-Pressure Water Mist Systems

The study of high-pressure water mist (WM) systems and their limitations highlights ongoing advancements in fire suppression, while also recognizing the challenges of cooling internal battery components, particularly in the confined space of an e-depot. Conventional external fire-fighting systems are ineffective at cooling battery cells due to the watertight nature of their metal casing [92]. High-pressure water mist systems are a potentially effective solution for fire protection in electric bus depots. The diffusion of water mist from these systems can reduce the intensity of thermal radiation from the flames to the surroundings and prevent the spread of fire and the collapse of the fire partition [154]. Multiple standards govern the design, installation, maintenance, and testing of water mist fire protection systems. These standards vary by country and application and include NFPA [126], CEN [155], ISO [156], and Standards Australia [157]. Previous studies primarily focused on static water misting units. In [158], researchers tested a mobile water mist device, which had to be manually operated by firefighters. [158]. The effect of water mist on fires is twofold.

Some of the mist is absorbed by the smoke without vaporizing, reducing the number of mist particles that reach the flame surface in the high-temperature zone. In addition, the mixing process of fuel, gas, and oxygen accelerates, reducing the cooling effect of the fine water mist. In addition, the water fog impacts the flame and increases the mixing area between the oxidant and fuel [158,159]. In [160], the WM has demonstrated the ability to quickly extinguish fires in large-capacity lithium-ion batteries. When WM was applied, the open flame was extinguished within one second. The cooling effect of the WM on the large LIB was analyzed from both a global and an instantaneous point of view. The TR development of the large LIB could only be completely interrupted when the WM was applied immediately after the activation of the safety vent. However, within 15 s, the rapid deterioration of the battery can make TR uncontrollable. Nevertheless, even when TR occurs, WM removes at least 65% of the heat generated by the battery [160]. A key limitation of high-pressure water mist systems is that their cooling effect is primarily confined to the exterior of the battery pack. In Santangelo et al. (2016) [160], an experimental comparison between high-pressure water mist (C1WM2.0 and C2WM2.0) and traditional sprinklers (C1SPK and C2SPK) has been conducted in an enclosed car park, with one discharge density for sprinklers (6.5 L min^{-1} m^{-2}) compared to two for water mist (1.5 and 2.0 L min^{-1} m^{-2}), respectively. Re-ignition occurred in sprinkler and water-mist experiments at the lower discharge density. Assuming that average temperature trend at the ceiling height is representative of the heat-release rate trend, it can be conservatively concluded that suppression was achieved only by water mist at the higher discharge density on both configurations. Water mist systems used significantly less water than sprinklers while achieving comparable or superior suppression efficiency. The lower water consumption of mist systems minimizes runoff and potential water damage, enhancing their environmental sustainability [161]. The effectiveness of water mist systems is significantly influenced by whether they are used in open areas or enclosed spaces. Xiaojie Tang et al. (2024) experimentally investigated the effectiveness of FWM cooling on TR hazard control in a confined space [161]. The confined space accelerated the TR triggering, with an average reduction of 8.3 % in TR triggering time due to inadequate heat dissipation conditions. Compared with open space, the average mass loss of LIBs in confined space increases by 14.6 % at 100 % of the state of charge of the LIB [162]. When mechanical ventilation is present, the performance of water mist systems further declines. As discussed by M. H. Alenezi et al. (2023), in the setup with mechanical ventilation, the amount of water required for fire suppression was greater than without, as a result of stronger combustion due to more oxygen blown in by the fan [162]. The ventilation fan displaced the maximum temperature zone from the tunnel center toward the air-inlet end (upstream). This shift occurred due to increased oxygen influx, which moved the fire center closer to the oxygen source. Therefore, when designing fire-suppression systems for road tunnels, it is important to consider the impact of ventilation fans not only on smoke removal but also on potential delays in fire suppression, which can lead to greater losses. Additionally, when determining the necessary water-storage volume, the increased water demand for fire suppression must be considered if ventilation fans are used. Finally, when determining the location of the fire-suppression zone, designers should account for the fire's movement toward the air inlet once the ventilation fans are activated [162]. Lu et al. (2020) investigated the performance of water mist to extinguish an alkane pool fire under roof ventilation condition [163]. It was found that the fire extinguishing time increased by 54 seconds at a ventilation rate of 50 m^3/min and by 202 seconds at 75 m^3/min. Furthermore, at a ventilation rate of 120 m^3/min, the water mist failed to extinguish the fire. Excessive air reduces fire-extinguishing efficiency, but appropriate ventilation can slightly enhance fire combustion and further strengthen the effect of cooling by water mist [154,164].

Zhou et al. (2018) [164] verified the fire-extinguishing performance of water mist using a cycling discharge mode in a test room equipped with smoke vents. The study concluded that water mist could not extinguish a gasoline pool fire (0.3 m $\times$ 0.3 m $\times$ 0.05 m) when the exhaust rate exceeded 0.6 m^3/s. However, when the exhaust rate was 0.15 m^3/s, the fire extinguishing time was 10 seconds shorter compared to scenarios without ventilation. Additionally, the cycling discharge mode of water mist proved to be more effective than the continuous discharge mode [154,165], see Table 10.

Table 10. Summary of experimental findings on water mist and fire suppression systems.

Study	Experiment	Key Findings
Santangelo et al. (2016) [160]	Comparison of high-pressure water mist (C1WM2.0, C2WM2.0) vs. traditional sprinklers (C1SPK, C2SPK) in an enclosed car park.	-Suppression was achieved only by water mist at higher discharge density, while re-ignition occurred at lower discharge densities in both water mist and sprinkler experiments.-Water mist used significantly less water than sprinklers but provided comparable or superior suppression efficiency. -The lower water usage of mist systems reduces runoff and potential water damage, making them environmentally favorable.
X. Tang et al. (2024) [161]	Effectiveness of FWM cooling on thermal runaway (TR) hazard control in confined space.	-Confined space accelerated TR triggering, reducing TR triggering time by 8.3%. -LIB mass loss in confined space increased by 14.6% compared to open space.
M. H. Alenezi et al. (2023) [162]	Effect of mechanical ventilation on water mist performance in fire suppression.	-More water was needed for suppression with ventilation due to increased oxygen supply. -Ventilation fans shifted the fire center toward the air-inlet end of the tunnel due to more oxygen being introduced. -Designers must consider ventilation effects when determining fire-suppression zones, water storage volumes, and the delay they might cause in suppressing the fire, which can increase losses.
Lu et al. (2020) [163]	Water mist performance in extinguishing alkane pool fire under roof ventilation.	-Fire extinguishing time increased by 54 s at 50 m^3/min and by 202 s at 75 m^3/min ventilation rates. -Fire could not be extinguished at 120 m^3/min ventilation rate. -Excessive ventilation reduced extinguishing efficiency, while moderate ventilation slightly enhanced fire combustion and further strengthened the cooling effect of water mist.
Zhou et al. (2018) [164]	Water mist with cycling vs. continuous discharge mode in a test room with smoke vents.	-Water mist failed to extinguish a gasoline pool fire, whose volume was 0.3 m $\times$ 0.3 m $\times$ 0.05 m, when the exhaust rate exceeded 0.6 m^3/s. -At 0.15 m^3/s exhaust rate, fire extinguishing time was 10 s shorter than without ventilation. -Cycling discharge mode was more effective than continuous discharge mode when tested in a room with smoke vents.

6.3. Li-ionFire Project: An Innovative Fire Suppression System

This EU initiative exemplifies cutting-edge research and innovation in fire safety, emphasizing early detection, integrated protection systems, and collaboration between manufacturers, fire brigades, and battery developers. The Li-ionFire Project introduced a highly innovative fire protection system for electric and hybrid vehicles. The project has played a leading role in addressing fire risks associated with BEBs, particularly those powered by lithium-ion batteries. As previously discussed, these batteries pose a significant fire risk due to their potential for rapid heat accumulation and toxic gas release when damaged [166]. The Li-ionFire project's objective is to validate, demonstrate, and commercialize an advanced fire protection system for e-buses. The main target of the Li-ionFire project is e-bus manufacturers such as Volvo, Iveco, Scania, Yutong, and MAN [166].

- Early detection and action:

Project partners investigated multiple techniques for early battery failure detection. Early system activation could restore the battery to a safe condition, preventing further deterioration. Even with late activation, the system could delay the battery reaching a critical state, allowing safe evacuation [166,167].

- Integrated fire protection system:

The Li-ionFire Project-validated system integrates several key features, including an early fire alarm that alerts operators to potential fire hazards. A point cooling system prevents thermal runaway by cooling the battery, while a fire detection and suppression system is designed to contain fire spread within the battery compartment [168]. The innovative aspect is the rapid interaction with the inside of the battery. Similar systems could be implemented through collaboration between battery pack developers and fire control authorities, such as fire brigades. Establishing cooperation between these stakeholders and vehicle manufacturers is essential for improved thermal emergency management.

6.4. Fire Guidelines for E-Bus Depots

The development of fire safety guidelines, such as those from NFPA, ensures standardized fire prevention and risk management practices, which are crucial for the safe expansion of e-bus deployments. Fire safety guidelines are essential to ensure the safety of operators, vehicles and the surrounding environment [169]. The NFPA is actively developing and refining fire prevention guidelines for buses equipped with lithium-ion batteries [170]. The project 'Fire Prevention in Transit Buses with Lithium-Ion Batteries and Risk Management' envisages the production of a guide for fire prevention in transit buses with lithium-ion batteries and risk management, with the aim of providing practical recommendations for original equipment manufacturers, battery companies, transit agency facilities, and vehicle maintenance workers. The project includes both qualitative and quantitative components, such as a literature review to gather relevant data. The information gathered and the modeling results are then used to develop a methodology and guidelines for hazard mitigation analysis (HMA), which allow for the qualitative and quantitative assessment of the safety of bus depots or other vehicle storage facilities [70]. Figure 6 summarizes the possible measures, divided and classified according to the stages of fire development according to CROW, a Dutch organization that deals with knowledge and innovations in the field of infrastructure, mobility, and the public environment [171], see Figure 6.

In general, to avoid fires in bus depots, it is advisable to follow a maintenance schedule for service equipment with a certain frequency that is defined by the specific type of maintenance [172].

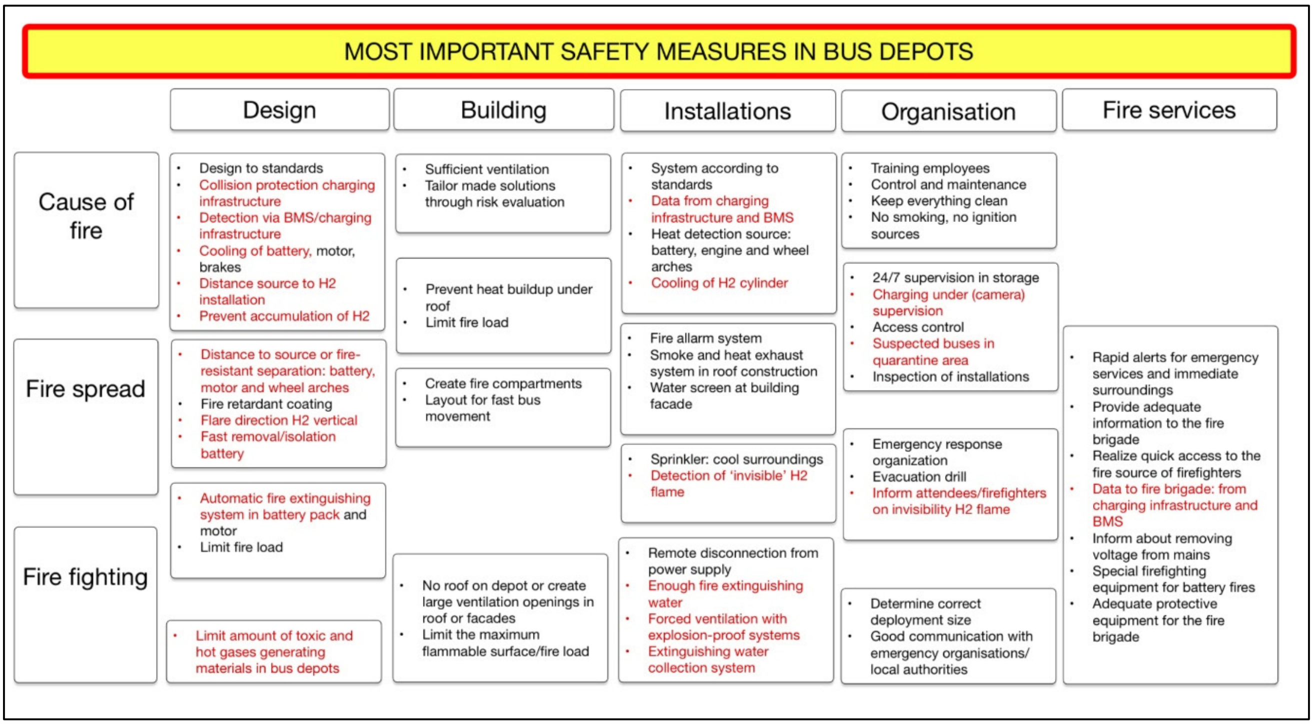

Figure 6. Overview of the most important safety measures, divided by type and classified according to the stages of fire development to be implemented in bus depots. Those in red are specific to zero-emission buses [171].

7. Cybersecurity in E-Bus

Cybersecurity in public transport focuses on protecting digital infrastructure, ensuring the autonomy and resilience of urban transit systems against external threats. This guarantees the safety and reliability of public transport operations [173]. Many urban areas are implementing strategies to promote the adoption of electric vehicles, especially in public transport. However, ensuring their security against cyber threats and unforeseen disruptions remains a priority. Speaking in a very general way, the following aspects of cybersecurity need to be paid attention to guarantee the security of IT systems related to electric buses:

- 1. Reliability of bus mechatronic systems;
- 2. Battery and power system reliability;
- 3. Monitoring energy levels and battery charging;
- 4. Reliability of the individual technical elements of the charging system;
- 5. Security and reliability of the public transport IT system [173].

Traditional methods relying on physical measurements to detect anomalies caused by cyber-attacks are insufficient for accurately assessing cyber-physical conditions. Moreover, standard intrusion detection systems (IDS), which rely on rule-based and anomaly detection methods, tend to generate a high number of false positives. Therefore, the autonomous use of cyber-attack detection tools, both on the cyber and physical side, shows limited capacity [174]. In [174], a mechanism was developed to combine real-time data from the cyber and physical domains to improve situational awareness of the whole system. It is shown how this increased awareness can help to reduce false positives in intrusion detection [174]. In [175], detection and protection systems were designed within proposed architecture for BEBs with Vehicle-to-Cloud (V2C) connectivity to deal with Distributed Denial-of-Service (DDoS) attacks. The analysis in this paper shows that DDoS attacks are particularly critical as they are easy to launch and difficult to defend against. By flooding the network with spam traffic, DDoS attacks can severely disrupt vehicle-to-cloud communication, potentially disabling all BEBs dependent on this connectivity [175]. The simulation results show that the proposed security systems can significantly reduce the probability of blockages between servers and field devices on the cloud side. Furthermore, for a field device protected by the proposed approach, DDoS attacks reduce the energy efficiency and battery life of the tested power management system by only 0.2288% compared to the benchmark results [175]. In the future, studies could be conducted on the detection and protection of other cyber-attacks on BEBs' energy systems, such as sensor attacks and 'man-in-the-middle' attacks [174,175]. Further studies could focus on collecting data from real attacks using machine learning methods to improve the attack detection system. Additionally, collecting more data on these attacks will improve the understanding of security vulnerabilities and allow for more precise risk assessments [175].

Past Cyber threats

Recent cybersecurity concerns have highlighted vulnerabilities in electric vehicles, including electric buses, that could be exploited in potential attacks. For instance, a significant threat known as the "Brokenwire" attack, discovered in 2022, targets the communication between electric vehicles and their charging infrastructure. This attack disrupts vehicle-to-charger communication, interrupting charging sessions and potentially affecting the operational efficiency of electric bus fleets [176]. Moreover, in 2023, researchers introduced the "Delayed Charging Attack" (DCA), which exploits both physical and communication vulnerabilities to delay charging services for electric vehicles. This attack has serious consequences for shared electric mobility systems, as it leads to inefficiencies in fleet management and availability, affecting both operators and passengers [177]. Such attacks not only impact the service capacity of electric buses but also compromise overall system reliability, leading to financial losses from reduced operational revenue [177].

AI and Cybersecurity

The integration of recent advancements in AI-driven cybersecurity enhances the protection of BEBs against cyber threats. AI technologies, particularly machine learning and deep learning, enable the development of advanced Intrusion Detection Systems (IDS) that can identify and mitigate potential risks in real time. For instance, AI algorithms can analyze large volumes of data collected from vehicle networks to detect unusual patterns or behaviors that may indicate a security breach. This capability enables a proactive approach to cybersecurity, as AI can predict and identify emerging threats before they materialize [178]. The use of predictive intelligence is crucial in safeguarding electric vehicles, allowing for rapid response and prevention. Moreover, AI-driven cybersecurity solutions are adept at monitoring the vehicle's communication protocols, such as CAN and Automotive Ethernet, which are essential for in-vehicle data exchange. By continuously observing these networks, AI-based Intrusion Detection Systems (IDSs) can efficiently detect malicious activities, ensuring timely responses and minimizing damage [179]. Additionally, the implementation of real-time monitoring powered by AI helps in maintaining a continuous watch over vehicle networks, further enhancing the security and integrity of the system [180,181]. By adopting AI-driven cybersecurity, electric buses can benefit from a more secure and resilient infrastructure, minimizing the risks associated with cyber threats.

Moving-Target Defense (MTD) and Blockchain in Charging Stations

More generally, cybersecurity issues will soon be included in standardization and proposals have already been made for the cybersecurity of charging infrastructures [182,183]. In [184], it is illustrated how the integration of EVs into power grid operations can potentially make the grid vulnerable to cyber-attacks from old and new equipment and protocols, including extremely fast charging infrastructure [184]. Existing designs for electric equipment implicitly assume a trusted environment (i.e., free of malicious attacks from a cyber security perspective). As a result, the design process used for safety-critical systems does not necessarily guarantee safe systems. This could seriously compromise the safety of extremely fast charging systems [185]. The adoption of 'Moving-Target Defense' (MTD), involves the use of strategies and technologies aimed at making it more difficult for potential attackers to locate, compromise, or damage electric vehicles. In an MTD approach, the system configuration is constantly changed to make the attacker's information obsolete and to make the system unpredictable. This can help defend against cyber-physical attacks, such as spoofing and replay attacks on the Controller Area Network (CAN) bus, which could infect the entire network through the BMS. It is a strategy that aims to protect against reconnaissance activities of enemy attacks on static platforms. By continuously changing system parameters and varying the attack surface of protected systems, MTD can make it more difficult for an attacker to identify, create, execute, propagate, and exploit [186]. In several studies, a new MTD switching strategy has been developed and implemented, which includes the use of redundant BMS units as a safeguard against potential contamination of the charging station and power grid during the fast-charging process [185,187]. Lastly, blockchain technology is increasingly being integrated into the charging infrastructure of electric buses. It offers a decentralized and secure way to manage energy exchanges, which is crucial for the operation of electric bus charging stations [188–190]. For example, blockchain can enable a mechanism to exchange charging rights between charging stations, ensuring fair allocation and secure transactions. Furthermore, it can facilitate peer-to-peer (P2P) charging platforms, allowing idle charging stations to be made available to others, thus optimizing the use of charging infrastructure [189]. Combined, MTD and blockchain can provide a robust security framework for charging stations, protecting against a range of potential cyber threats. However, these technologies are still emerging, and further research and development is needed to realize their full potential [186,190], see Figure 7.

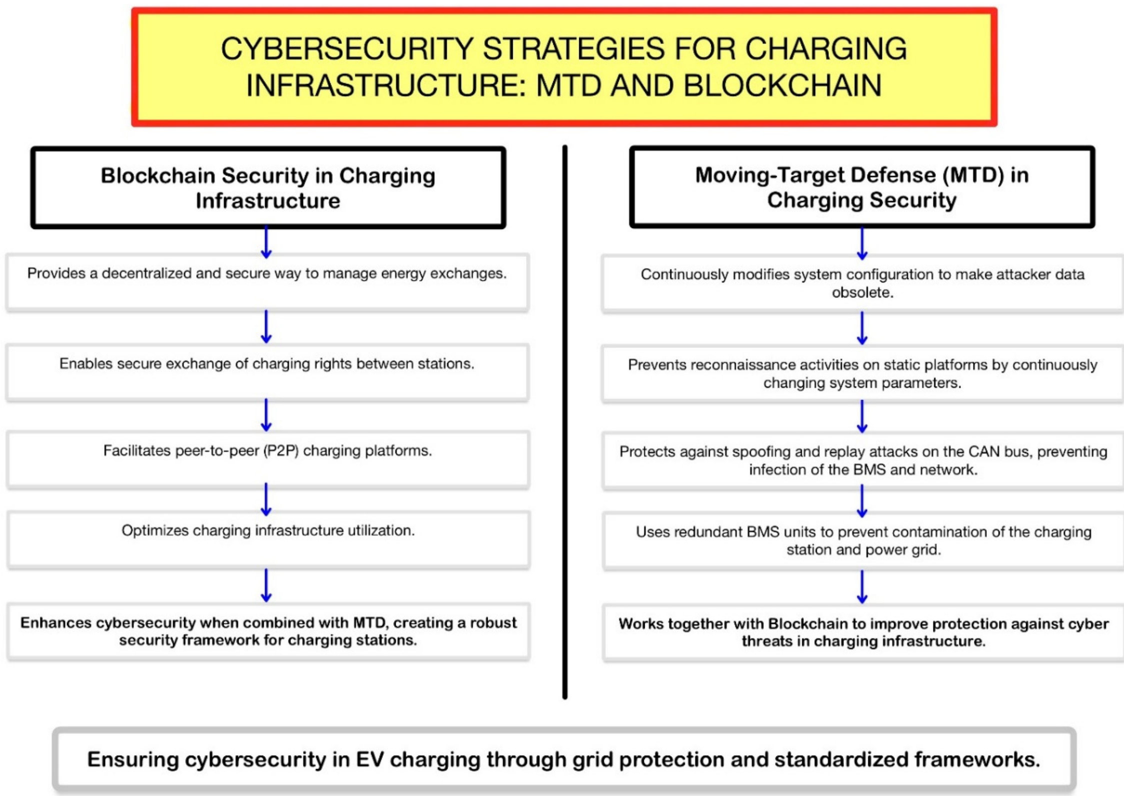

Figure 7. How blockchain security and MTD enhance cybersecurity in EV charging infrastructure.

8. Conclusions

This study conducted a comprehensive literature review on the safety of Battery Electric Buses (BEBs). The analysis started with an examination of safety tests on BEBs, covering the vehicle structure, the Rechargeable Energy Storage System (REESS), and battery packs. Key reference standards and norms were outlined, and relevant studies were summarized for each test. The review then explored BEB charging standards, covering conductive charging, inductive charging, and battery swapping, with particular attention to fast charging stations. Fast charging technology enables continuous operation, reducing the need for large onboard batteries. However, findings from the ASSURED project highlighted challenges in mitigating the adverse effects of high-power charging in electric buses. The review next addressed thermal runaway (TR), a critical safety concern for BEBs, and examined potential mitigation strategies. It identified significant gaps in fire safety regulations for buses, with particular reference to material qualification methods and the adaptation of outdated standards to electric buses. The safety of BEBs in enclosed spaces was analyzed, focusing on fire and explosion risks. In tunnels, BEBs can increase the likelihood of transitioning from deflagration to detonation, requiring effective mechanical ventilation to facilitate evacuation. BEBs were found to reduce the backlayering length, influencing ventilation efficiency. Electric bus depots were also reviewed, using the Westraven depot in Utrecht as a case study to explore safety measures. Contributions from the Li-ionFire EU Project were noted in designing fire suppression systems to enhance depot safety. Fire safety guidelines for e-bus depots, including those from NFPA and the Dutch CROW-KpVV program, were reviewed. Cybersecurity challenges in electric public transport were analyzed, focusing on denial-of-service (DDoS) attacks, which are easy to launch but difficult to mitigate. Emerging solutions like Moving Target Defense strategies and Blockchain for charging stations were briefly reviewed. Despite its importance, research on BEB cybersecurity remains in its early stages. The article also explored the potential role of Artificial Intelligence (AI) in mitigating these threats, highlighting how AI-driven security systems can enhance intrusion detection, predict cyber-attacks, and respond in real time to minimize disruptions. Finally, the review highlighted the lack of full-scale-fire test data for electric buses compared to passenger EVs, with most fire risk insights based on accident reports. This is primarily due to two factors: the high costs of experimental testing and the safety constraints and equipment requirements for full-scale tests. It concluded by emphasizing the need for further studies on BEB fire safety to address these critical gaps.

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Nomenclature

ACD	Automated Connection Device
AMT	Automated Mechanical Transmission
BEB	Battery Electric Bus
BEM	Boundary-Element Method
BEV	Battery Electric Vehicles
BMS	Battery Management Systems

CAN	Controller Area Network
DCA	Delayed Charging Attack
DDoS	Distributed Denial of Service
DSOs	Distribution System Operators
EESS	Electrical Energy Storage System
EV	Electric Vehicles
FEM	Finite Element Method
FMEA	Failure Mode and Effects Analysis
FMVSS	Federal Motor Vehicle Safety Standards
FTA	Fault Tree Analysis
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
HMA	Hazard Mitigation Analysis
HRR	Heat Release Rate
ICEB	Internal Combustion Engine Bus
ICV	Internal Combustion Vehicle
IDS	Intrusion Detection Systems
IT	Information Technology
LFP	Lithium Iron Phosphate
LSR	Least-Squares Regression
MTD	Moving Target Defense
NCA	Lithium Nickel Cobalt Aluminum Oxide
NHTSA	National Highway Traffic Safety Administration
NMC	Lithium Nickel Manganese Cobalt Oxide
PCM	Phase Change Material
RBFNN	Radial-Based Neural Network
REESS	Rechargeable Energy Storage System
TR	Thermal Runaway
V2C	Vehicle-to-Cloud
WM	Water Mist
ZEB	Zero Emission Bus

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