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Risk Analysis Of Battery Charging Approaches In Electric Vehicles: A Comparative Safety Assessment

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Abstract

As the adoption of electric vehicles continues to rise, there is a growing concern regarding the potential for battery fire accidents during the charging process. This study delves into the factors responsible for initiating battery fires in relation to various electric vehicle charging methods as home charging, public fast charging and battery swapping. The primary objective is to find the root causes of these incidents and access their consequences. Additionally, the research explores a range of proactive measures that can be employed to mitigate the risks associated with different charging approaches. The findings highlight the necessity for establishing regulations and guidelines to safeguard electric vehicle users. Ultimately, the study concludes by identifying a safer electric vehicle charging approach in terms of reliability, availability, maintenance, and cost-effectiveness, along with providing recommendations to enhance battery fire safety in electric vehicles.

Keywords: lithium-ion batteries, electric vehicles, public fast charging, home charging, battery swapping, battery safety, preliminary hazard assessment

1. Introduction

The world is moving towards a greener future to combat pollution and the harmful effects of global warming. One of the ways to achieve this is by replacing traditional vehicles with electric vehicles (EVs) that use clean and eco-friendly technology. The battery is a crucial component and the main power source for an electric vehicle. Among the various types of batteries available, lithium-ion batteries (LIBs) are the most popular choice due to their numerous advantages. They have a low self-discharge rate, a long lifespan, a high energy density, and high efficiency (W. Chen et al., 2019). Over some years, the fast advancement of LIB technology led to a major global shift in the automotive industry towards EVs. But the dangers and fire risk connected to these high energy density batteries have emerged as a significant EV safety concern (Christensen et al., 2021). Battery related safety accidents of EVs occur frequently and the annual number of incidents has been sharply rising (Gong et al., 2017). Up to 2023, popular EV maker Tesla has had 182 battery EV fire incidents, with 53 fatalities (Capulet, 2023). The majority of these accidents are associated with fire caused by thermal runaway in the EV battery pack. The primary trigger factors for thermal runaway are internal defects, mechanical, electrical and heat abuses (Zhang et al., 2021). All these factors result in internal short circuit (Ren et al., 2021) causing fire and explosion with the release of gases and chemicals.

This study compares and examines the fire hazard risk associated with different EV battery charging technologies as public fast charging, home charging and battery swapping. Several research works have been reported for understanding fire risks associated with EV battery. (P. Sun et al., 2020) reviewed fire safety hazards associated with thermal runaway of LIBs. To improve inherent safety and suppress LIB fire, (J. Sun et al., 2021) suggested use of automatic cooling, battery thermal management system (BTMS) and fire suppression agents.

A review of the literature has revealed some research gaps and observations. Below is a list of these gaps.

- Due to the high driving performance requirements, high charging speeds, inevitable traffic accidents, environmental factors, and growing energy density of battery packs, the overall fire risk and hazards of EVs are still poorly understood.
- Battery charging approach can significantly alter risk due to fire and its consequences in battery for EV applications. However, there is a lack of exclusive literature discussing the effects of various battery charging strategies on fire risk.
- To prevent EV battery fire incidents, a safer EV charging procedure is required. Research must prioritise a thorough understanding of failure mechanisms and the efficient construction of safe batteries.
- The risk and safety evaluation of new battery swapping technology is unresearched. In order to prevent fire accidents caused by battery swapping, more research is required to identify potential hazards and causal factors.

This study intends to assess the safety risks connected with various EV battery charging strategies, such as home charging, public fast charging stations, and battery swapping. In order to identify and assess the main risks connected to the system, many aspects of each system are examined in terms of hardware, function, and energy storage for each charging method. The performance of EV charging mode can vary widely based on factors including reliability, availability, maintenance, safety risks and cost. The study concludes with the identification of safer approach of EV charging to minimize risk of EV fire due to battery for overall safety. The findings of this study can support the safe adoption of EVs by assisting regulators, policymakers, battery producers, and EV manufacturers in making decisions.

2. Preliminary hazard assessment

The world is moving more and more towards EVs. Thus, it is crucial that battery charging techniques be effective, dependable, and safe. The first option that springs to mind when charging batteries is home charging, which calls for special infrastructure at home. Since fast charging infrastructure is expensive and their usage at every residence is prohibited for safety reasons, this way of charging takes longer to fully charge the vehicle. Public fast charging stations have been installed at various locations around cities or towns to enable charging in less time. Alternative to these, battery swapping is also being considered these days in an effort to bring availability up to level with traditional fossil fuel-powered vehicles and cut down on battery charge time to a few minutes. This section is the preliminary hazard assessment (PHA), which examines a few recent global EV battery fire incidents and performs preliminary hazard list (PHL) with system details for individual charging approach that is classified according to severity and frequency.

2.1. Electric vehicle battery fire accidents

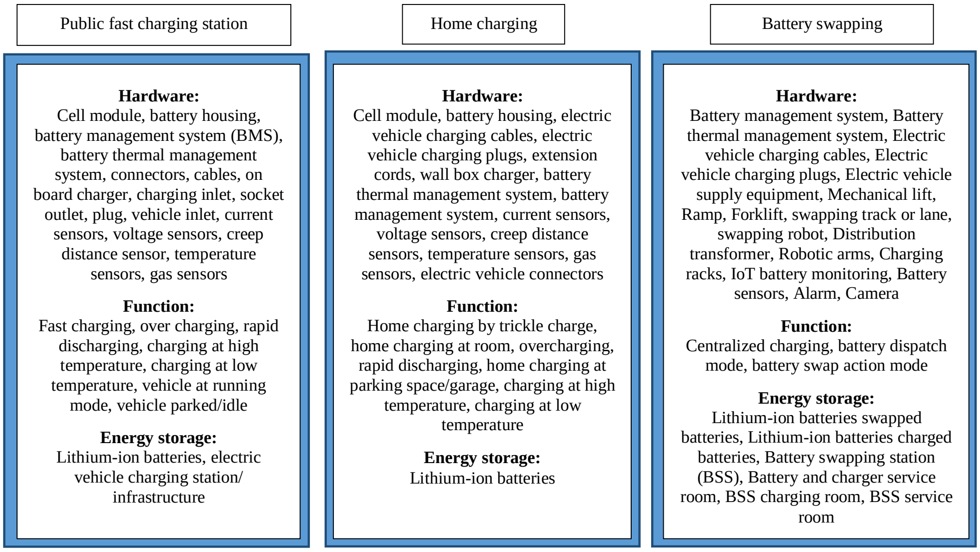
The main cause of EV fire danger is the risks connected to their battery packs. The number of EV battery fire accidents has increased, making them more noticeable. Because of the charging mode, driving performance, inescapable traffic accidents, and growing energy density of the battery pack, these fire and LIB threats are more dangerous in EVs. Table 1 lists a few recent incidents involving EV battery fires along with potential reasons for the fires. It has been noted that heat, mechanical and electric abuse, defective cells or manufacturing defects, and thermal runaway are the primary causes of battery fires.

Table 1. List of recent electric vehicle battery fire accidents

Place of accident	Year	Mode of charging	Possible cause
New South Wales (Jackson, 2023)	September 2023	Home charging	Heat abuse
Sydney (Beazley, 2023)	September 2023	Public fast charging	Mechanical abuse
New York (The Associated Press & ABC News, 2023)	June 2023	Public fast charging	Electric abuse
India (Ramasubramanian, 2023)	April 2023	Battery swapping	Faulty cells

2.2. System details

We have conducted an initial examination of PHL from the perspective of vehicle users and other affected. The goal of this investigation is to comprehend how different EV battery charging strategies affect an EV's overall safety. This analysis is performed considering the commonly available information on the types of battery charging approaches from literature, documentary report and standards on EV battery operation and safety. For every EV charging method, Figure 1 lists the key system components needed for PHL in three categories: hardware, function and energy storage.



Public fast charging station

Hardware:
Cell module, battery housing, battery management system (BMS), battery thermal management system, connectors, cables, on board charger, charging inlet, socket outlet, plug, vehicle inlet, current sensors, voltage sensors, creep distance sensor, temperature sensors, gas sensors

Function:
Fast charging, over charging, rapid discharging, charging at high temperature, charging at low temperature, vehicle at running mode, vehicle parked/idle

Energy storage:
Lithium-ion batteries, electric vehicle charging station/ infrastructure

Home charging

Hardware:
Cell module, battery housing, electric vehicle charging cables, electric vehicle charging plugs, extension cords, wall box charger, battery thermal management system, battery management system, current sensors, voltage sensors, creep distance sensors, temperature sensors, gas sensors, electric vehicle connectors

Function:
Home charging by trickle charge, home charging at room, overcharging, rapid discharging, home charging at parking space/garage, charging at high temperature, charging at low temperature

Energy storage:
Lithium-ion batteries

Battery swapping

Hardware:
Battery management system, Battery thermal management system, Electric vehicle charging cables, Electric vehicle charging plugs, Electric vehicle supply equipment, Mechanical lift, Ramp, Forklift, swapping track or lane, swapping robot, Distribution transformer, Robotic arms, Charging racks, IoT battery monitoring, Battery sensors, Alarm, Camera

Function:
Centralized charging, battery dispatch mode, battery swap action mode

Energy storage:
Lithium-ion batteries swapped batteries, Lithium-ion batteries charged batteries, Battery swapping station (BSS), Battery and charger service room, BSS charging room, BSS service room

Fig. 1. System details for individual mode of electric vehicle charging

2.3. Severity rating and frequency classification

When a battery does fail, this may have several outcomes e.g., fire or explosion. These different hazards have been classified by the European Council for Automotive Research and Development (EUCAR) (Y. Chen et al., 2021) shown in Table 2. Here thermal runaway with explosion is the most severe event. Table 3 shows frequency classification of three modes of EV charging with A as frequent, B as probable, C as occasional, D as remote and E as improbable. The risk related to fire accident is a function of the frequency of the event and the severity of its potential consequences in the form of risk category, and can be classified as critical, marginal and safe. Hazards that are identified as critical have a high likelihood of occurring and a severe consequence if they do occur. These hazards require immediate attention and corrective action. Hazards that are identified as marginal have a moderate likelihood of occurring and may have moderate to severe consequences if they occur. These hazards require attention and corrective action, but the risk may not be urgent as critical hazards. The hazards that are identified as safe have low likelihood of occurring and minimal consequences if they occur. These hazards may still require monitoring and management to maintain safety, but they do not require immediate corrective actions.

Table 2. Frequency classification for three modes of EV charging

Frequency rating	Description
A	Frequent
B	Probable
C	Occasional
D	Remote
E	Improbable

Table 3. Severity rating for three modes of electric vehicle charging based on EUCAR hazard levels

Severity Rating	Description
1 (Catastrophic)	• Thermal runaway with explosion • High odor of leaking toxic gases and chemicals • Disintegration of cells • More than 60% burn • Loss of lives and properties • Reignition of fire
2 (Critical)	• Rupture of batteries • Sparks with fire or flame • No major explosion, but flying parts of the active mass observed • Major leakage of flammable gas and chemicals • Electric shock • 30-60% burn • Loss of lives and properties
3 (Marginal)	• Passive protection activated with minor defect/damage • No major leakage or venting • No explosion • 5-30% burn. • Slight release of smoke or gas
4 (Negligible)	• No passive protection ruptures with minor defect/damage • No effect with no loss of functionality • User get bit scared but no injuries. • People nearby feel something in not right. • <5% burn.

3. Critical hazards in electric vehicle battery charging approaches

All the three above-mentioned EV battery charging approaches have benefits and challenges of their own. All approaches have the possibility to face thermal runaway leading to EV battery fire accidents. For that, proper investigation of the hazards responsible for battery triggering battery fire with respect to electric vehicle charging approaches is needed to be done. This section discusses some critical hazards associated with each battery charging approach.

3.1. Public fast charging station

There are several hazards recorded with public fast charging station. The main operational modes for this type of EV battery charging are while charging, overcharging, rapid discharging, charging at high and low temperatures, vehicle at running mode and idle state. Table 4 shows classification of hazards associated with public fast charging station.

Most critical hazards observed are due to thermal runaway, battery degradation and other defects or part failures. Fast charging at public stations can harm your electric vehicle (EV). Overcharging using the wrong charger, or charging too quickly can overheat the battery, possibly causing a dangerous situation. Charging in extreme temperatures or with a malfunctioning charger can also lead to problems. Physical damage from accidents or submerging the battery in water can result in serious issues. Additionally, charging overnight or in very cold conditions can wear out the battery faster. Problems with the charging station itself, like defects, damage, or cyber-attacks, can disrupt services and pose safety risks for EV users.

3.2. Home charging

Similar to public fast charging stations, several hazards associated with home charging are listed in Table 5. Main operating modes for home charging are charging at home and parking, overcharging, rapid discharging, charging at high and low temperature and vehicle at parking or idle.

Overcharging an electric vehicle (EV) battery at home, especially overnight, can lead to overheating, causing degradation and potential thermal runaway. Rapid discharging or using the wrong charger may also trigger overheating and dangerous situations. Exposure to high or low temperatures, inadequate battery thermal management, and faulty cooling systems can contribute to thermal runaway. Fast charging, continuous low-current charging, and calendar aging result in battery degradation, reducing overall performance. Defective wall box chargers, extension cords, and leakage in charging equipment pose risks and can damage the EV. Faulty cells, structural deformation, and foreign particles further threaten battery health. Properly calibrated BMS and BTMS are crucial for safe and efficient charging, preventing potential hazards.

Table 4. Hazards identified for public fast charging station mode of EV charging.

Operational Mode	Hazard	Failure mechanism	Risk Cat.
While charging	Battery may get short circuit due to external terminal damage leading to thermal runaway with release of toxic gas and chemicals, affecting driver and nearby travellers. (Nedelea, 2022)	Thermal runaway	Critical **(2B)**
	Battery may get separator rupture due to extrusion or puncture, which may cause fire and explosion. (Pietsch, 2021)	Thermal runaway	Critical **(1C)**
	Battery internal component failure due to swelling of electrodes leading to change in internal electrochemical properties of battery. (Saptarshi, 2021)	Battery degradation	Marginal **(4B)**
	Any leakage in battery due to excessive heat will lead to battery failure with a chance of explosion affecting lives and properties. (Lambert, 2017)	Thermal runaway	Marginal **(3C)**
	Aging of battery may change electrochemical properties of batteries and lead to poor performance with premature battery failure. (Ghosh, 2021)	Battery degradation	Marginal **(4A)**
	Prolonged charging with fast charging technology heats up the EV battery and degrades over time with rising concern of thermal runaway. (Lambert, 2019)	Battery degradation and thermal runaway	Critical **(2B)**
	Incorrect mode of charging with low current results in degradation of battery with possibility of thermal runaway. (Reporter, 2019)	Battery degradation and thermal runaway	Critical **(1A)**
	Exposure of EV connectors to water will bring defect in charging mechanism, including damage to entire battery pack. (Singh, 2019)	Part failure	Marginal **(3C)**
	Failure of charging supply equipment will result in improper flow of power through EV connectors affecting power deliverability. (Ians & Ians, 2019)	Part failure	Marginal **(3C)**
	Defect in any safety equipment in battery creates short circuit and lead to spread of fire. (Ahluwalia, 2022)	Part failure	Critical **(2B)**
	External battery sensor faults affect normal operation of BMS to read measurements for SOC estimation. (Hu et al., 2021)	Part failure	Marginal **(4A)**
	Charging at public charging stations increases cyber-attacks due to dependencies on data, software and sensors affecting coordinate operation system. (Mukherjee, 2023)	Part failure	Marginal **(3B)**
	Any manufacturing and design defect due to poor cell quality and shoddy battery design can result in short circuit. (Lekach, 2021)	Part failure	Critical **(1A)**
Overcharging	Battery may get short circuit because of exceed in current levels due to overcharge or overnight charging leading to thermal runaway. (Lambert, 2019b)	Thermal runaway	Critical **(1A)**
	Use of non-prescribed charger will cause overcharging or charger failure leading to thermal runaway. (Lambert, 2016)	Thermal runaway	Critical **(1B)**
Rapid discharging	After many cycles of complete discharge, the metallic dendrites grow between the electrodes and separators leading to accelerated battery degradation with possible chances of an internal short circuit. (Tesla, 2023b)	Battery degradation and thermal runaway	Critical **(2B)**
Charging at high temperature	Battery may lead to explosion and fire resulting from breakdown of protective SEI layer due to charging at high ambient temperature. (Parisien, 2022)	Thermal runaway	Critical **(1A)**
Charging at low temperature	Low temperature charging will lead to deposition of Li ions on to SEI layer to form dendrites, resulting cell performance by accelerated battery degradation and possibility of thermal runaway. (Paukert, 2022)	Thermal runaway and battery degradation	Critical **(2B)**
Vehicle at running mode	Any external mechanical abuse in form or accident produces localized internal heating of battery as a result of frictional heating leading to fire and explosion. (Lambert, 2016b)	Thermal runaway	Critical **(2A)**
	Collision of pedestrian and EV driver due to low noise evolution by EVs may cause external damage to EV. (Chang, 2019)	Part failure	Marginal **(4B)**
Vehicle at idle mode	Ignition of fire after EV being started to run just after being charged. (Loveday, 2020)	Thermal runaway	Critical **(1A)**
	Defect in cooling system or BTMS causes difficulty in temperature handling of battery. (Mukherjee, 2022)	Thermal runaway and part failure	Critical **(1A)**
	Tripping on charging cables at charging station due to low lighting, causes damage to supply equipment and threat when a person walks over it. (Christmas, 2017)	Part failure	Marginal **(4B)**
	While restarting EV after submerged in water for long time will result in short circuit followed by thermal runaway as water sweeps inside the battery pack and corrodes leading to fire in entire pack. (Kuttan, 2022)	Thermal runaway	Critical **(1D)**
	Calendar aging of battery takes place irrespective of charging/discharging cycle, leading to battery degradation. (Dubarry et al., 2017)	Battery degradation	Marginal **(4A)**

Table 5. Hazards identified for home charging station mode of EV charging

Operational Mode	Hazard	Failure mechanism	Risk Category
Charging at home	Improper installation of wall box charger at home may lead to thermal hazard with chances of electric shock (GOI, 2019).	Thermal runaway and part failure	Critical **(2B)**
	Explosion of battery while charging at home leading to thermal runaway with burns and death of family members. (Express Mobility Desk, 2022)	Thermal runaway	Critical **(1B)**
	Defect in the onboard charger may lead to overheating and battery degradation as there is a risk that too much current will flow into the battery from the beginning, which will heat the battery and shorten battery's lifespan. (Kumar, 2021)	Battery degradation	Marginal **(3B)**
	Leakage of current due to torn cables or faulty charging accessories will be a risk to family members at home of getting electric shock. (Villazon, 2020)	Part failure	Marginal **(2C)**
	Faults in battery sensors or improper functioning will mislead to get proper critical information that can be provided to BMS which ensures battery module protection. (Auto, 2022a)	Part failure	Critical **(2B)**
	Faults in BMS will provide incorrect reading of battery SOC after charging at home, resulting in range anxiety and frequent charging of vehicle (Veda et al., 2019).	Part failure	Critical **(3A)**
	Faults in BTMS may lead to danger of thermal runaway due to no control over rising temperature while charging at home. (India, 2022)	Thermal runaway and part failure	Critical **(1A)**
	Corrosion in EV supply equipment will lead to external short circuit with malfunctioning while charging at home. (Staff, 2019)	Part failure	Marginal **(3C)**
	Any manufacturing or assembly defect in initial state because of poor cell quality and shoddy battery design can result thermal runway while charging. (Nair, 2022a)	Thermal runaway	Critical **(2B)**
	Unavailability of electricity at home will make EV idle and of no use. Users have to depend on other charging options for instant charging of vehicle. (TIMESOFINDIA.COM, 2022)	Part failure	Marginal**(4B)**
Overcharging of battery at home	Overcharging caused dure to exceed in current levels because of use of non-prescribed charger will initiate thermal runaway with the release of toxic gas at home. (Special, 2022b)	Thermal runaway	Critical **(1A)**
Rapid discharging of battery at home	Rapid discharging or discharged state of battery for a long time leads to accelerated battery degradation with possible chances if internal short circuit resulting in thermal runaway (Ouyang et al., 2018).	Battery degradation and thermal runaway	Marginal **(3B)**
Charging at parking/garage	Battery explosion can be a result of hot temperature at parking space with chance of loss of life due to smoke inhalation and burns inside home. (Lopez, 2014)	Thermal runaway	Critical **(1A)**
	Use of unapproved extension cords for charging at parking space may result in voltage drop issues leading to fire and shock to people nearby. (Russo, 2020)	Thermal runaway and part failure	Critical **(2A)**
	Overloading of electrical system while charging at parking space which will cause the circuit breaker to trip, or in extreme case cause damage to the electrical system. (Klein, 2019)	Part failure	Marginal **(3C)**
Charging at high temperature	Charging of EV at home during summer or in tropical areas will lead to explosion and fire resulting from breakdown of protective SEI layer due to charging at high ambient temperature. (Desk, 2023)	Thermal runaway	Critical **(1A)**
Charging at low temperature	Charging of EV at home during winter or cold region will lead to deposition of Li ions on to SEI layer to form dendrites, resulting cell performance by accelerated battery degradation and possibility of thermal runaway (Zhao et al., 2022).	Thermal runaway and battery degradation	Marginal **(3C)**
Vehicle at parking/idle	Calendar aging of battery takes place while leaving the EV unplugged irrespective of charging/discharging cycle, leading to battery degradation (Dubarry et al., 2017).	Battery degradation	Marginal **(4A)**

3.3. Battery swapping

Like other two modes, different hazards for battery swapping are also listed in Table 6. Different modes for battery swapping are swap, centralized charging, battery storage, dispatch mode and vehicle at rest or idle.

Table 6. Hazards identified for battery swapping mode of EV charging

Operational Mode	Hazard	Failure mechanism	Risk Category
Swap	Negligence in health monitoring including previous swap history and present SOC level will give wrong indication of present health status, thereby leading to early battery degradation and EV failure.	Battery degradation	Critical **(2B)**
	Improper functioning of robotic arms such as fastening of bolts around battery packs may arise due to damage in the arms or the control system failure.	Part failure	Marginal **(2C)**
	Incorrect reading of camera for detecting battery location by swapping robot will lead to failure of initiation of swap action along wrong details capture of battery past swap history.	Part failure	Critical **(2B)**
	Misalignment of positioning swapped battery in place of depleted battery because of any offset or angled gap in positioning results in causing imbalance, thereby leading to battery damage as well as failure.	Part failure	Marginal **(3C)**
	Miscommunication or non-functionality of communication app between user and BSS gives wrong idea to drivers to reach BSS for swap action.	Part failure	Marginal **(3B)**
	Lack of adequate swapping infrastructure and services due to damaged swapping robots, charging cables and other accessories will lead to poor service to users along with longer charging time.	Part failure	Marginal **(4A)**
	Insufficient or unavailability of EV supply equipment at battery swapping station (BSS) will lead to poor service to customers with incomplete swap action.	Part failure	Marginal **(3B)**
	Breakage of ramp or base due to mishandling of weight of vehicle where uplifting of vehicle takes place to locate the position of batteries.	Part failure	Marginal **(2C)**
	Corrosion of mechanical lift will troubleshoot cascade forklift failure, thereby affecting swapping action performance.	Part failure	Marginal **(3C)**
Centralized charging	Damage to mechanical lift will stop the lifting action of vehicle where swapping robots will exchange depleted batteries with charged batteries.	Part failure	Marginal **(2C)**
	Damaged BMS caused due to mechanical shock, vibration, temperature fluctuations or humidity will reduce performance of battery.	Battery degradation	Marginal **(3B)**
	Overcharging by service providers at charging room of BSS will lead to fire and damage to other batteries and BSS.	Thermal runaway	Critical **(2B)**
	Broken charging plugs at BSS will lead to abnormality in charging resulting to fire at the BSS.	Thermal runaway	Critical **(2B)**
	Any mechanical damage to charging rack will trigger battery abuse leading to fire and damage to properties at BSS	Part failure	Critical **(1B)**
	Cable damage due to wear and tear in power and data transmitting cords, wires and cables will lead to electric shock and possible fire at the BSS.	Part failure	Critical **(2B)**
	As swapping robots are installed at a particular mark, incorrect marking due to slip or absence of operator will not help drivers to reach swap points to initiate swap action.	Part failure	Marginal **(3C)**
Battery storage	Improper storage of charged and discharged batteries beyond operating limit will lead to fire and damage to other batteries at BSS and result in faster degradation.	Thermal runaway and battery degradation	Critical **(2B)**
	Storage of extremely discharged batteries not in a safe operating limit will cause faster degradation of batteries due to loss of battery capacity causing loss of active materials from positive plates of batteries.	Battery degradation	Marginal **(3C)**
Battery dispatch mode	Mishandling of swapped batteries from charging room to automated swap robot will cause mechanical abuse causing thermal runaway at BSS.	Thermal runaway	Critical **(2B)**
	Poor handling of charged batteries through forklift from BSS will induce mechanical abuse due to result of any form of crush, penetration or collision leading to fire at BSS.	Thermal runaway	Critical **(2B)**
Vehicle at rest/idle	Damage to swapping robot in form of physical or damage in the mechanical body with electrical control will lead to stopping of swap action and increase in waiting time.	Part failure	Marginal **(4B)**
	Damage to swapping robot as a result of errors in manufacturing or design or assembly will affect in lowering performance of swap action.	Part failure and battery degradation	Marginal **(4B)**
	Swapped battery failure with aging as these batteries are not the new ones, which makes them more prone to accelerated degradation.	Battery degradation	Marginal **(4A)**

During the battery swapping process, the batteries must be moved from the centralized charging room to the swapping process. Mishandling of batteries during this process can lead to physical damage, which may result in battery fire. The charging racks can also be susceptible to damage during battery swapping process. If the swapping robot collides with charging racks, mechanical damage can result in possible fire or explosion. There is another risk of excessive piling up of batteries, which can cause physical damage and leakage. Therefore, swapping robot must ensure to handle a limited number of batteries at a time. The swapping robot can also present a hazard if it malfunctions or comes into contact with personnel or equipment.

4. Comparison of charging approaches

This section discusses the summary of the work with safer EV charging mode identification. Table 7 is created by comparing the safety risks associated with each mode of EV charging, taking into account the dominant failure modes identified through hazard observation.

Table 7. Comparison of safety risks for charging approaches based on dominant failure causes

	Electric abuse	Heat abuse	Mechanical abuse	Battery degradation	Other defects/Part failure	Overall safety risk
Home charging	High	High	Low	Medium	Medium	**Medium**
Public fast charging	High	High	Medium	High	High	**High**
Battery swapping	Low	Low	High	Low	High	**Low**

Various hazards exist across different modes of EV charging, including electrical, heat, and mechanical abuses, along with battery degradation and defects. Home and public fast charging stations pose a higher risk of electrical abuse due to potential issues like overcharging and use of unapproved chargers. Heat abuse is more likely in home and public fast charging due to environmental conditions. Mechanical abuse is less in home charging but a concern in battery swapping due to potential stress on batteries. Home charging usually results in slower battery degradation than fast charging, while battery swapping may lead to slower degradation due to less wear and tear. Battery swapping stations require a more complex setup but offer improved safety through controlled charging. Hazards in home and fast charging primarily involve EV fires, while battery swapping hazards are acceptable with standardized guidelines to ensure safety within the swapping ecosystem.

Comparison of reliability, availability, maintainability and safety performance of different charging approaches against cost are provided in Table 8.

Table 8. Comparison of performance attributes for different charging approaches

Charging approaches	Reliability	Availability	Maintainability	Safety risk	Cost
Home charging	Low	Medium	High	High	Low
Public fast charging	Medium	Medium	Medium	High	Low
Battery swapping	Medium	High	High	Medium	Medium

Home charging offers simplicity but has reliability issues, limited capacity, and potential for long charging times. Fast charging stations face reliability challenges and longer charging durations as batteries age. Battery swapping addresses range anxiety with high availability but requires a widespread network. Maintenance is easier for fast charging stations, while home charging and battery swapping involve complexities. Safety risks are lower in battery swapping, but potential hazards exist. Cost-wise, home and fast charging are currently more economical, while battery swapping incurs infrastructure and personnel costs, potentially offset by battery-as-a-service policies. Each approach has trade-offs, considering factors like convenience, safety, maintenance, and cost. Ultimately, the choice depends on individual needs, location, and budget.

5. Conclusion and future scope

This article emphasizes the critical importance of identifying potential hazards in EV charging approaches to mitigate safety risks and alleviate range anxiety. Comparative study of safety risks and performance attributes for different charging approaches highlights the advantage of battery swapping as a safer mode compared to home charging and public fast charging station approaches.

We identified critical hazards associated with each charging approach as battery thermal runaway, battery degradation and part failure or defects. Our study also highlights the need for rigorous safety testing protocols and the implementation of advanced safety features, such as BMS, health monitoring systems and unique identification numbers for swappable batteries. The future scope includes developing life cycle cost models for assessing battery longevity based on usage and environment, enabling appropriate charging models. Additionally, there is a focus on creating cost-effective BSS with robotic swapping and energy-efficient charging. Models will be developed to study and optimize EV battery behaviour over the life cycle, considering urban and rural density. By adopting prevention strategies and safety measures, EV manufacturers, charging station operators, regulatory authorities, and emergency response teams can effectively minimize fire hazards in EVs and promote sustainable transportation.

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