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Review Article

Electric Vehicle Technologies in the Smart Grid Era: A Comprehensive Review

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Electric vehicles (EVs) present an efficient solution for reducing greenhouse gas (GHG) emissions and enhancing grid power quality. They offer multiple advantages over traditional internal combustion engines (ICEs), including lower emissions, reduced dependance on oil, higher energy efficiency, quieter operation, zero emissions, and improved air quality by minimizing the release of toxic chemicals into the atmosphere. However, there is a lack of literature that comprehensively reviews the factors that can facilitate the assimilation of EV technology. Therefore, this paper provides a comprehensive review of EV technologies, focusing on the growth of global EV adoption and the various types of EVs, including all-EVs and hybrid EVs (HEVs). The comparative analysis of different HEV technologies is presented, covering full HEVs, mild HEVs, and plug-in HEVs (PHEVs). The paper also discusses the different classifications of HEVs based on electrification level and energy source, along with a comparative analysis of their configurations. Furthermore, the EV architecture is examined, with a specific focus on electric motors, battery management systems (BMSs), batteries, and charging technologies, including conductive and wireless charging systems. The challenges in EV charging and the associated charging standards are also addressed. The paper concludes by highlighting the need for the advancement of EV technologies and infrastructure to overcome the significant barriers to rapid EV adoption, while demonstrating how smart grid technologies enhance EV charging efficiency, grid resilience, and energy sustainability.

Keywords: battery chargers; charging infrastructure; electric motors; electric vehicles

1. Introduction

Electric vehicles (EVs) are among the cleanest and most environmentally friendly transport solutions proposed for widespread adoption globally [1]. They have significantly influenced the automotive sector. Since EVs are four times more energy efficient than gasoline-powered vehicles, a 1% increase in EV sales in a city can lower local carbon dioxide (CO_2) emissions by 0.096% and nearby CO_2 emissions by 0.087% [2]. The major issue associated with climate change and global warming is the increasing amount of greenhouse gas (GHG) emissions [3]. The growing concerns about energy security and climate change have prompted a global transition toward a more sustainable transport system. The adoption of EVs emerges as the optimal solution for mitigating GHG emissions and enhancing energy security [4–6]. It is well established that EV transition immediately reduces GHG emissions, toxic air pollution, and improves public health [7]. Motor vehicles with gasoline or diesel engines are the primary source of air pollution emissions in developing countries. In contrast, EVs do not specifically emit GHG emissions. The EVs are cheaper, safer, produce zero emissions, less noise pollution, less chances of major fire or explosions, reduced dependance on foreign oil, and integrate renewable energy sources (RESs), unlike

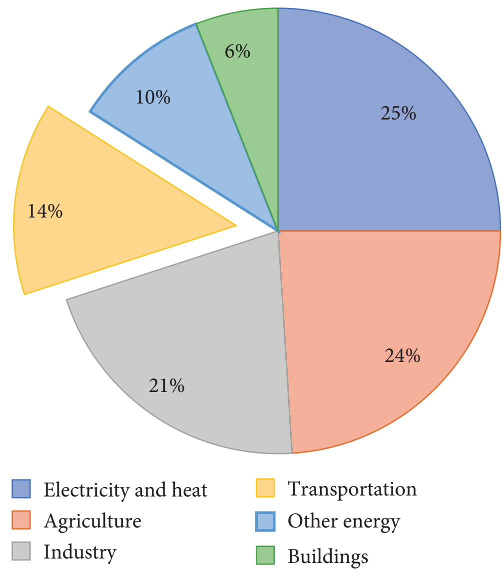


Figure 1: Global greenhouse gas emissions by economic sector.

traditional combustion engine vehicles [8]. Additionally, EVs provide better ride quality and comfort, with a very smooth drive and greater acceleration over extended distances [9].

Figure 1 illustrates the distribution of GHG emissions across various economic sectors globally. The percentages represent the contribution of each sector to the total GHG emissions. The largest contributors are electricity and heat, accounting for 25%, followed closely by agriculture at 24%, and industry at 21%. transportation, responsible for 14% of emissions, plays a significant role, while other energy and buildings contribute 10% and 6%, respectively [10]. In order to achieve net-zero GHG emissions by 2050, decarbonization efforts must be accelerated across all sectors, with a particular focus on transportation [11]. The shift to EVs is viewed as a strategic action to reduce transportation-related emissions while also realizing extra benefits within the wider context of decarbonization efforts [12].

Exponential growth of global EV sales has been identified by the International Energy Agency (IEA)'s Global EV 2023 Outlook report [13]. This annual report comprehensively analyzes global developments in electric mobility, including EV and charging infrastructure deployment, battery demand, electricity consumption, oil displacement, GHG emissions, and relevant policy advancements. According to this report, the global EV market has been growing rapidly over the past 5 years. From 2017 to 2022, EV sales have jumped from approximately 1 million to over 10 million. It took 5 years, from 2012 to 2017, for EV sales to grow from around 100,000–1 million, showing the exponential nature of EV sales growth.

Figure 2 illustrates the global sales of battery EVs (BEVs) and plug-in hybrid EVs (PHEVs) between 2014 and 2024. The most recent IEA Global EV Outlook 2025 study demonstrates remarkable advancements [14]. Sales in 2024 totaled 17.3 million, reflecting a 25% increase compared to the previous year, comprising 10.8 million BEVs and 6.5 million PHEVs. The extra 3.5 million EVs sold in 2024 surpassed total global EV sales in 2020, highlighting the market's significant growth. The increase in EV sales is attributed to various factors, including the government policies supportive of EVs, such as tax rebates, terms of subsidies, and other benefits help the EV market boost up.

In the automotive sector, the global market for EVs reached \$561.3 million in 2023, accounting for 18% of global vehicle sales, whereas it is expected to reach \$967 billion by the end of 2028 [13, 15]. According to Allied Market Research, the value of the global EV market was valued at \$163.01 billion in 2020. From 2021 to 2030, the market is expected to grow at a compound annual growth rate (CAGR) of 18.2%, reaching \$823.75 billion [16].

The technology of EVs is still facing many technological, environmental, economic, and social challenges. The technological challenges include the integration of EVs charging systems and energy storage systems (ESSs). The ESS, which is required by every EV has become one of the major technological challenges because of the availability of raw materials such as nickel, cobalt, manganese, and lithium, which must be high-grade raw materials to ensure optimal battery performance, maximize its utilization throughout its entire lifespan, and provide safe operation [17]. The socio-technical challenges include the consumer attitudes, current policies, institutions, technological infrastructure, and societal constraints [18]. The social challenges include a range of anxiety, limited range, long charging time, and insufficient charging infrastructure of EVs [19, 20]. The extraction and manufacturing processes involved in producing EV batteries have adverse environmental impacts, including pollution, habitat destruction, and carbon emissions. Moreover, the expansion of EV charging infrastructure also presents environmental challenges, demanding energy, resources, and land for the construction of new stations and associated facilities [21, 22]. Many researchers have been working on the various aspects of EVs [23–25]. However, there still exists a significant shortcoming, such as insufficient research on big data processing in EV charging facilities, limited communication methods, and poor charging infrastructure. With

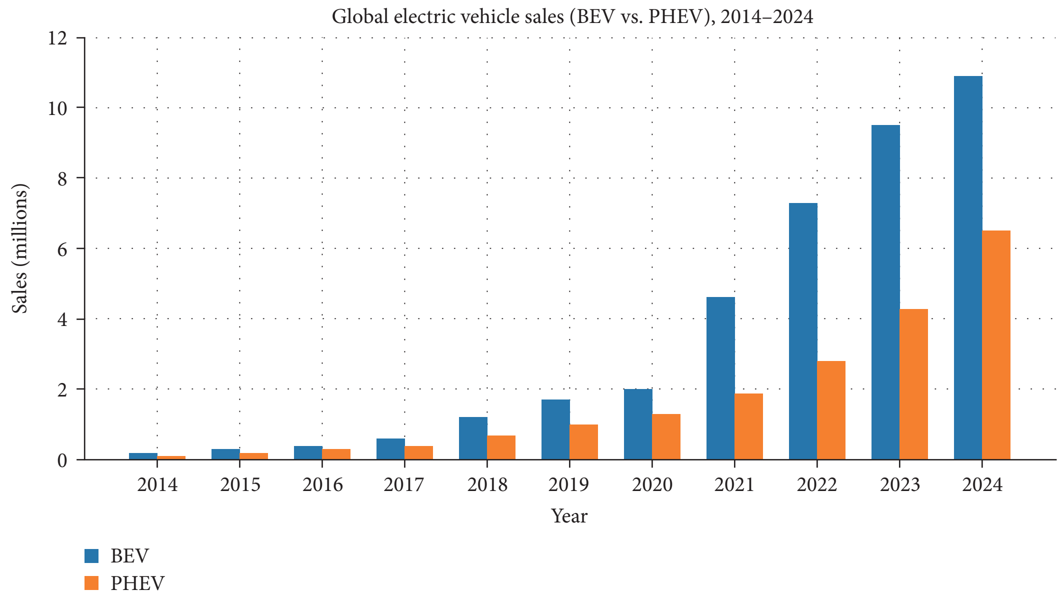


Figure 2: Global sales of EVs.

the increasing popularity of EVs, smart grids are becoming crucial for the management of EV charging and energy delivery. Smart grids facilitate bidirectional communication between EVs and the power system, balance loads, and improve grid resilience. Technologies, such as vehicle-to-grid (V2G) and smart charging mitigate peak demand strain and facilitate renewable energy integration by utilizing EVs to act as ESSs. These developments are essential for the sustainable scaling of EV utilization while facilitating global decarbonization objectives.

Previous studies have examined EV technologies from different perspectives. In [26], the authors studied the technologies and readiness levels of EVs, highlighting the technological preparedness of various EV components. However, the study did not specifically address the technological development challenges facing EVs. The authors in [19] conducted a thorough examination of essential components, technologies, and challenges related to various types of EVs. While the research gathered significant data on EVs, it did not include an analysis of the challenges in the technical development of EVs based on the collected data. The authors in [27, 28] have summarized and categorized the factors influencing the adoption of EVs by the public. They have also categorized the influential factors contributing to consumer preferences for EVs. The authors in [29] have studied the latest development in EV technology focusing on charging management strategies and smart grids, opportunities following EV development, and the impacts of EV rollout. The authors in [30] reviewed the present state, technological advancements, and future prospects related to automotive fuel cells. In [31], the authors highlighted the significance of fuel cells in decarbonization roadmaps, such as the target of selling four million fuel cell, EVSs by 2030 in the ambitious 2DS (2°) scenario outlined by IEA. Authors also addressed the higher cost of FCEVs compared to internal combustion engine (ICE) vehicles as a crucial factor impeding their widespread adoption. In [32], the authors have examined the technological advancements in EV batteries. The authors in [33] described the charging technologies, related standards, charging levels, and charging modes. The authors also stated issues and research gaps about EV chargers and charging technologies. In [34], the authors outlined the current available wireless charging technologies for EVs. The study also offers wireless transformer structures that have been investigated with a range of ferrite forms. Due to wireless power transfers (WPTs), the safety issues are also discussed with the current development in international standards. The authors also investigated developing technologies and conducted simulations utilizing the finite element method. However, despite these studies offering a comprehensive analysis of EV development, the technology of EVs is emerging quickly. Therefore, the main contributions of this paper focus on the following three aspects. First, it discusses the recent EV technologies, presenting a comparison study and classifications. Second, it thoroughly examines EV architecture, including electric motors, battery management systems (BMSs), batteries, and charging technologies, including conductive and wireless charging. It also addresses challenges in EV charging. Finally, it summarizes the EV charging standards.

The rest of this paper is organized as follows: in Section 2, a discussion of EV technologies is covered, along with a comparison study and classifications. Section 3 focuses on EVs' architecture, covering electric motors, BMSs, Batteries, and charging technologies, including conductive charging and wireless charging, along with a discussion on challenges in EV charging. EV charging standards are covered in Section 4. Finally, Section 5 concludes the paper by summarizing key findings and proposing directions for future research in the evolving landscape of EVs.

2. EV Technologies

The adoption of EVs requires highly efficient technologies and enhanced EV infrastructure. Currently, EVs are classified into

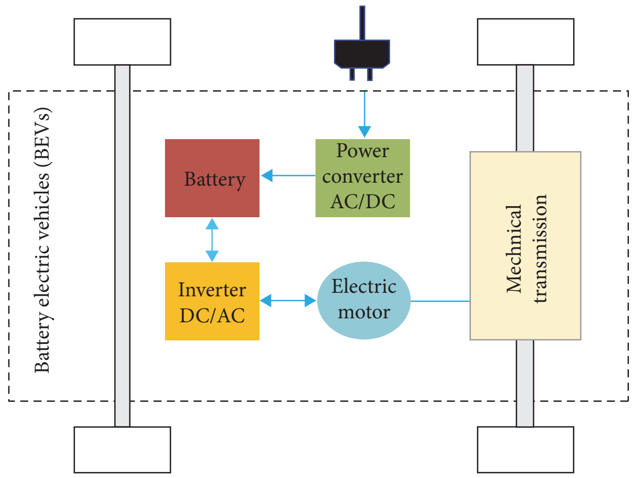


Figure 3: Schematic diagram of battery electric vehicles.

four types, which are BEVs, fuel cell EVs (FCEVs), hybrid EVs (HEVs), and PHEVs [35]. The BEV is a vehicle that relies solely on the chemical energy stored in rechargeable battery packs for propulsion [36]. Whereas, the PHEVs run on electric batteries and fuel, which integrate an electric motor with an ICE. It is capable of generating electricity through regenerative braking, and it can also be charged with an external EV charger [1]. The HEVs are same as PHEVs, but they cannot be plugged in and charged with an external EV charger [37]. FCEVs offer a clean and efficient alternative to traditional ICEs. Powered by hydrogen, they generate electricity through a fuel cell and battery combination, resulting in zero harmful emissions and superior energy efficiency [38]. The most used vehicles currently are the ICE, whereas EVs accounted for 14% of the global car sales in 2022 [13]. In this section, various types of EVs are investigated and compared to assess their respective advantages in the advancement of a more sustainable and environmentally friendly transportation future.

2.1. All-EVs. All-EVs, often called EVs or BEVs, do not rely on gasoline and are powered by a large battery that drives one or more electric motors. Presently, these vehicles offer a driving range of 200 to over 300 miles on a fully charged battery, depending on the model [39]. This range continues to expand with the introduction of new models. It does not contain an ICE and does not rely on fossil fuel. All-EVs do not release any harmful emissions, in contrast to traditional gasoline-powered vehicles. These vehicles are categorized into BEVs and FCEVs.

2.1.1. BEVs. BEVs utilize batteries as their primary source of energy. They can be charged through two different methods: by plugging in or through regenerative braking. Figure 3 shows the schematic diagram of the BEVs. These vehicles do not contain an ICE and do not rely on fossil fuel. To recharge the batteries, the electric motor can operate as a generator by converting the kinetic energy into electric energy while braking. While in operation, these cars don't release any pollution into the environment. Additionally, when electricity is generated using RES, its environmental benefits increase [40].

The main advantage of BEVs is that they can reduce GHG emissions [41]. Additionally, they have lower service maintenance and repair costs, higher energy efficiency, lower maintenance frequency, faster acceleration, and noiseless and emission-free operation compared to the ICE vehicles. Furthermore, they are very cost-efficient in the long term of ownership, and they are very safe to drive [42]. One of the biggest disadvantages of BEVs is their higher purchase prices compared to ICE vehicles. Additionally, owning an EV car comes with challenges, such as the need for an established charging infrastructure, longer charging times in comparison to refueling ICE vehicles. Other concerns include battery life, an inadequate network of charging stations, and the necessity for travel planning [43].

In 2022, there were about 18 million BEVs in use worldwide. In that year, the global fleet of BEVs increased by about 7.3 million, a consistent increase since 2016, as Figure 4 illustrates [44]. It is also demonstrated that the adoption of BEVs has increased considerably, indicating a significant shift in the global automotive landscape toward EVs. A growing acceptance and integration of electric mobility solutions is reflected in the continuous increase in the number of newly added BEVs, highlighting the growing significance of environmentally friendly and sustainable transportation options.

2.1.2. FCEVs. FCEVs utilize hydrogen gas to run an electric motor. The fuel cell transforms energy stored as hydrogen into electricity [38]. Those vehicles have higher efficiency than conventional ICE vehicles and do not produce any harmful emissions [45]. They release water vapor and warm air. FCEVs use advanced efficiency-enhancing technology, such as regenerative braking systems, to capture and store the energy lost during braking in a battery [46]. Figure 5 shows the design diagram of the FCEVs. FCEVs exhibit an operational range of 300–400 miles on a single tank and can be replenished in approximately 10 minutes at hydrogen fueling stations [47]. FCEVs and the hydrogen infrastructure to power the fuel them are in the early stages of deployment [45]. FCEVs can serve as mobile and adaptable power generators during periods of parking.

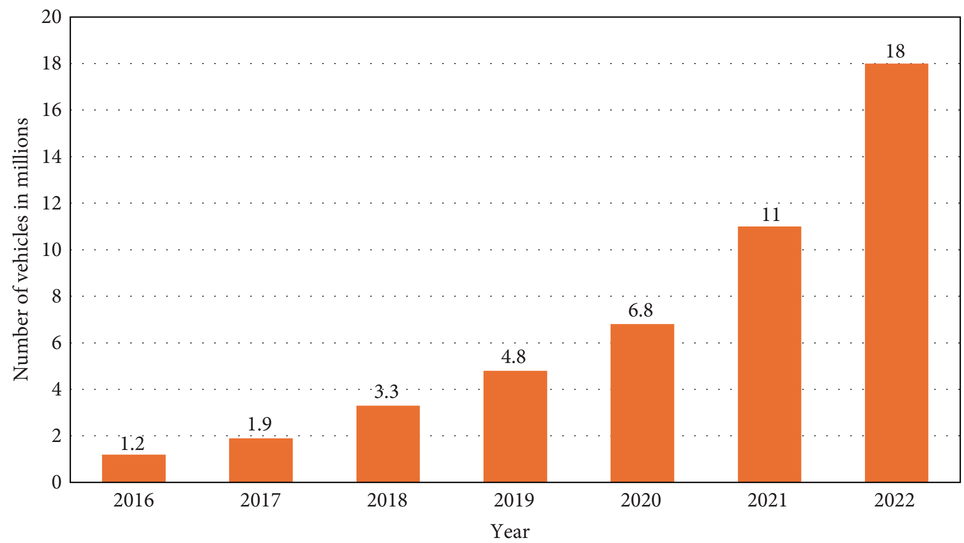


Figure 4: Worldwide number of battery electric vehicles in use from 2016 to 2022.

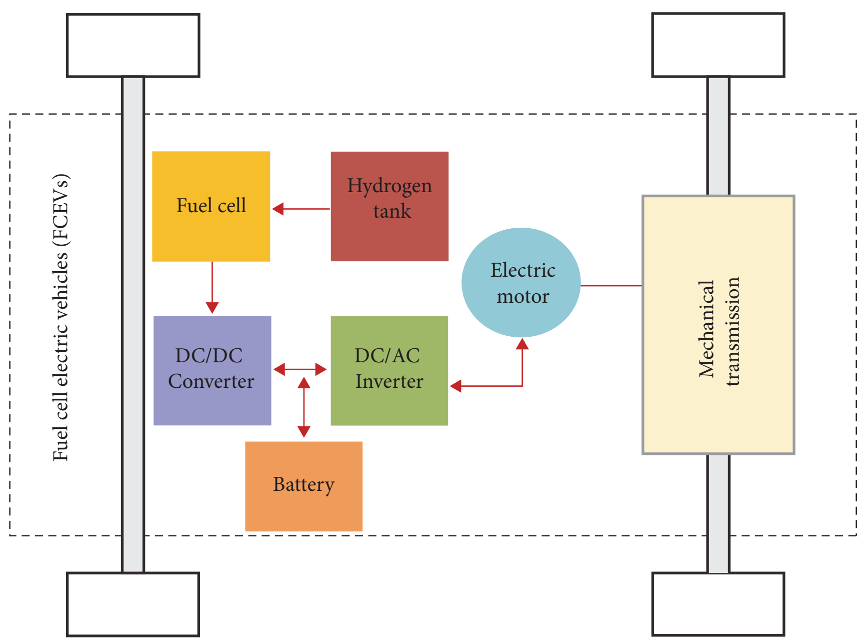


Figure 5: Schematic diagram of fuel cell electric vehicles.

Consequently, FCEVs have the potential to play an important role in a future energy system by meeting mobility requirements and simultaneously supporting the heat and electricity sectors [48].

Low-temperature fuel cells, such as proton exchange membrane fuel cells (PEMFCs), are commonly used for automotive applications [49]. They rely on pure hydrogen and oxygen from the air, necessitating vehicles or recharging stations to be equipped with hydrogen tanks. Hydrogen storage pressure and tank volume are critical safety considerations. A major problem with fuel cells is their slow transient response, which is incompatible with the high slew rate and pulsed currents that are common in the applications that are being considered [50]. Oxygen starvation or flooding phenomena may occur if the necessary amounts of hydrogen and oxygen are not readily available to meet the instantaneous current demand [51].

According to data from the IEA's latest Global EV Outlook 2023 report, the number of FCEVs on the world's roads grew by 40% in 2022 compared to 2021, totaling more than 72,000 vehicles [13]. This significant increase in the use of FCEVs shows the technology's growing significance in the global automotive landscape and is a significant move in the direction of alternative and sustainable propulsion systems.

2.1.3. Comparative Analysis of All-EVs. Table 1 provides a comprehensive comparative analysis of different full EVs.

Table 1: Comparative analysis of different full electric vehicles.

Term	Battery electric vehicles (BEVs)	Fuel cell electric vehicles (FCEVs)
Energy source	• Electricity stored in a battery	• Hydrogen gas stored in a tank (chemical reaction between hydrogen and oxygen in the fuel cell)
Refueling/charging	• Plugged into an electric grid	• Filled with hydrogen at a station (similar to gasoline)
Range	• Typically 250–400 miles per charge	• Can reach 300–400 miles on a single fill
Refueling/charging time	• 30 min to several hours, depending on charger type	• 5–10 min, similar to gasoline vehicles
Emissions	• Zero tailpipe emissions, but emissions depend on electricity source	• Zero tailpipe emissions, only water vapor produced
Cost	• Lower cost than FCEVs	• Higher cost than BEVs due to complex fuel cell technology
Maintenance	• Generally lower maintenance costs	• More complex technology could lead to higher maintenance costs
Infrastructure	• Widely available charging infrastructure	• Limited hydrogen refueling stations
Environmental impact	• Battery production and disposal have environmental concerns	• Hydrogen production and transportation can have environmental impact
Popular cars	• Tesla Model 3 • Hyundai Ioniq 5 • Kia EV6	• Hyundai Nexo SUV • Toyota Mirai • Riversimple Rasa

Each category is compared based on key parameters, such as energy source, refueling/charging, range, refueling/charging time, emissions, cost, maintenance, infrastructure, and environmental impact.

BEVs derive their energy from electricity stored in a battery, a technology that has become increasingly popular due to its simplicity and familiarity. These vehicles are charged by being plugged into an electric grid, allowing for flexibility in terms of charging locations, which can range from home charging stations to public charging infrastructure.

In terms of range, BEVs typically offer between 250 and 400 miles on a single charge, catering to the needs of various drivers. However, the charging time can vary significantly, taking anywhere from 30 min to several hours depending on the type of charger used. This range and charging time make BEVs suitable for daily commuting and shorter trips, although the charging infrastructure continues to improve, enhancing the viability of longer journeys. One of the main advantages of BEVs is their minimal emissions, as they produce zero tailpipe emissions during operation. However, it is essential to consider that the overall environmental impact may depend on the source of electricity used for charging. The cost of BEVs is generally lower than FCEVs, making them more available to a wider range of consumers.

In contrast, FCEVs utilize hydrogen gas stored in a tank as their primary energy source. The unique feature of FCEVs lies in the chemical reaction between hydrogen and oxygen in the fuel cell, generating electric power to drive the vehicle. Refueling FCEVs is comparable to the traditional gasoline-filling process, taking around 5–10 min. However, the availability of hydrogen refueling stations remains a limiting factor, constraining the practicality of FCEVs in certain regions. FCEVs are known for their impressive range, typically reaching 300–400 miles on a single fill of hydrogen. The quick refueling time and extended range make FCEVs suitable for drivers who prioritize longer-distance travel and seek a refueling experience similar to that of conventional vehicles. Similar to BEVs, FCEVs produce zero tailpipe emissions during operation, with water vapor being the only byproduct. However, the environmental impact may arise during the production and transportation of hydrogen, highlighting the importance of considering the entire lifecycle of the vehicle. The cost of FCEVs is generally higher than that of BEVs, primarily due to the complexity of fuel cell technology. This factor, coupled with the limited hydrogen refueling infrastructure, contributes to the comparatively lower adoption rate of FCEVs in the market.

2.2. HEVs. HEVs are powered by an electric motor as well as an ICE. The electric motor is powered by energy stored in batteries. The battery is charged through an ICE and regenerative braking. Typically, in traffic electric motor alone powers the vehicle using the power stored in batteries, whereas at high speeds or on highway cruising, the ICE powers the vehicle [52]. This mechanism increases fuel efficiency and reduces carbon emissions, which is the main positive point of these vehicles. The drawbacks of HEVs are that these vehicles can be expensive to buy and maintain because they have an ICE, electric motor, and batteries, which are very expensive. On long-term ownership, these vehicles are very cost-efficient and reliable [53]. HEVs can be divided into two categories according to the electrification level and based on the type of

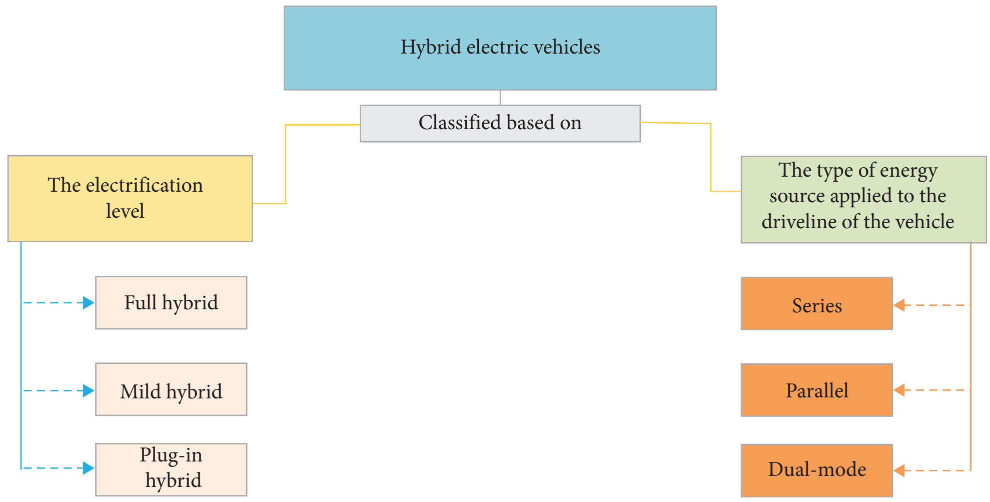


Figure 6: Classifications of hybrid electric vehicles.

energy source applied to the driveline of the vehicle, as shown in Figure 6 [54]. The following subsections explain these classifications of the HEV.

2.2.1. HEVs Classifications Based on the Electrification Level. The HEV's electric and combustion systems are ranked according to their degree of hybridization. The significance of the electric system increases with the degree of hybridization. When a hybrid car reaches a significant percentage of hybridization, the amount of electric component is increased. In other words, as the rate of hybridization increases, the environmental effect decreases, but the complexity of the vehicle system rises until a heat engine is no longer necessary. The sections that follow provide details on this categorization approach.

2.2.1.1. Full HEVs. A full hybrid electric car, also known as a self-charging hybrid, utilizes both a combustion engine and an electric motor to drive, either simultaneously or independently [55]. While they are the most prevalent type of hybrid vehicle, their battery size limits the amount of electric charge they can hold. Consequently, they can only cover short distances, typically up to a mile, on electric power alone, suitable for shorter urban journeys. When the combustion engine engages, full hybrids have sufficient power to cover longer distances, providing a total driving range comparable to regular petrol or diesel vehicles. This makes them an optimal choice for long-distance drivers. Full hybrid electric cars also incorporate regenerative braking to enhance efficiency. Unlike traditional cars, where kinetic energy is wasted during deceleration, regenerative braking in hybrids converts kinetic energy into electricity, storing it in the battery [56]. This feature contributes to their fuel efficiency, particularly in urban driving scenarios.

2.2.1.2. Mild HEVs. Similar to full hybrids, mild hybrids integrate an electric motor alongside a combustion engine. However, in contrast to full hybrids, mild hybrids cannot solely run on electric power. Instead, their smaller electric motor, directly connected to the engine or transmission, delivers a power boost during acceleration, improving efficiency. The main differences between mild and full hybrid vehicles are the system voltage and system power. Full hybrids can operate for extended periods on electric power, while mild hybrids typically have limited electric driving ranges. However, recent advancements suggest the possibility of increasing electric range in mild hybrid systems [57].

Mild hybrids represent a cost-effective hybrid solution for owners. Similar to full hybrids, they deliver enhanced fuel efficiency and reduced emissions compared to conventional nonhybrid vehicles [58]. These hybrids are gaining popularity as a way to enhance the performance of standard petrol and diesel engines, particularly in response to stricter emission standards. In terms of the driving experience, mild hybrids offer a driving feel similar to traditional nonhybrid cars [59].

2.2.1.3. PHEVs. In the PHEV, the primary energy source is still the combustion fuel engine. There are two sources to power the vehicle, which is the electrical motor and the ICE. The batteries, which store electricity, can be charged through a plug and subsequently supply power to the electric motor when required [60]. A plug-in hybrid is an advanced version of a full hybrid. They are equipped with a larger battery compared to full hybrids; they have the capability to cover significantly longer distances using electric power alone, typically ranging from 15 to 50 miles depending on the specific model [61]. The vehicle's overall efficiency is increased through the use of an electric motor and battery. While braking, the electric motor operates as a generator, recharging the battery. Even in hybrid mode, PHEVs utilize less fuel and generate less pollution than conventional ICE due to the assistance of their electric motor and battery [62]. Smaller engines can be used with the electric motors, which increases the fuel efficiency of the EVs, and this does not compromise the performance of the vehicles.

PHEVs have several benefits, including being more fuel-efficient, having fewer emissions, and being environmentally friendly [63]. The drawbacks of plug-in hybrid cars are expensive as they have an engine and electric motor. Furthermore, plug-in hybrid vehicles deliver a lot less power. Compared to other car types, the maintenance cost of these vehicles is slightly higher because they have two power sources.

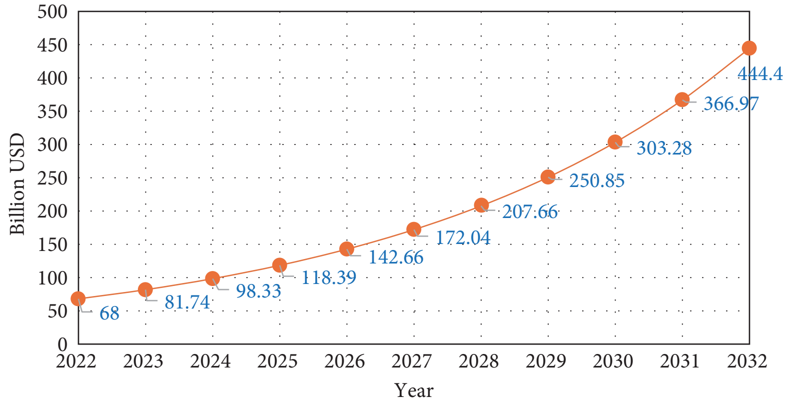


FIGURE 7: Hybrid electric vehicles market size from 2022 to 2032 in billon USD.

2.2.1.4. Comparative Analysis of the Different HEVs Based on the Electrification Level. The HEVs incorporate both an electric motor, utilizing energy stored in batteries, and an ICE. The diverse technologies employed in HEVs offer various benefits. Due to the rise in petroleum prices around the world, automakers have introduced new technologies for hybrid vehicles, which are now considered as an important role of the future of the automotive industry.

The hybrid vehicles market is experiencing an increase in popularity, with a CAGR of 20.7% from 2018 to 2022 and projected growth of 21.6% through 2033. This year's particularly strong increase can be attributed to global government initiatives aimed at reducing emissions in the transportation sector [64]. Figure 7 illustrates the projected advancement of the HEVs market from 2022 to 2032. According to the forecast, gasoline hybrids are set to dominate, exceeding US$130 million by 2032. Meanwhile, stored electricity HEVs are expected to experience slower but steady growth with a CAGR of 6%. Regionally, the U.S. is expected to lead the pack with a CAGR of 8.2% through 2032. In 2022, Europe accounted for 19.20% of revenue share, while Asia Pacific held a substantial 42% [65].

Table 2 presents a comparison of the three HEV types. It delves into their engine and electric motor configurations, fuel consumption and emissions levels, cost and charging requirements, system voltage and electric-only driving range, battery capacity, and overall technology complexity. Additionally, it highlights the driving experience and ideal scenarios for each type, even popular car models within each category.

2.2.2. HEVs Classifications According to the Type of Energy Source Applied to the Driveline of the Vehicle. The main parts of an HEV are an electric motor, battery, converter, ICE, fuel tank, and control board. The various ways and sizes in which these components can be integrated lead to variations in the design of vehicles. Drivetrains, categorized as parallel, series, and dual-mode designs, vary based on how these components are integrated.

2.2.2.1. Parallel Configuration. Similar to conventional cars, the engine of a parallel HEV provides propulsive torque directly to the wheels to drive the vehicle. In order to increase the engine's power output, an electric motor that runs on a battery pack is also mechanically connected to the driveline. The torque that is produced by the engine and motor is combined and delivered to the wheels via a mechanical coupler [66]. This HEV is among the most popular on the market because of its special features, which include increased efficiency for extended driving distances and increased switching flexibility between ICEs and electric motors. The main advantage of this system is that it only needs a small battery backup, which lowers the total cost, and that it charges the battery both when the engine is operating and during regenerative braking [67]. However, because of their complicated hybrid drivetrain, parallel hybrids can be more expensive than conventional gasoline-powered cars and may require additional maintenance [68]. The design diagram for a parallel HEV is shown in Figure 8.

2.2.2.2. Series Configuration. In a series HEV, both the electric motor and the ICE directly propel the driveline. This configuration is employed for charging the battery and supplying power directly to operate the motor, as illustrated in Figure 9. Series HEVs typically utilize traction motors to propel the vehicle independently, while the ICE is linked to a generator [54]. The engine in this configuration does not provide propulsive torque to drive the vehicle. The primary purpose of this engine is to convert fuel potential energy into mechanical energy, which a generator can then convert this energy into electrical energy. An inverter is utilized to drive the motor using the electrical energy [66]. Since the electric motor operates as the vehicle's primary power source, series hybrids often achieve higher fuel efficiency than parallel hybrids. They are a good option for drivers who drive a lot in cities because they also typically have a longer electric-only range than parallel hybrids. However, series hybrids might not match the performance of parallel hybrids and may come with a higher cost. The main drawbacks of this arrangement are the dual power conversions, from electric to mechanic in the motor and from mechanic to electric in the generator, and the size of the electric machine attached to the output shaft [69].

2.2.2.3. Dual-Mode Configuration. Dual-mode HEV, also referred to as series–parallel (SP) EV or power-split HEV, combines the characteristics of both series and parallel hybrids. The driveline architecture of the dual-mode HEV is illustrated

Table 2: Comparative analysis of different hybrid electric vehicles based on the electrification level.

Term	Full hybrid	Mild hybrid	Plug-in hybrid
Description	• Combines an electric motor with a gasoline engine, seamlessly switching between them for optimal fuel efficiency	• Small electric motor integrated with engine, boosting power and improving efficiency with stop–start/regenerative braking	• Combines large battery and gasoline engine for extended electric driving
Engin and motor	• Gasoline + electric motor	• Gasoline + small electric motor	• Gasoline + large battery and electric motor
Fuel consumption	• Significantly lower than conventional vehicles, especially in urban driving	• Slightly lower than conventional vehicles, primarily benefits from engine stop–start and regenerative braking	• Significantly lower than conventional vehicles, can achieve near electric-only consumption on short trips
Emissions	• Lower than conventional vehicles, especially in urban driving	• Lower than conventional vehicles, but emissions occur even during electric-only driving due to electricity generation	• Lowest of all HEVs, can achieve near zero emissions on short trips
Cost	• Higher than conventional vehicles and mild hybrid EVs, due to larger battery and electric motor	• Lower than plug-in hybrid EVs, but slightly higher than conventional vehicles	• Highest of all HEVs, due to larger battery and electric motor
Charging	• No external charging required • Regenerative braking and gasoline engine	• No external charging required • Regenerative braking only	• Requires regular external charging to maximize electric range and fuel efficiency • Regenerative braking and external charging
System voltage	• High (typically 200 V or more)	• Low (typically 12 or 48 V)	• High (typically 300 V or more)
Electric-only driving:	• Can drive for several kilometers on electric power alone	• Only for short distances or stop-and-go traffic	• Can drive for several dozen kilometers on electric power alone
Battery capacity	• Large	• Small	• Large (chargeable)
Fuel efficiency	• High	• Moderate	• High (combined), lower when battery depleted
Technology complexity	• High	• Low	• High
Driving experience	• Smooth, seamless transition between electric and gasoline modes	• Similar to ICE vehicles, but with potential for slightly improved fuel efficiency and acceleration	• Similar to HEVs, but with potential for additional electric-only driving
Best suited for	• Lower mileage or urban drivers	• Short commutes, stop-and-go traffic	• Long commutes, frequent electric charging
Popular cars	• Honda Civic • Kia Niro • Hyundai Tucson	• Kia Sportage • Nissan Qashqai	• Hyundai Santa Fe • Volvo XC60 Recharge

in Figure 10. The term dual-mode does not define a distinct classification but rather signifies an operational approach within the power-split hybrid architecture. It describes the vehicle's capability to dynamically transition or optimize between series and parallel hybrid modes in response to varying driving conditions, enhancing efficiency and performance.

Dual-mode power-train configurations combine the advantages of series and parallel hybrid powertrain designs. These configurations can be adapted to a range of operating environments, enhancing system performance [70]. Depending on the driving situation, their controller chooses between either of them. Electric propulsion or series ICE-assisted operation is ideal for low-speed and low motive power requests; parallel operation is used in other cases, taking advantage of a mechanically efficient coupling between the ICE and the wheels, possibly via a simplified (or even single-speed) gearbox. As a result of the multiple energy conversions that occur in a series operation, the parallel operation is more efficient, especially when traveling at high speeds [71]. However, the high price of these vehicles is a drawback since they are more complex due to the combination of parallel and series systems.

2.2.2.4. Comparative Analysis of the Different HEV Configurations. Table 3 presents a comparative analysis of the three HEV configurations: series, parallel, and SP. It delves into various aspects, including engine and motor configuration, fuel efficiency, emissions, cost, electric-only driving range, performance, technology complexity, driving experience, and suitability for different driving scenarios. Each configuration is assessed for its strengths and weaknesses. Additionally, popular

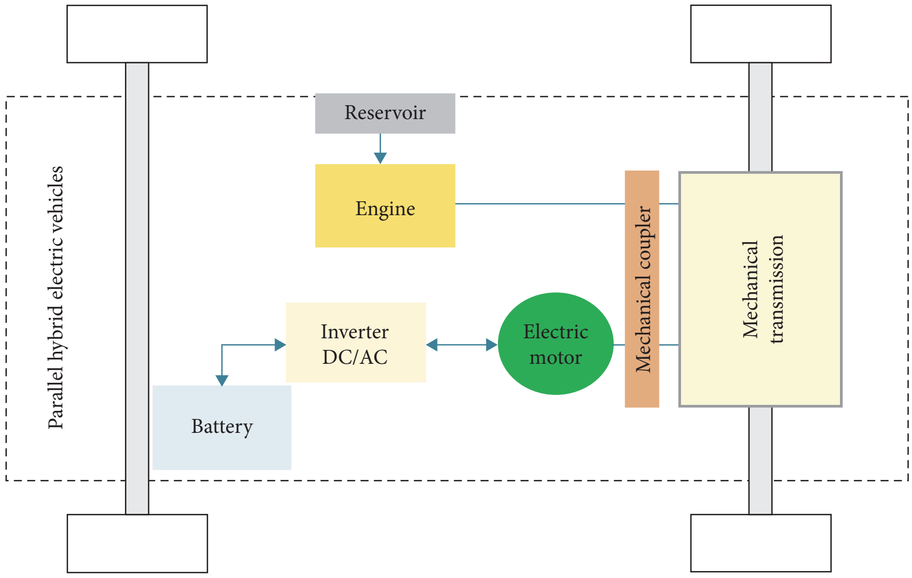


FIGURE 8: Schematic of parallel hybrid electric vehicle.

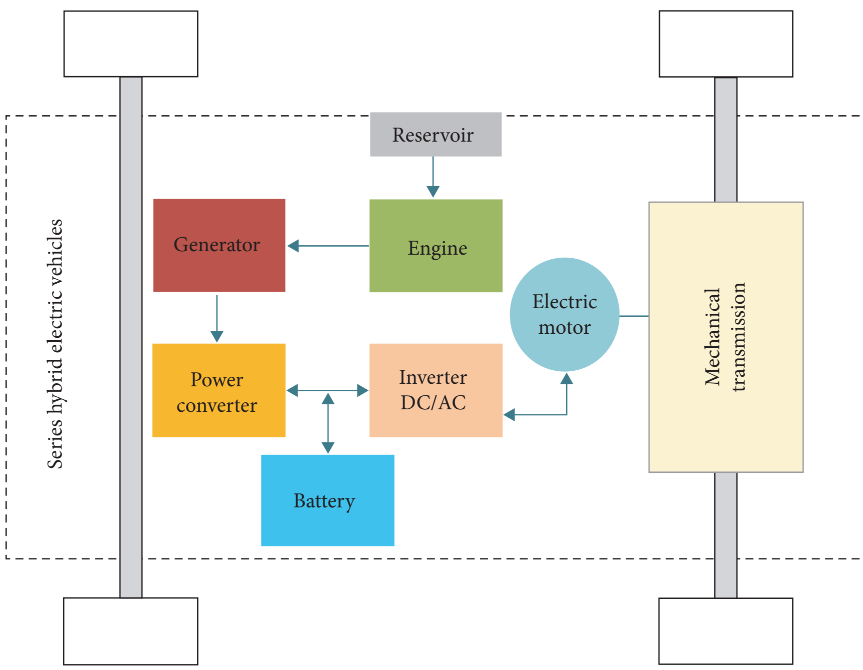


FIGURE 9: Configuration of series hybrid electric vehicle.

car models associated with each configuration are listed for reference and consideration.

2.3. Comparative Analysis of Different Vehicle Technologies. Table 4 provides a comparative analysis of the three different car technologies: ICE, hybrid, and full electric. Each technology is compared based on various criteria, offering a comprehensive overview of its engine type, fuel efficiency, emissions, cost, electric-only driving capability, performance, charging methods, maintenance requirements, driving experience, and suitability for different types of drivers.

ICE vehicles, powered by conventional gasoline or diesel engines, have long been a staple in the automotive industry. Known for their familiarity and straightforward operation, ICE vehicles offer moderate fuel efficiency. While they present a cost-effective option for drivers prioritizing affordability and conventional performance, they are associated with higher CO_2 and pollutant emissions compared to their hybrid and EVs. Hybrid vehicles, characterized by a combination of a gasoline engine and an electric motor, represent a bridging of traditional and electric technologies. Hybrids achieve high fuel efficiency, especially in urban driving conditions, making them attractive

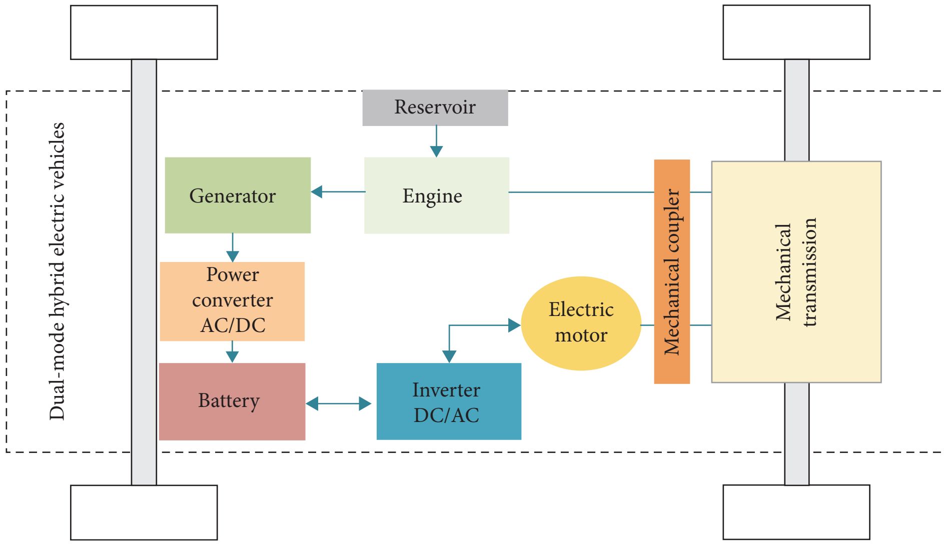


FIGURE 10: Configuration of dual-mode hybrid electric vehicle.

TABLE 3: Comparative analysis of different hybrid electric vehicles based on the vehicle configuration.

Term	Series configuration	Parallel configuration	Series–parallel configuration
Engine and motor configuration	• Gasoline engine powers generator, electric motor powers wheels	• Gasoline engine and electric motor power wheels independently	• Gasoline engine can directly power wheels or power generator, electric motor powers wheels
Fuel efficiency	• Highest in urban driving due to engine operating at optimal efficiency	• Good in urban and highway driving, can vary depending on electric motor size and usage	• High in all driving scenarios
Emissions	• Lowest in urban driving due to engine operating at optimal efficiency	• Higher than series hybrids due to engine involvement, lower than conventional vehicles	• Varies depending on mode, can be low during electric-only driving and higher during engine use
Cost	• Highest due to larger electric motor and double conversion process	• Lower than series hybrids due to simpler technology	• Highest due to most complex technology
Electric-only driving	• Longest due to dedicated generator and large battery	• Limited, primarily for stop-and-go driving	• Varies depending on mode, can have both extended electric-only range and direct engine power
Performance	• Limited due to lack of direct engine connection to wheels	• Good due to both engine and motor power	• Strongest due to ability to use both engine and motor directly
Technology complexity	• High	• Moderate	• Very high
Driving experience	• Smooth and quiet, seamless transition between electric and engine modes	• Similar to conventional vehicles with potential for improved fuel efficiency and acceleration	• Combination of series and parallel modes, offering both quiet electric driving and powerful engine performance
Best suited for	• City driving, prioritizing fuel efficiency and eco-friendly driving	• Balanced mix of city and highway driving, seeking efficiency, and performance	• Drivers seeking the best of both worlds, high efficiency, strong performance, and extended electric range
Popular cars	• Chevrolet Volt • BMW i3 REX • Fisker Karma	• Honda Insight • Hyundai Tucson Hybrid • Hyundai Ioniq • BMW X5 530e.	• Toyota Prius • Lexus CT 200 h • Ford Fusion Hybrid • Toyota RAV4

Table 4: Comparative analysis of different car technologies.

Term	Internal combustion engine (ICE)	Hybrid	All-electric
Engine type	• Gasoline or diesel	• Gasoline + Electric motor	• Electric motor (powered by battery)
Fuel efficiency	• Moderate	• High, especially in urban driving	• Very high
Emissions	• High CO_2 and pollutants	• Reduced CO_2, tailpipe emissions only from gasoline	• Zero emissions
Cost	• Lower	• Higher than ICE	• High, due to large battery
Electric-only driving	• None	• Up to several dozen miles	• Unlimited (dependent on battery range)
Performance	• Varies, typically good	• Varies, good or prioritized for efficiency	• Varies, can be strong but often prioritized for efficiency
Charging	• Refueling with gasoline or diesel	• Regenerative braking and external charging	• External charging at stations or home and regenerative braking
Maintenance	• Relatively simple and affordable	• More complex than ICE	• Requires regular battery checkups
Driving experience	• Familiar	• Smooth and quiet transitions	• Smooth and quiet
Best suited for	• Drivers who prioritize affordability and performance	• Drivers who prioritize high fuel efficiency and eco-friendliness	• Drivers who prioritize zero emissions and convenient charging infrastructure
Popular cars	• Hyundai Elantra • Mazda 3 • Subaru Impreza • Honda Civic	• Renault Clio • Toyota Corolla • Kia Sportage • Dacia Jogger Hybrid	• Mercedes-Benz EQS • Hyundai Ioniq 5 • Tesla Model 3 • Volkswagen ID.4

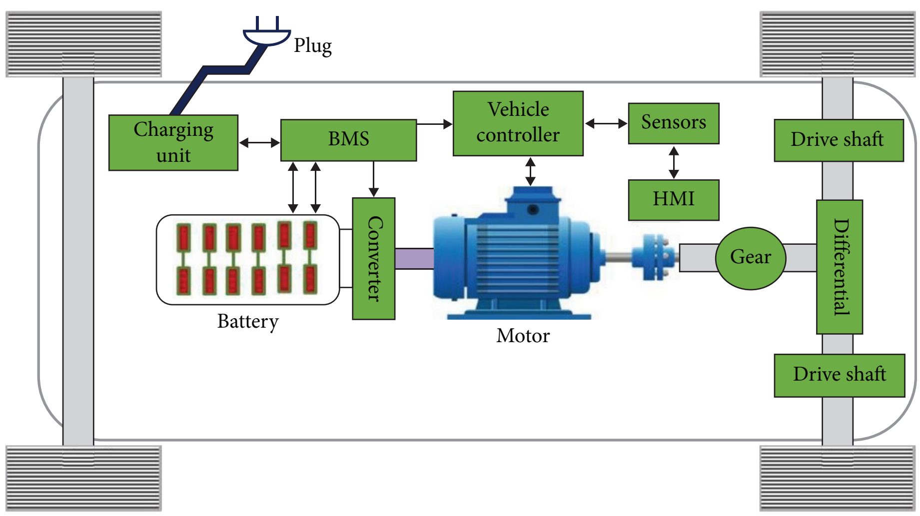


Figure 11: Components of electric vehicles.

to drivers who prioritize eco-friendliness. With reduced CO_2 emissions and the ability to operate on electric power alone for short distances, hybrids strike a balance between traditional and environmentally conscious driving. However, their expensive costs tend to be higher than those of ICE vehicles, reflecting the integration of electric components. All-EVs, relying on an electric motor powered by a battery, mark a significant shift toward sustainable transportation. Offering very high fuel efficiency and producing zero emissions during operation, EVs are designed for drivers prioritizing zero emissions and environmental sustainability. Despite their environmental benefits, all-EVs generally come with higher costs, largely due to the substantial investment in battery technology. They provide unlimited electric-only driving range, making them a compelling choice for drivers committed to reducing their carbon footprint.

3. EVs Architecture

The architecture of EVs plays a significant role in the development and implementation of EVs. The objective of this section is to describe the components used for EVs. The EVs carry several components, as shown in Figure 11. The main components are explained in the following subsections.

3.1. Electric Motor. One of an EV's primary components is the electric motor. In EVs, various kinds of electric motors are employed. The different motor types that are frequently used

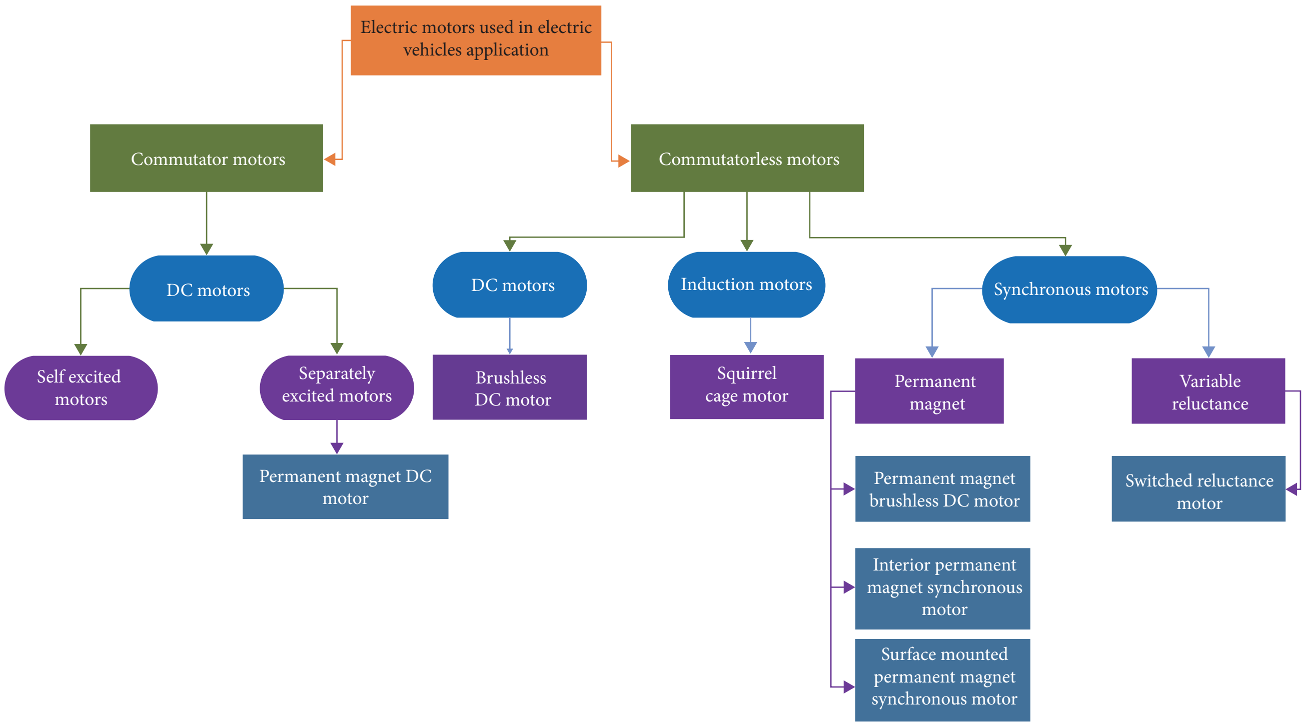


Figure 12: Electric motors used for EVs.

in EV technology are shown in Figure 12. Selecting the motor for an EV is an essential decision that impacts the overall performance of the vehicle. When choosing motors for EVs, attributes like ease of controllability, low maintenance costs, high power density, and simple design are prioritized [72]. Electric motors in EV applications can be divided into two major types: AC and DC motors, and these motors are either with commutator or without commutator [73]. A commutator is used in all DC and some AC electric motors, which is a rotary electric switch that periodically reverses the current direction between the rotor and the external circuit. DC motors are categorized into brushed DC motors and brushless DC (BLDC) motors. Brushed DC motors are infrequently employed in EV applications due to their numerous drawbacks, including large size, low efficiency, and the need for regular maintenance [74]. On the other hand, BLDC motors exhibit higher efficiency. Both types of motors boast low cost, high torque at low speed, and easy speed control [75]. AC motors are highly robust, characterized by long life expectancies, high efficiency, minimal maintenance requirements, increased reliability, and regenerative capability, allowing the conversion of braking energy back into batteries. The next subsections discuss the different AC and DC motors used in EVs.

3.1.1. DC Motors. DC motors offer several advantages in EVs, including robust construction and simple control. They exhibit suitable torque–speed characteristics, delivering high torque at low speeds. However, they come with certain drawbacks, such as size, low efficiency, reduced reliability, high maintenance requirements, and limited speed due to friction between brushes and collectors. There are two main types of DC motors: brushless and brushed DC motors. Brushed DC motors are becoming less common due to advancements in power electronics.

The BLDC motor is a synchronous motor powered by DC electricity. This motor shares similarities with a DC motor equipped with a permanent magnet. These motors do not have a commutator or a brush. The efficiency and starting torque of these motors are very good [76]. This motor is widely utilized in EVs due to its traction characteristics, effectively addressing challenges like aerodynamic drag, kinetic resistance, and rolling resistance drag [77]. There are two kinds of BLDC motors: in-runner and out-runner. The out-runner or hub type features the rotor positioned externally, while the stator is located internally. The rotor is a moving component of an electromagnetic system in the electric motor, which spins due to the interaction between windings and the magnetic field, which produces torque around the rotor's axis. The stator is a stationary part of the motor that provides a rotating magnetic field. In EVs, the wheel is directly connected to the exterior rotor, eliminating the need for an external gear system and requiring less space for motor mounting. In-runner type, it needs an external transmission system to transfer the power to the wheels [78]. The schematic for the in-runner BLDC motor inside the EV is displayed in Figure 13. All the components, including the drive circuit, position circuit, and protective circuit, are integrated with the BLDC motor. The main advantages of BLDC motors include their small size, compact nature, extended lifespan, and the provision of a higher torque-to-weight ratio, making them particularly suitable for city driving conditions [79]. The main drawbacks of BLDC motors

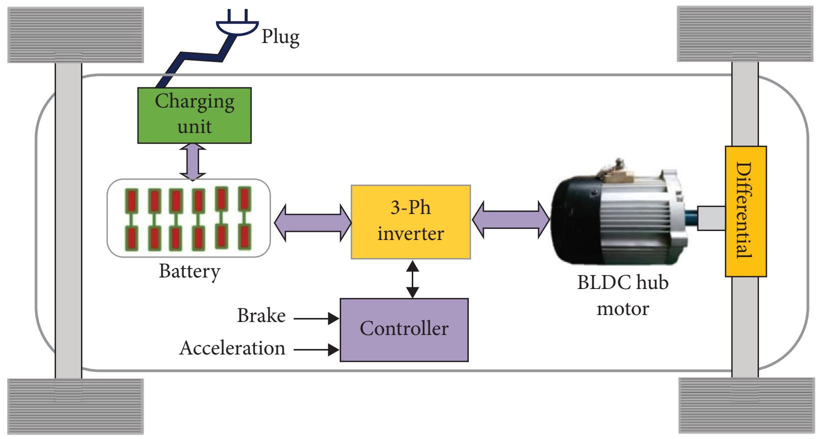


FIGURE 13: In-runner brushless DC motor.

include high vibrations at lower speeds, complex wiring requirements, elevated costs attributed to permanent magnets, and electrical overload limits that might diminish the life of permanent magnets under thermal conditions [74].

3.1.2. Permanent Magnet Synchronous Motors (PMSMs). The PMSM incorporates permanent magnets on the rotor, resulting in a high torque-to-current ratio, increased power density, traction characteristics, and efficiency, along with robustness comparable to the BLDC motor [80]. These motor types are generally considered costly and are commonly utilized by various automakers in their vehicles, including models like Honda Accord, Chevy Bolt, Toyota Prius, BMW i3, and others [81]. The battery's power is transmitted to inverters, and subsequently, it is conveyed to the brushless wheel hub mounted (BWHM) and PMSM situated in all four wheels of EVs. These motors' main benefits are their small size, low weight, minimal copper losses, lack of field winding, low manufacturing costs, high efficiency, and overall compact design [82]. The main drawbacks of these motors include their inability to generate high flux density and lower induced torque per ampere. Additionally, rotor position sensing is necessary. The PMSMs are divided into two main types, which will be explained next.

3.1.2.1. Permanent Magnet BLDC (PM BLDC) Motor. PM BLDC motors are highly efficient machines with low maintenance costs and excellent torque-speed characteristics [83]. Power electronics developments have accelerated the creation and broad use of PM BLDC motors, which are widely used in flywheel energy storage, EVs, and other applications [84]. These motors utilize permanent magnets in place of rotor windings. This design results in higher efficiency compared to induction motors, as there are no rotor losses. However, PM BLDC motors have a limited constant power operation region due to the weakening of the permanent magnet field by the stator field. To extend this region for the broader requirements of EVs, conduction angle control can be employed, allowing for a speed range reaching three to four times the base speed. PM BLDC motors have limitations in terms of torque, influenced by factors such as high temperatures that reduce the remnant flux density and, consequently, the motor torque capacity. Mechanical forces and the cost of magnets are considered significant disadvantages. Additionally, the increased centrifugal forces at higher motor rotation speeds can pose safety concerns, potentially leading to the breakage of magnets.

3.1.2.2. Interior Permanent Magnet (IPM) Motor. IPM motors are being used in most EVs in the market owing to their excellent performance characteristics, including their high-power density, high efficiency, and wide constant-power speed range. It utilizes only magnetic torque from a magnet [85, 86]. This motor design mitigates the risk of the magnet being detached due to centrifugal force. The IPM motor incorporates reluctance through magnetic resistance alongside magnetic torque, achieved by embedding a permanent magnet directly in the rotor. This motor is mostly employed by two-wheeler manufacturers [87]. The permanent magnet inside and outside the outer rotor is fixed and surface-mounted independently. The three-phase windings of the inner rotor link with three accumulator rings on the rotating shaft, and the electric energy is transmitted by the electric brush. The stator machine (SM) is made up of the stator and outer rotors with their external permanent magnets. The double-rotor machine (DRM) is made up of an inner rotor and an outer rotor that both have permanent magnets inside. Both the DRM and the SM can be considered as a PMSM. The main advantages of this motor design include high torque density, high power density, a wide operating range, high efficiency, and a lightweight construction. These features make it particularly suitable for application in light EVs [88]. As the rotational speed increases, a more significant field weakening becomes necessary, leading to an increase in losses in both copper and steel due to the increased amplitude of the armature current. The losses at high speeds have the potential to cause critical overheating, property degradation, and demagnetization of permanent magnets. Another drawback associated with IPM motors is their high cost, primarily attributed to the utilization of expensive rare-earth magnets. One of the main disadvantages of IPM motors is their relative power lag, as the power is lower compared to other motors, restricting their usability to two-wheelers or compact EVs [89].

3.1.2.3. Surface-Mounted Permanent Magnet (SPM) Motor. SPM is an electric motor characterized by a simple magnetic

Table 5: Comparison between EV motors.

Types of motors	BLDC	ACIM	PMSM	SRM	IPMM
Power (HP)	80–160	100–400	250–600	150–300	60–200
Weight (kg)	100–180	150–200	120–180	150–200	80–150
Reliability (years)	15–20	12–15	10–12	13–18	12–15
Cost ($)	5000–12,000	8000–14,000	10,000–18,000	9000–15,000	6000–10,000

circuit design, rapid responsiveness, linear torque–current characteristics, consistent speed–voltage characteristics, and a stable operating speed [90]. The permanent magnet in this motor is attached to the rotor's surface [91]. This kind of motor has a high torque to inertia ratio, high power density, high efficiency, and good dynamic performance. It can be controlled with relatively simple algorithms [92]. Although the SPM is made of a simple structure and has shorter end connections, it suffers from high-speed eddy-current loss, very little transient overload power, and a high uncontrolled generator voltage [93].

In [86], authors compared SPM and IPM synchronous motors for electric traction. SPM motors offer equivalent continuous power with simplified construction, but struggle with high-speed de-excitation losses. IPM motors demonstrate superior overload capability but contend with higher Joule losses at low speeds and potential fabrication expenses due to intricate slot and segment requirements.

3.1.3. AC Induction Motor (ACIM). ACIMs are favored in EVs due to their immunity to demagnetization, uniform air gap, simple structures, durability, and cost-effectiveness. Efficiency standards, set by IEC and NEMA, categorize an ACIM with IE3 class as over 95% efficient [94]. Another advantage is its compatibility with an inverter, allowing for easy modification of the vehicle speed by adjusting the output frequency, with minimal errors and no maintenance required [95]. It is composed of two cylindrical laminations and a rotor, which is typically a squirrel cage made of conductive bars inserted through slots [96]. Despite the advantages, drawbacks include eddy-current loss at high speed, limited transient overload power, and high uncontrolled generator voltage.

3.1.4. Switched Reluctance Motor (SRM). SRMs offer several advantages that make them suitable for various applications, including EV. SRMs are robust and have a simple construction. They are double saliency motors with concentrated coils mounted on each phase around diametrically opposite stator poles. SRM rotors don't have windings or permanent magnets. They offer simplicity, high power density, uncomplicated control, robust structure, high-speed capabilities, cost-effectiveness, and low energy consumption, making them suitable for EV applications. However, the main drawbacks of SRMs include weight, torque ripple, and higher noise issues compared to other types of motors [97].

3.1.5. Comparative Analysis of Electric Motors Used in EV Technologies. Several criteria, including efficiency, cost, reliability, innovation, and controllability, must be considered. In the context of industrial applications, particularly in EVs and more, factors must be taken into account. The most motors employed in EVs are PMSMs, induction motors, and BLDC motors [73, 98]. In terms of efficiency, the permanent magnet brushless motor takes the lead, closely followed by an induction motor with comparable efficiency. Several vehicle manufacturers, including Nissan, Honda, and Toyota, have actively adopted these motors [74].

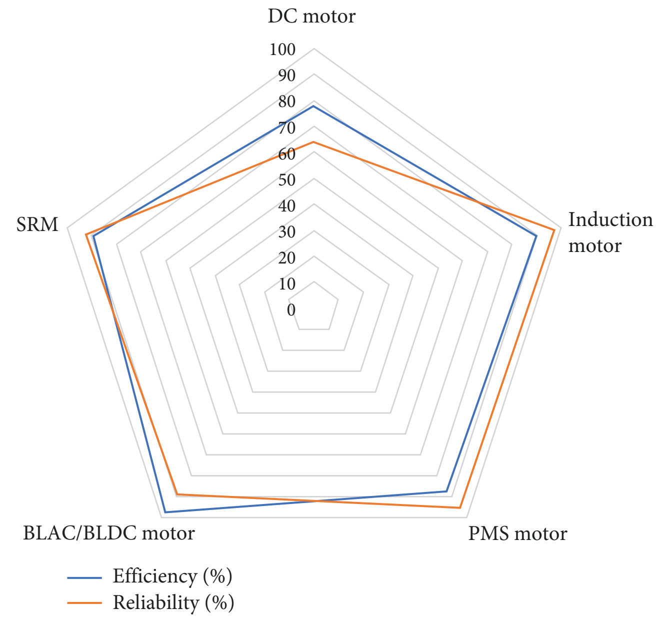


Figure 14: Comparison of electric motors used for electric vehicles in terms of efficiency and reliability.

Table 5 presents the main features of different motors that are commonly available in the EV market. The permanent magnet brushless motor is the most commonly used electric motor in EVs due to its traction and reliable characteristics. The efficiency of an electric motor serves as a link between its mechanical and electrical performance, reflecting how well it converts electrical power into mechanical output. In the context of experimental analysis, findings presented in Figure 14 indicate that induction motors exhibit an efficiency of 91%, whereas BLDC motors show an efficiency exceeding 95%. The superior efficiency of BLDC motors is attributed to the absence of rotor losses, establishing them as the most efficient and productive motor type. In contrast, DC motors display an efficiency of only 78%, making them less favored by EV manufacturers. In terms of reliability, when comparing various electric motors, the SRM and ACIM emerge as the most reliable options. DC motors exhibit a slightly lower level of dependability, while permanent magnet motors also demonstrate reliability, as depicted in Figure 14.

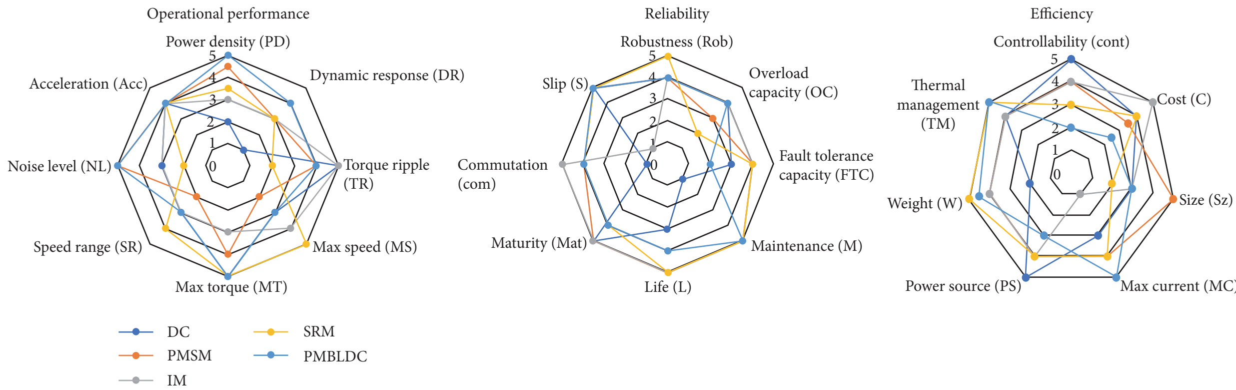


Figure 15: Comparison of electric motors used for electric vehicles in terms of efficiency and reliability, and operational performance [100].

In [99], the author assesses electric motors, considering factors like regenerative braking efficiency and power density across various load ranges. The evaluation classifies motors based on their collective performance with a hybrid ESS (HESS) for optimal efficiency and sizing. Results indicate that permanent magnet and induction motors emerge as top choices when considering all criteria, while the synchronous reluctance motor outperforms the induction motor specifically in key factors influencing hybrid storage system performance.

In [100], the authors conducted a multicriteria comparison of electric motors in electric traction systems to guide the selection of the most suitable motor for specific applications. The analysis indicates that, despite the induction motor better meeting major powertrain requirements, EV manufacturers primarily utilize the PMSM. A comparison of EV electric motors based on ongoing vehicle boundary specification parameters is presented in Figure 15. A higher score indicates a better element as determined by scoring each motor type and using the criteria listed in the graphs. It is shown that the induction machine leads in reliability, maturity, stability, fault tolerance, low cost, and maintenance. Followed by PMSM, PMBLDC, and SRM due to torque ripple, high noise, and weaker dynamic response. This classification does not mean the ACIM is better than the PMSM for the electric traction application.

According to Lulhe and Date [101], there has been several technologies implemented, and some are still to be evaluated to increase the efficiency of EVs. The authors stated that the PMSM motors have more advantages over SRM and IM, but there is a scope for designing a new induction motor with good efficiency and higher starting torque. In [102], the authors investigated that the induction motor is the most cost-effective, whereas the brushless motor drive is the most productive. In [103], the authors concluded that the performance of traction motor and powertrain products is theoretically improved, and the authors found a research gap in innovative technologies like motor design optimization and control algorithms, robustness design, multiphysical simulation analysis, system integration with jointly considered motors, next-generation motor system based on silicon carbide (SiC) devices, controllers and transmissions, efficient motor cooling methods, and new material development and applications.

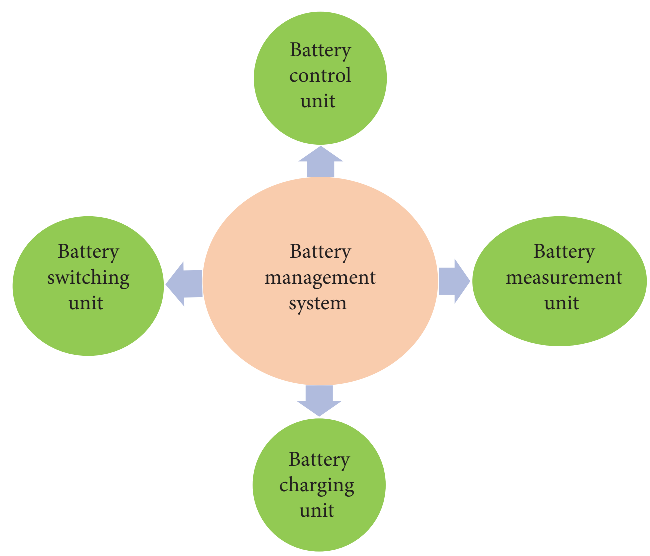


Figure 16: Battery management system.

3.2. BMS. The BMS market size was approximately $7.5 billion in 2022, and it is anticipated to experience a 19.1% growth from 2023 to 2032, according to a report from Allied Market Research [104]. This growth is attributed to the increased sales of EVs, contributing significantly to the automotive sector, which, in turn, impacts the global BMS market.

BMS in EVs includes a battery switching unit, battery control unit, measurement unit, and charging unit, as shown in Figure 16 [105]. The main purpose of the battery control unit is to process the data that has been collected from the measurement unit, define the variables and conditions of the battery charging unit, and the battery switching unit. Battery measurement is provided through control algorithms that run on the microcontroller. The measurement unit observes the battery level and charging state. The battery switching unit is primarily responsible to ensure that the battery is separated from any power source. The charging unit is designed to provide high performance while minimizing power consumption, implementing battery charging algorithms optimized for EVs [106]. It makes sure that the battery charging process is applied

Table 6: Comparison of different types of electric vehicle battery cells.

Term	Lithium-ion Cobalt	Lithium-ion Manganese	Lithium-ion Phosphate	Nickel-metal	Lead-acid	Ultracapacitor
Cycle life	500–1000	100–1000	1000–2000	1000	200–300	>50,000
Charge time	(2–4) h	(1–2) h	(1–2) h	(2–4) h	(8–16) h	(1–10) s
Charge temperature		−40 to 65°C		−40 to 65°C	−40 to 65°C	−40 to 65°C
Discharge temperature		−20 to 60°C		−20 to 65°C	−20 to 50°C	−40 to 65°C
Cell voltage	3.6 V	3.7 V	3.2–3.3 V	3.7 V	2 V	2.3–2.7 V
Charge/discharge efficiency		70%–85%		70% slow charge 90% fast charge	90%	85%–98%
Cost		High		Moderate	Low	High

serially, and batteries must not be charged simultaneously, else it has the potential to cause a short circuit during parallel charging. To increase a battery bank's amp-hour capacity while maintaining a constant voltage, two or more batteries are connected in parallel. BMS manages the extensive array of rechargeable battery cells, including battery state estimation and battery balancing in EVs. It plays a crucial role in ensuring the safe and efficient operation of batteries, protecting the battery, optimizing battery utilization, and facilitating communication with other control units within the EV. Charging an EV battery is a simple process, but the main challenges lie in the charge time and the limited availability of charging stations. Charging stations serve the purpose of delivering energy to the vehicle and are generally categorized into three main groups: Level 1, Level 2, and Level 3. EVs utilizing an AC Level 1 charger typically require around 8–14 h to charge the car. In contrast, a Level 3 charger, also known as a DC fast charger, can significantly reduce charging time to approximately 15–30 min [107]. Automobile manufacturers are actively working on enhancing charging time and battery efficiency, as well as improving the charging infrastructure and conducting research on EV battery chargers.

3.3. EVs Battery. A fundamental element of any EV is the battery, playing a vital role as the power source for the EV motor and charging system. Proper battery management is essential to prevent overcharging or over-discharging, which could result in battery damage, reduced lifespan, and potential safety hazards, such as fire or explosions. EV batteries generally comprise numerous small individual cells arranged in a parallel configuration to achieve the required voltage and capacity. The range and power capabilities of an EV are contingent upon the size and specifications of its battery. Four commonly used types of rechargeable batteries for EV applications are lead-acid batteries, nickel-metal hydride (NiMH) batteries, lithium-ion (Li-ion) batteries, and ultracapacitors [1, 108]. Among these, Li-ion batteries stand out as the most reliable and widely used choice in EVs due to their lightweight nature, low maintenance requirements, and comparatively lower cost [109]. EVs primarily operate on Li-ion batteries, a technology that is becoming increasingly affordable and efficient over time. Figure 11 illustrates the configuration of battery packs and power converters within EVs, while Table 6 provides a comparison of various types of rechargeable batteries used in EV applications. Comparing EV battery cells reveals a trade-off between cost, performance, and lifespan. Li-ion batteries, including their cobalt, manganese, and phosphate variations, offer the best overall performance in terms of cycle life and efficiency but come at a higher price. Nickel-metal batteries strike a more cost-effective balance, while lead-acid batteries are the most affordable but have limitations in range and durability. Ultracapacitors stand out with incredibly fast charging and energy transfer, but their limited capacity restricts them to specific applications rather than long-range driving. The following subsections provide detailed information on different battery types.

3.3.1. Lithium-Ion Batteries. The Li-ion battery is now an ideal option for EVs due to its relatively high energy density, low self-discharge rate, high voltage, long service life, high reliability, and rapid charging characteristics [110]. Lithium-based batteries are on track to make EVs more prevalent by addressing the climate concerns associated with fossil-fueled vehicles. This is due to significant investments made by both the public and private sectors in research and development, processing, and manufacturing, as well as advancements in anodes (lithium and silicon), cathodes (high nickel), designs, supply chain development, and the circularity of Li-ion batteries [111]. The advantages and disadvantages of Li-ion batteries in EVs are presented in Table 7.

3.3.2. NiMH Batteries. The nickle-metal batteries were widely utilized for EVs like Prius at the beginning of the 1990s due to their environmental friendliness. However, this battery technology faced significant drawbacks, including poor cold performance and memory effects. Additionally, issues such as extended recharge times and high self-discharge rates during idle periods were the most concerning [35].

These battery-type components include an anode of hydrogen, a cathode of nickel hydroxide, and a potassium hydroxide [112]. These batteries are commonly used in PHEVs and HEVs as they have a much longer life cycle than lead acid batteries, and they are safe and abuse-tolerant [113]. The price of the nickle-metal battery is relatively high due to the use of platinum as a catalyst, and the heat generation is high due to the anode of hydrogen, which produces heat while recharging, which is the main deficiency of these batteries. Table 8 presents the advantages and disadvantages of NiMH batteries in EV applications.

Table 7: Advantages and disadvantages of lithium-ion batteries in electric vehicles.

Advantages	Disadvantages
• High energy density, allowing for longer range on a single charge • Long lifespan, withstanding numerous charge/discharge cycles before significant degradation • High energy transfer efficiency, minimizing energy loss during charge and discharge • Delivers high power output, enabling swift acceleration and responsive driving • Supports various fast charging technologies, significantly reducing charging time • Can be recycled and reused, minimizing environmental footprint.	• The high energy density of battery contributes to heavier battery packs, impacting vehicle weight and handling • More expensive than other battery technologies like lead-acid • Requires efficient battery management systems and thermal control to maintain performance • The risk of bursting • High power demands can contribute to faster degradation and heat generation • Degradation over time.

Table 8: Advantages and disadvantages of nickel-metal hydride batteries in electric vehicles.

Advantages	Disadvantages
• Enables longer driving range than lead-acid • Minimizes energy loss during charging and discharging • Lower cost than lithium-ion • Can last for several hundred charge cycles before significant degradation • Can be fully charged in a few hours compared to lead-acid • Safer in case of accidents or improper disposal compared to lead-acid.	• Shorter driving range compared to advanced EVs • Loses charge faster when not in use • May increase initial EV purchase price compared to budget options • Mining of some raw materials can have environmental consequences • Requires specialized control system and potentially higher maintenance costs.

3.3.3. Lead-Acid Batteries. Lead-acid batteries stand as one of the oldest and most established rechargeable battery technologies [114], characterized by lead electrodes submerged in a sulfuric acid electrolyte. Renowned for their high-power output and cost-effectiveness, these batteries find ideal applications in specific contexts. Automotive starting batteries, backup power systems, and uninterruptible power supplies benefit from the reliability and affordability of lead-acid batteries, making them a staple choice in various industries [115].

Lead-acid batteries are less efficient than other battery types because of their specific gravimetric energy density, which ranges from 30 to 50 Wh/kg [102, 116]. These batteries have a lifespan of 500–1000 cycles, and it takes a significant amount of weight, more than 500 kg, to produce one kWh of electricity, which is needed to travel 200 km [35]. Lead-acid batteries have a lower lifespan compared to ESSs that utilize Li-ion and supercapacitors. The use of lead-acid batteries harms the operation of transport vehicles [117]. In contrast to conventional lead-acid batteries, Li-ion batteries demonstrate a remarkable threefold increase in efficiency and boast an extended lifespan of up to 20 years. Vehicles equipped with Li-ion batteries gain the advantage of additional storage capacity, enabling them to move with greater energy efficiency and reduced bulk [118]. Lead-acid batteries are inexpensive and recyclable, which is one of the most significant aspects of any battery technology. The benefits and drawbacks of using lead-acid batteries in EV applications are shown in Table 9.

Table 9: Advantages and disadvantages of lead-acid batteries in electric vehicles.

Advantages	Disadvantages
• Significantly cheaper: makes EVs more affordable for budget-conscious consumers • Delivers good starting power when new • Compatible with basic chargers and infrastructure • Can last for several 100 charge cycles with proper care.	• Requires frequent charging due to low energy density • Increases overall vehicle weight and reduces efficiency • Loses more energy during charging and discharging, reducing range • May require replacement sooner • Requires careful monitoring and maintenance.

3.3.4. Ultracapacitors. Ultracapacitors are energy storage devices that, in contrast to electrochemical batteries, can be charged instantly and produce electricity, making up for tens of megawatts of power in the short term. They may operate in a wider temperature range and last for at least 15 years without the need for maintenance or replacement. Because it discharges quickly and gives the vehicle a lot of power, the supercapacitor is used as a secondary energy source [119].

EVs are frequently used as easily accessible power sources in the market. EVs, in particular, require different amounts of power over time due to unexpected accelerations and decelerations that occur during the regeneration period. The battery must absorb a significant transient charging current during this acceleration and regeneration period, which simulates variations in pulse load and may have a negative impact on battery performance. To address this issue, a *supplementary* energy storage technology, ultracapacitors, is employed to solve the negative impact on the battery [120]. Ultracapacitors are unable to provide high power and high energy supply systems for EVs at the same time. Consequently, the batteries provide the vehicle's long-term autonomy while the ultracapacitors handle short-term power requirements [121]. Vehicle energy consumption rises with the number of ultracapacitors used. This is because using ultracapacitors increased the mass of the energy system, which raised the total energy consumption of the vehicle [122]. Table 10 presents the advantages and disadvantages of utilizing ultracapacitors in EV applications.

The main components of the EVs discussed above are depicted in Figure 11. Other components shown in the figure include the converter, vehicle controller, sensors, human–machine interface (HMI), gear, drive shaft, and differential.

Table 10: Advantages and disadvantages of ultracapacitors in electric vehicles.

Advantages	Disadvantages
• Ideal for regenerative braking and fast acceleration • Performs well in extreme temperatures • Long cycle life • Pair well with batteries to compensate for their slow charging and power delivery limitations • More affordable than lithium-ion batteries for peak power applications.	• Requires large and heavy modules for limited range • Cannot sustain power output for extended periods • Loses more energy during charging and discharging compared to batteries • Require specialized control and management systems for optimal performance • Can increase vehicle weight and impact efficiency.

The converter, whether integrated into the EV or part of EV chargers, plays an essential role in converting the vehicle's voltage, typically from AC to DC. The motor controller controls the performance of the motor in the EV. It integrates motor speed and expected battery range. The sensors are used in EVs to detect quality defects, to check the battery temperature, and vehicle performance. Different sensors are used for different roles in EVs. The HMI is a software-based that replaces physical wires and controls with software parameters. It connects the EV to the user of the EV. The gear, drive shaft, and differential are linked together, which helps the tires of the EV to rotate.

3.4. EVs Charging Technologies. The future of EVs depends on ongoing efforts by automakers worldwide to enhance both the vehicles and the supporting EV charging infrastructure, aiming for broader implementation. To speed up the battery charging process, an efficient EV charging system is necessary. This essential component, which is mostly dependent on power conversion stages, makes it easier for electrical energy to move from the power grid to the EV batteries. Consequently, these EV chargers can be categorized based on various criteria, such as the charger installation, energy transfer direction, charger structure, connection type, and the source of energy, as shown in Figure 17 [123–125].

3.4.1. Conductive Charging System. Charging systems play an essential role in powering the batteries of hybrid and EVs, ensuring their efficient operation. These systems are broadly categorized into two main types: conductive charging and wireless charging systems. In conductive charging, an EV is charged at the station by connecting it to the power supply via a cable. On the other hand, the wireless charger operates through WPT technology [126, 127]. These chargers are further categorized into on-board and off-board chargers. In on-board EV charging infrastructure, the EV charger circuitry is housed inside the vehicle along with the ESS. In contrast, off-board EV charging infrastructure separates the charging circuitry, making it distinct from the EV itself [125].

The conductive charger is a conventional device that transfers power through direct contact through a cable. A standard electrical outlet or a charging station can be used to supply the cable [128]. Conductive charging offers several advantages, including economic viability, rapid charging capabilities, straightforward operation, and high efficiency [129]. This charging system comprises a power converter device, connector, and incorporates various power factor correction (PFC) mechanisms. It is further categorized into AC charging and DC charging systems as shown in Figure 18 [130].

The EV battery can be conveniently recharged while still mounted on the vehicle by establishing a connection to an external power source, such as a wall outlet. This technology commonly involves charging the battery using either DC or AC. Serving as a primary method for recharging an EV, this approach is not only applicable at home but also at designated recharging stations [60].

AC charging is carried out using AC chargers. Various topologies have been introduced for single-phase and three-phase EV chargers. These include an AC/DC converter, PFC components, and a DC/DC converter. AC charger systems are categorized into on-board, situated inside the vehicle for slow charging [131]. An EV's on-board system is used to charge it using AC power, and it handles converting outlet current to battery current. As a result, it takes in AC and transforms it into DC, which is then delivered to the vehicle battery.

The on-board charger is specifically designed for a low charging rate, aiming to charge the vehicle's battery gradually over an extended period, typically taking 5–8 h for a full charge. Considering the constraints of allowable payload and limited space within the EV, the on-board charger is made to be lightweight and compact [132].

The Society of Automotive Engineers (SAE) has established a standard for various EV charging levels. This standard defines charge levels for both AC and DC charging [133]. According to Schroeder and Traber [134], the most common method for charging EVs is through residential infrastructure, with Level 1 and Level 2 charging being the most widely used. Level 1 charging represents the slowest and simplest charging method, requiring no additional infrastructure, and any standard wall outlet can be utilized, as shown in Figure 19. In the United States, a typical 120 V/15 A wall outlet serves Level 1 charging, exclusively as an on-board charger. Figure 19 also includes the electrical powertrain, comprising the traction inverter and the electric motor. Additionally, it includes DC–DC converters serving auxiliary loads and facilitating the interface between the high voltage traction battery and the low voltage battery [135]. While its cost is lower than other charging levels, the drawback is the extended time required for the EV to reach a full charge. However, owing to its low power rating, this charging level has the least impact on distribution systems [136].

In public and residential areas, level 2 charging stations are most frequently utilized [129]. The main difference between charging Levels 1 and 2 is the voltage [137]. Level 2 charging operates with voltages of 208 V or 240 V, currents reaching up to 80 A, and a charging power of 19.2 kW. EV owners favor Level 2 over Level 1 due to its quicker charging time compared to level 1. This may require the installation of dedicated EV supply equipment (EVSE) for public or home charging [136]. Most vehicles are being designed to accept a Level 2 AC on-board charging at less than 30 A [138]. The architecture of the

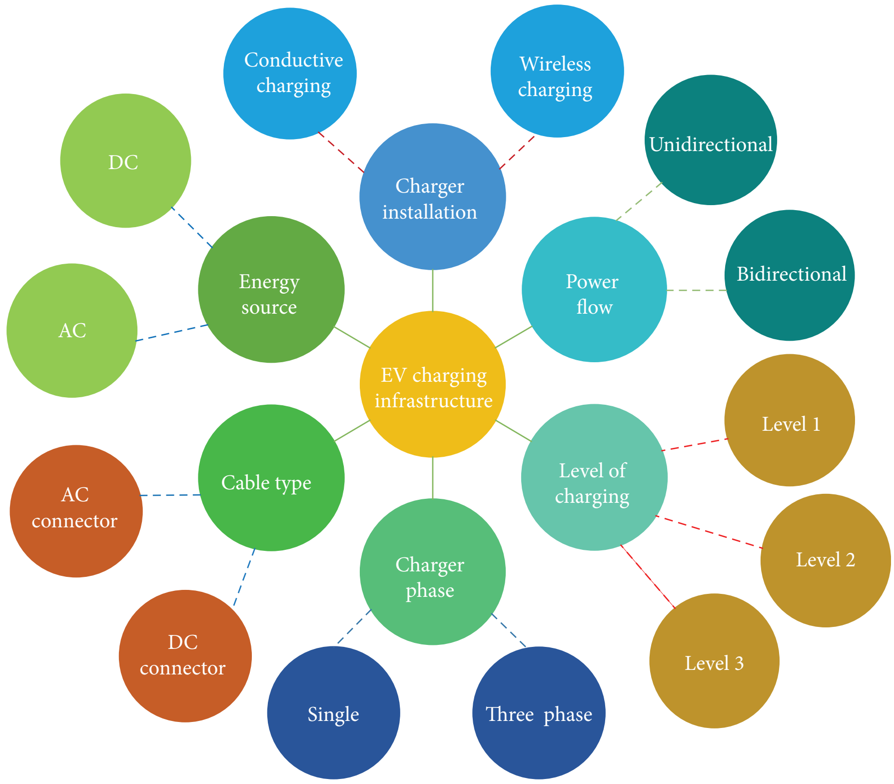


Figure 17: Electric vehicles' battery charging architectures.

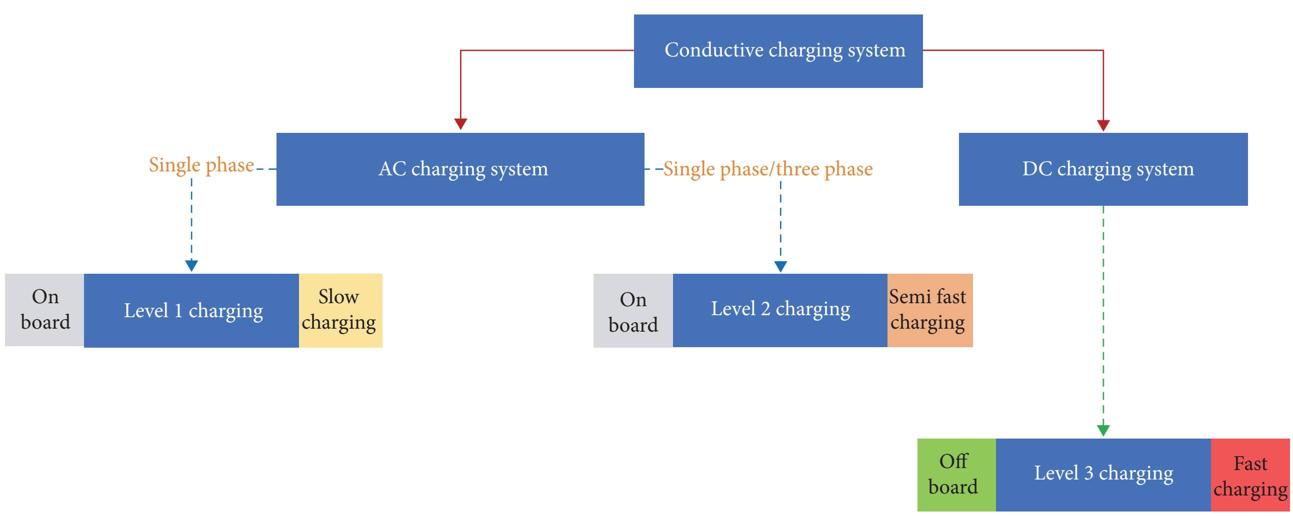


Figure 18: Classifications of conductive charging systems for electric vehicles.

Level 2 charging system remains consistent with Level 1, as depicted in Figure 18, with the only adaptation being the replacement of the socket with EVSE.

The increasing adoption of EVs necessitates efficient and versatile charging solutions. While onboard chargers, integrated within the vehicle, have dominated early EV infrastructure, an alternative approach, off-board charging, is gaining momentum.

Off-board charging departs from the conventional paradigm by shifting the conversion process from the vehicle to the charging station. In this charging system, the station houses a DC–DC converter, responsible for converting AC grid power into DC electricity compatible with the vehicle's battery, as shown in Figure 20 [139]. This eliminates the need for the on-board charger to perform the conversion, allowing for several key advantages. They remove size constraints on the in-vehicle converter, enabling more powerful units in the station. These converters deliver faster DC power, reducing charging time and energy losses, contributing to efficiency and environmental impact. They offer V2G charging [130, 140–142].

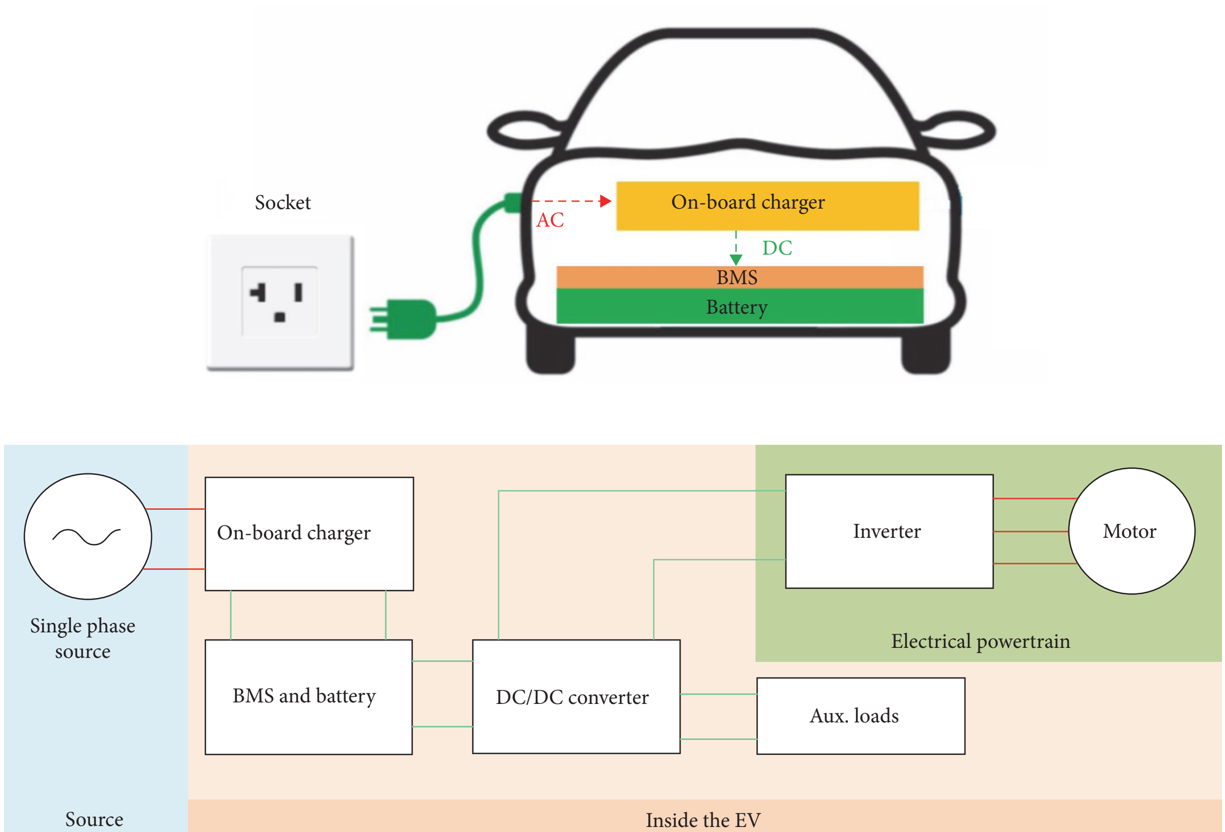


FIGURE 19: On-board charger on a BEV for Level 1 charging.

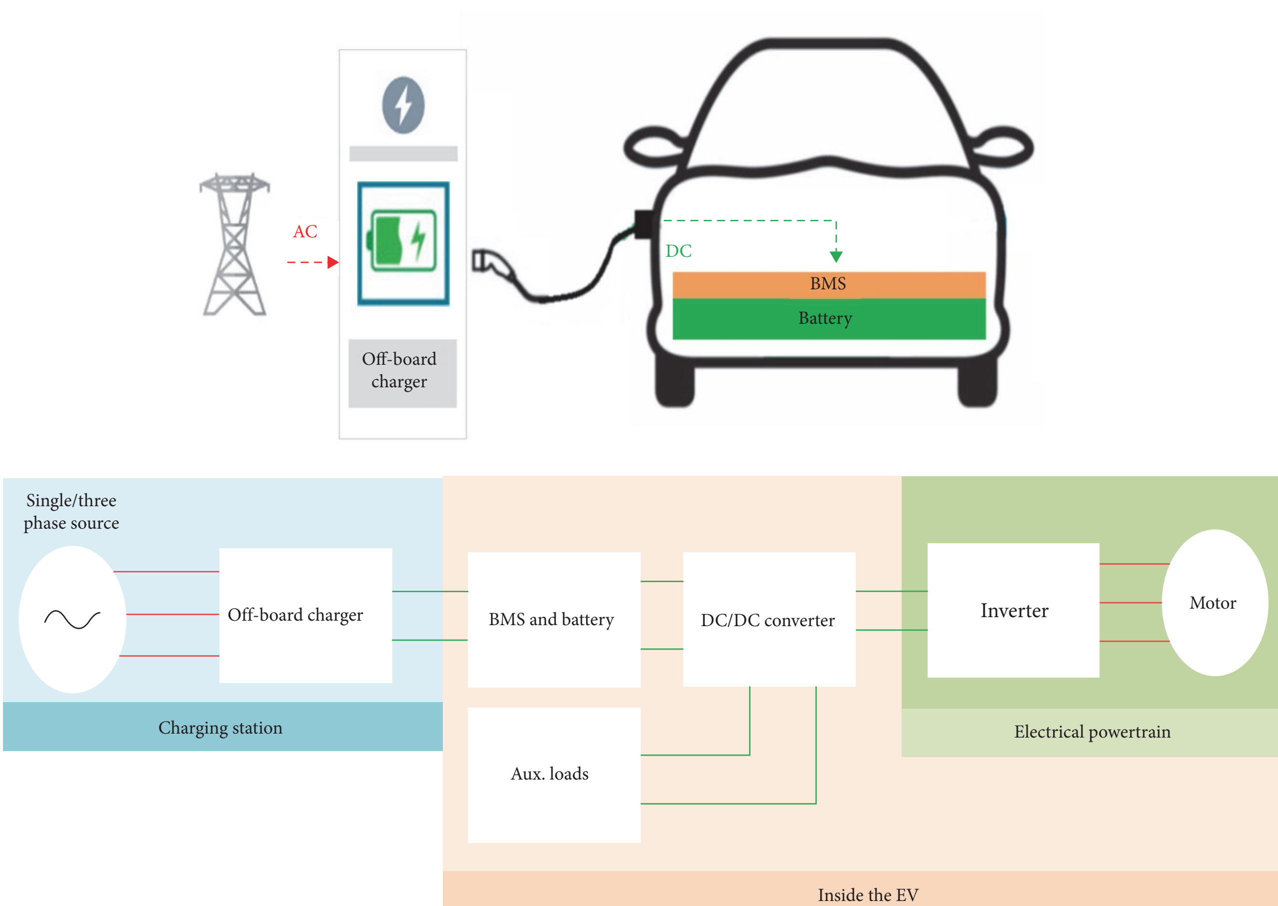


FIGURE 20: Off-board charger on a BEV for Level 3 charging.

TABLE 11: Comparative analysis of conductive AC and DC charging methods for electric vehicles.

Term	AC conduction method/on-board charging	DC conduction method/off-board charging
Conversion	• AC power converted to DC power within the vehicle	• AC power converted to DC power by the charging station
Voltage	• Typically uses standard grid voltage (110/220 V)	• Uses high voltage DC power (200–600 V)
Power output	• Lower power output (3–7 kW)	• Higher power output (36–240 kW)
Charging time	• Slower charging times (several hours to full charge)	• Faster charging times (15–30 min for 0%–80% charge)
Efficiency	• Lower efficiency due to on-board conversion losses	• Higher efficiency due to direct DC-to-DC transfer
Infrastructure	• Requires readily available AC outlets at home or public charging stations	• Requires dedicated DC charging stations with high-voltage infrastructure
Vehicle impact	• Requires on-board charger, adding weight and cost to the vehicle	• No on-board charger needed, potentially reducing vehicle weight and cost
Battery impact	• Slower charging generally less stressful on battery longevity	• Frequent fast charging can potentially degrade battery lifespan overtime
Cost	• Lower cost due to simpler technology and existing infrastructure	• Higher cost due to specialized equipment and dedicated infrastructure
Applications	• Ideal for overnight home charging or slower public charging	• Ideal for long-distance travel and public fast charging stations

However, the shift toward off-board charging also presents certain challenges. The primary concern lies in the potential impact on battery lifespan. While fast charging offers undeniable convenience, frequent high-power charging cycles can potentially lead to accelerated degradation of the battery's capacity [143].

DC fast charging, also referred to as charging Level 3, usually requires 15–20 min to fully charge a battery from 0% to 80%. Regardless of the charging level, the last 20% of the battery is always charged slowly. Level 3 charging usually involves voltages between 200 and 600 V and power outputs between 36 and 240 kW. According to SAE standards, DC Fast Charging can be classified into two levels: DC Level 1 and DC Level 2. DC Level 1 charging stations, besides their 36-kW power output, have a current flow capacity of 80 A. On the other hand, DC Level 2 chargers possess a current flow capacity of 200 A and a power output of 90 kW [129]. A comparative analysis between conductive AC and DC charging is presented in Table 11. The presented table offers a comprehensive comparative analysis of conductive AC and DC charging methods for EVs, focusing on essential attributes and distinctions between the two approaches. In terms of conversion, the AC conduction method involves the conversion of AC power to DC power within the vehicle, while the conversion in DC conduction method takes place at the charging station. The AC method typically utilizes standard grid voltage (110/220 V), contrasting with the DC method that employs high-voltage DC power (200–600 V). The power output of the AC method is lower (3–7 kW), making it suitable for overnight home charging or slower public charging, while the DC method boasts higher power output (36–240 kW), making it ideal for long-distance travel and public fast charging stations. Furthermore, differences in charging times, efficiency, infrastructure requirements, vehicle and battery impacts, costs, and specific applications are presented.

Chargers for EVs are categorized into three levels, each representing different charging capabilities and technologies. These levels include Level 1 AC, Level 2 AC, and Level 3 DC, with the latter further subdivided into Level 1 DC and Level 2 DC. The details of these charging levels are included in Table 12, providing a comprehensive comparative analysis. It evaluates different aspects of charging levels, focusing on key parameters. Level 1 AC relies on the AC grid with a voltage range of 120 V or 240 V, featuring low current and a charging time exceeding 4 h. This level exhibits low efficiency, is cost-effective with standard outlets, and is compatible with all EVs. Level 2 AC operates similarly from the AC grid, offering moderate current, a charging time of 2–4 h, and moderate efficiency. It involves moderate infrastructure costs with dedicated chargers and is compatible with most EVs. Level 3 DC employs a DC station with a voltage range of 200 V to 600 V, high current, and a rapid charging time of 15–30 min. It demonstrates high efficiency, accompanied by high infrastructure costs for dedicated DC stations, and is suitable for some EVs, requiring specific adapters. The impact on the battery increases with each level, from low to very high. Level 1 AC is primarily used for home charging, Level 2 AC serves home and public charging needs, Level 3 DC is designed for public charging, and long-distance travel charging applications.

The EV charging systems are classified into either unidirectional or bidirectional, based on the direction of power flow, as shown in Figure 21. Unidirectional chargers are utilized for charging EVs, ensuring a unidirectional power transfer. On the other hand, bidirectional chargers serve a dual purpose, facilitating both charging and discharging processes [144]. This bidirectional capability is particularly advantageous for V2G applications, enabling EVs to not only receive electricity for charging but also contribute by feeding surplus power back into the grid, contributing to the concept of bidirectional energy flow and enhancing grid stability [145]. Unidirectional

Table 12: Comparative analysis of charger levels for electric vehicles based on SAE.

Term	Level 1 AC	Level 2 AC	Level 3 DC	
			Level 1 DC	Level 2 DC
Power source	• AC grid	• AC grid	• DC station	• DC station
Voltage	• 120 or 240 V	• 240 V	• 200–600 V	• 200–600 V
Current	• Low (12–16 A)	• Moderate (24–80 A)	• High (Up to 80 A)	• Very high (Up to 200 A)
Charging time (0%–80%)	• More than 4 h	• 2–4 h	• 15–30 min	• 10–20 min
Efficiency	• Low	• Moderate	• High	• Very high
Infrastructure cost	• Low (standard outlets)	• Moderate (dedicated chargers)	• High (dedicated DC stations)	• Very high (network of DC stations)
Compatibility	• All EVs	• Most EVs	• Some EVs (adapter needed)	• Specific adapters needed
Impact on battery	• Low	• Moderate	• High	• Very high
Applications	• Home charging	• Home and public charging	• Public charging	• Public and long-distance travel

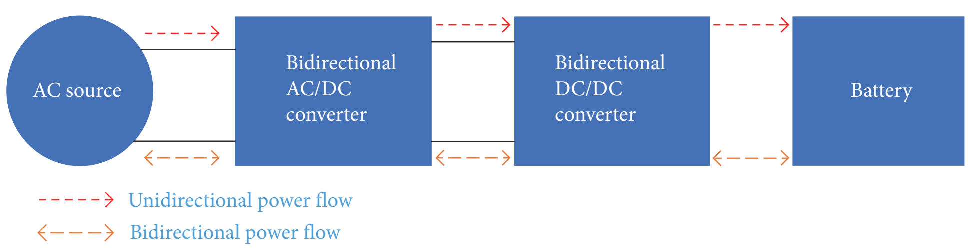


Figure 21: General unidirectional and bidirectional topology.

charging requires less hardware, simplifying connectivity and reducing battery wear. In contrast, a bidirectional charging system not only ensures stable power conversion but also facilitates energy injection from the battery back into the grid alongside conventional charging capabilities. This bidirectional functionality enhances overall system resilience and flexibility, contributing to a dynamic energy ecosystem [146]. Table 13 provides a comparative analysis between unidirectional and bidirectional chargers for EVs.

It is demonstrated from Table 13 that the unidirectional chargers facilitate one-way energy flow, directing electricity solely from the grid to the vehicle's battery. The power flow involves AC/DC conversion within the vehicle, delivering DC power to the battery. Their primary functionality is limited to charging the EV battery, resulting in generally lower infrastructure costs and lower stress on the battery. Unidirectional chargers are compatible with all EVs, suitable for various power levels, but have limited potential for grid integration.

On the other hand, bidirectional chargers enable two-way energy flow, allowing electricity to be transmitted from the grid to the battery and vice versa. AC/DC conversion occurs in the charger, sending DC power to the battery and AC power to the grid. Beyond charging the EV battery, bidirectional chargers can provide power back to the grid, offering additional functionality known as V2G capability. This added functionality increases infrastructure costs, introduces potential stress on the battery due to increased cycles and faster degradation from V2G operations, and may require specific hardware or software compatibility for V2G features. While bidirectional chargers are suitable for Level-2 charging, they exhibit significant potential for grid integration, contributing to grid stability and renewable energy integration. However, bidirectional chargers are currently less widespread in the market but are growing rapidly.

The conductive EV charging infrastructure requires the incorporation of EV charging connectors, sockets, and plugs to supply the necessary power for recharging EVs. A charging station is a physical structure with one or more charging points, each featuring a shared user identification interface [125]. Different types of connectors are used by EV manufacturers for AC and DC charging due to differences in charging powers and standards [147]. Charging connectors follow the standards of SAE, IEC, and IEEE [148, 149]. Table 14 demonstrates various connectors and charging ports produced in accordance with various standards.

3.4.2. Wireless Charging System. A wirelessly charged EV is a vehicle that receives charging through WPT technology, eliminating the need for any physical contact with the vehicle during the charging process [150]. WPT presents an optimal solution for EV charging due to its automatic nature, convenience, reliability in harsh environments, resistance to vandalism, and versatility for implementation on roads, public parking areas, private parking spaces, and bus stops [151, 152]. Additionally, the incorporation of in-motion wireless charging holds the promise of offering an unlimited driving range, minimizing downtime, and significantly reducing the size of onboard batteries. This reduction contributes to lower EV prices, smaller

Table 13: Comparative analysis between unidirectional and bidirectional chargers of electric vehicles.

Term	Unidirectional chargers	Bidirectional chargers
Direction of energy flow	• One-way: electricity from grid to battery	• Two-way: electricity from grid to battery and battery to grid
Power flow	• AC/DC conversion occurs within the vehicle, delivering DC power to the battery	• AC/DC conversion occurs in the charger, sending DC power to the battery and AC power to the grid
Functionality	• Charging EV only	• Charges EV battery and can provide power back to the grid
Infrastructure cost	• Generally lower cost	• Requires additional hardware and communication infrastructure for V2G/G2V functionality
Impact on battery life	• Generally lower stress on battery (low charging time)	• Increased cycles and potential faster degradation due to V2G (fast charger)
Vehicle compatibility	• Compatible with all EVs	• May require specific hardware or software compatibility for V2G/G2V features
Power rating	• Suitable for all power level	• Only suitable for Level-2
Potential for grid integration	• Limited	• Significant, can contribute to grid stability and renewable energy integration. They can provide and store energy during peak and off-peak hours
Current market availability	• Widely available	• Less widespread, but growing rapidly

dimensions, and reduced weight, ultimately enhancing operational efficiency [153]. The potential of wireless charging technology extends to expediting the proliferation of EVs, enhancing people's lifestyles, and contributing to the creation of a better world for future generations [154].

Major EV manufacturers have developed a range of solutions to address the charging needs of EVs during their journeys. These solutions include the establishment of charging stations, installation of charging points, and even wireless charging pads buried under the highways. Additionally, efforts have been attempted to perform away with connected charging options, requiring EVs to stop for extended periods of time in order to charge and require a physical connection via wires. Consequently, there is a need to transition toward wireless charging techniques. The aim of this transition is to increase EV owners' satisfaction and lessen their stress related to having to wait while their vehicle is charging [155]. According to [156–158] many automakers and aftermarket companies, such as Plug-less, Sema Connect, and WiTricity, offered wireless EV charging features in their cars. Automakers, such as Nissan and Toyota are developing this feature and intend to incorporate it into their next generation of EVs [19]. Wireless charging is highly beneficial as it eliminates the necessity to carry bulky chargers in the car, providing a safe and convenient charging solution. Wireless charging is considered safe due to the absence of wiring and cables, providing convenience for EV users in public parking spaces. However, the installation cost of wireless charging is relatively higher compared to traditional chargers, potentially adding weight to an EV. Additionally, wireless chargers generate more heat than standard chargers. There are also concerns about the long-term effects of electromagnetic rays produced by wireless chargers, which may pose potential harm to people in the vicinity [159–161].

The classification of wireless EV charging, illustrated in Figure 22, includes static [159, 162], dynamic [163, 164], and quasi-dynamic [165] methods. Alternatively, another categorization is based on the field's travel distance, distinguishing between near-field technologies [166, 167] (such as inductive, magnetic resonance coupling, and permanent magnet coupling) and far-field approaches (utilizing microwave and laser technologies) [161, 168]. Within this classification, inductive wireless charging emerges as the most common technique. This is mainly because, in contrast to magnetic resonance coupling systems, it has a more compact and simplified structure as it lacks a resonant circuit. As a result, installing the inductive wireless charging technique beneath EVs is quite useful.

In static charging, EVs receive wireless charging while parked near the charging platform. This method is highly convenient for users, especially in home or office parking settings [169]. Static charging systems are similar to conventional plug-in chargers but offer unique advantages, such as the user-friendly "park and charge" feature [170]. Furthermore, with little assistance from the driver, static charging systems can easily replace plug-in chargers, thereby resolving safety issues with electric shock and trip hazards [34].

The dynamic charging mode, also known as in-motion charging, presents an interesting and challenging method for EV charging. This unique approach occurs while the vehicle is in motion on the roadway [171]. Its importance lies in its effectiveness for supporting highway driving, addressing the high energy requirements of vehicles, and overcoming limitations in access to stops and parking spaces [154]. The dynamic

Table 14: Connectors for charging electric vehicles.

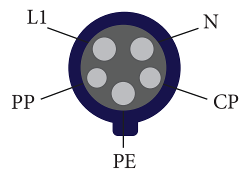
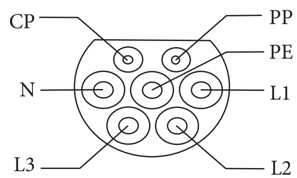
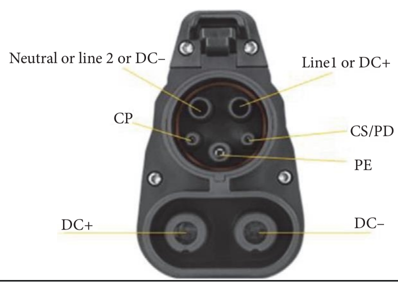
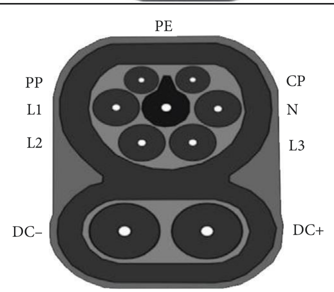
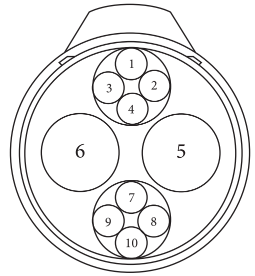
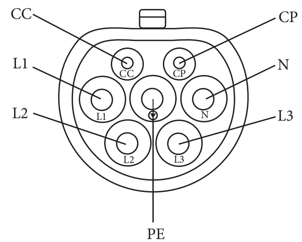
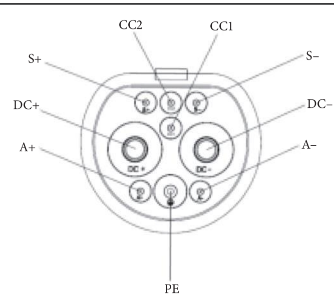
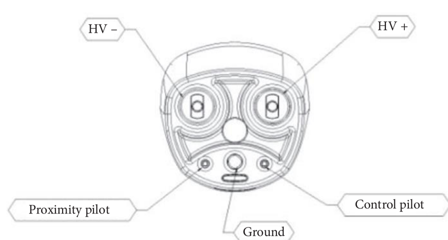
Connector type	Graphical view	Pins number	Capacity	Voltage	Current rating	Region	Manufacturer/year
SAE J1772/IEC 62196-2 type 1		5	7.7 kW (Level 2)	120–240 V single phase	Up to 80 A	• North America (AC/DC) • Japan (AC) • South Korea (AC)	Yazaki 2009
IEC 62196-2 type 2 Mennekes		7	7.4–43 kW	230 V single phase 400 V three-phase	Up to 63 A	• European Union (AC)	Mennekes 2009
CCS combo 1-AC/DC combined charging connector		7	• AC charging: up to 41.5 kW • DC charging: up to 90 kW	• AC: 240/415 V • DC: up to 1000 V	• AC: 16–63 A • DC: up to 200 A	• North America (DC) • South Korea (DC)	Standardized connector 2012
CCS combo 2-AC/DC combined charging connector		9	• AC charging: up to 41.5 kW • DC charging: up to 300 kW	• AC: 240/415 V • DC: up to 1000 V	• AC: 16–63 A • DC: up to 350 A	• European Union (DC)	Standardized connector 2014

Table 14: Continued.

Connector type	Graphical view	Pins number	Capacity	Voltage	Current rating	Region	Manufacturer/year
CHAdeMO		10	Up to 900 kW	Up to 1500 VDC	Up to 600 A	• North America (DC) • Japan (DC) • South Korea (DC) • European Union (DC)	CHAdeMO Association in Japan 2010
GB/T 20234C		7	Up to 48 kW	Up to 440 V	Up to 63 A	• China (AC)	Standardization Administration of China 2015
GB/T 20234 DC		9	Up to 250 kW	Up to 1000 V	Up to 250 A	• China (DC)	Standardization Administration of China 2015
Tesla supercharger		5	Up to 144 kW	Up to 480 V	Up to 300 A	• North America (DC/AC) • European Union (DC/AC)	Tesla 2003

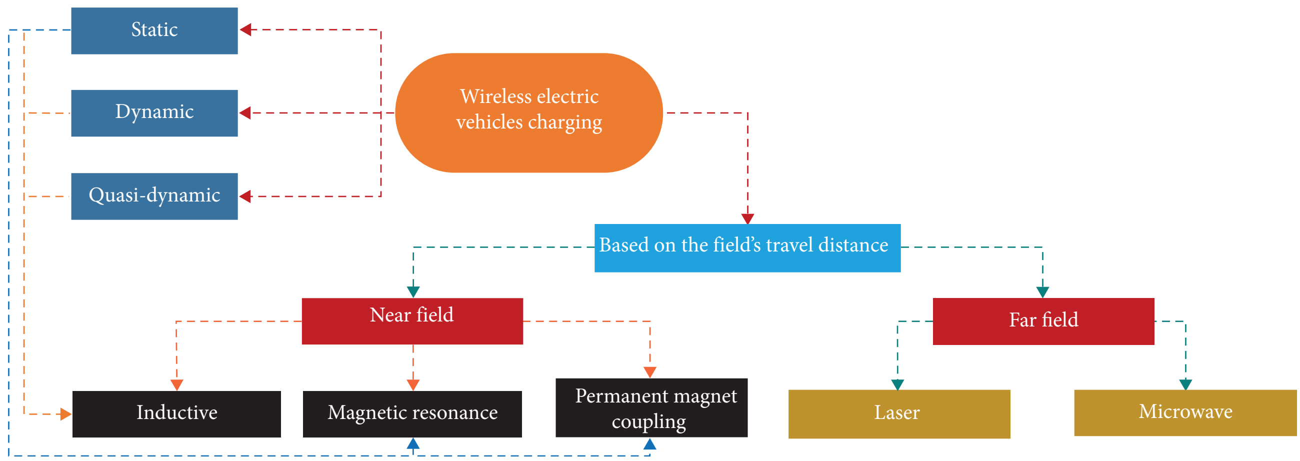


FIGURE 22: Wireless electric vehicles charging methods.

TABLE 15: Comparative analysis static, dynamic, and quasi-dynamic wireless charging methods for electric vehicles.

Term	Static charging	Dynamic charging	Quasi-dynamic charging
Charging location	• Parked vehicle, stationary charging	• Charging while driving	• Moving vehicle, low speeds and stops
Efficiency	• High	• Moderate to high	• Moderate to high
Charging time	• Relatively longer	• Shorter (on-the-go charging)	• Shorter (improved over static)
Initial cost	• Lower	• Higher	• Moderate
Safety	• Low risk	• Safety concerns during motion	• Enhanced safety during motion
Infrastructure requirements	• Basic charging stations	• Complex infrastructure	• Intermediate infrastructure
Vehicle compatibility	• Most EVs with compatible receivers	• Specific EVs with high-power receivers	• Most EVs with compatible receivers
Applications	• Home, workplace, public parking	• Highways, long-distance travel	• Traffic lights, bus stops, low-speed zones
Main drawbacks	• Slowest charging, requires parking	• High infrastructure cost, safety concerns, specific vehicles	• Slower than dynamic, localized infrastructure needed

charging scheme considers various temporal movements, such as vehicle arrival and departure times, trip history, and any unexpected instances of EV arrivals or departures. Moreover, having the capacity to charge while driving would eliminate the need for big batteries in electric cars, which would drastically lower their price [172]. While this approach is more realistic in considering the relations of EVs in both space and time, it does bring about increased complexity and requires advanced control infrastructure [138].

Quasi-dynamic wireless charging is a relatively recent approach compared to static charging and dynamic charging modes. This concept enables EVs to charge during transient stops, such as traffic signals, intersections, and bus stops, as well as while driving at low speeds [161, 165]. The concept of quasi-dynamic charging relies on achieving a balance between the advantages and disadvantages of dynamic and static charging modes. The aim is to reduce range anxiety while also keeping the overall cost of the infrastructure for charging to a minimum [160, 161]. A comparison between the static, dynamic, and quasi-dynamic wireless charging methods is presented in Table 15. Static charging is for parked vehicles, highly efficient but slow. Dynamic charging occurs while the vehicle is in motion, is efficient, but costlier, and has safety concerns. Quasi-dynamic charging suits low speeds and stops, balancing efficiency and infrastructure needs. Each has trade-offs: static is slow, dynamic is costly with safety concerns, and quasi-dynamic is slower with localized infrastructure.

WPT through electromagnetic fields is achieved through either far-field or near-field methods [154]. A comparison between near-field and far-field charging methods is provided in Table 16. Near-field operates over short distances (millimeters to centimeters) for static charging (home, public, workplace), using magnetic or electric fields with moderate to high efficiency and lower infrastructure costs. Drawbacks include limited distance and precise alignment needs. Far-field spans longer distances (meters to tens of meters) for highways, long-distance travel through electromagnetic radiation, featuring moderate efficiency, but higher infrastructure costs (dedicated lanes, antennas). Far-field drawbacks involve lower efficiency, safety concerns, and specific vehicle requirements.

Table 16: Comparative analysis between near-field and far-field charging methods for electric vehicles.

Term	Near-field charging	Far-field charging
Transmission distance	• Short (millimeters to centimeters)	• Long (meters to tens of meters)
Energy transfer	• Through magnetic fields or electric fields	• Through electromagnetic radiation
Efficiency	• Moderate to High	• Moderate
Infrastructure cost	• Lower (existing parking infrastructure)	• Higher (dedicated charging lanes, antennas)
Application	• Static charging, such as home, public, and workplace charging	• Dynamic charging, such as on-road or highway charging
Technology	• Inductive, magnetic resonance, permanent magnet coupling	• Microwave, laser
Main drawbacks	• Limited distance, requires precise alignment	• Lower efficiency, safety concerns, specific vehicles needed

Far-field techniques are capable of transmitting energy over substantial distances from the transmitter [171]. Far-field WPT uses electromagnetic radiations in the GHz frequency range, such as lasers, to transfer power [173] and microwave [174]. This technology involves a three-step process: initially converting electrical energy into radio frequency, microwave, or laser; second, transmitting the converted energy through space; and finally, collecting and converting the power at the destination back into electrical energy [161]. Meanwhile, far-field charging technologies, still under extensive research, are anticipated to be the future trend in wireless charging methods for EVs [175].

Laser charging technology has the capability to provide significant power, though with limited efficiency. This method involves the complex process of transferring power by converting electrical current into a laser beam. Referred to as power beaming, the power is transmitted in the form of a laser beam to the receiving end. The electromagnetic radiation spectrum of the laser is closer to the visible part of the spectrum. Special laser photovoltaic (PV) converters optimized for monochromatic light conversion are employed in this application [176]. Enhancing the efficiency of this charging technology necessitates stringent precautions and limitations. Any misdirection of the laser beams poses a potential hazard to life and results in energy loss.

Among the diverse WPT systems, radio waves or microwaves boast the longest history. In 1904, N. Tesla conducted WPT using 150 kHz radio waves. In 1964, W. C. Brown achieved the flight of a battery-less helicopter powered by a 2.45 GHz magnetron [177]. In addition to having control over the direction of the microwave beam at a desired location, microwave power transmission can achieve an extended transmission range. However, the transmission efficiency in microwave charging appears to be lower compared to other WPT methods. Through this wireless function, EVs are charged by a microwave beam from the transmitter, which the receiver then captures [178].

With near-field power transmission, there is no need for a conversion medium or a high-frequency range of conversion because the electrical power is transferred within a constrained area [179]. In this context, the transmitter only emits power when within the receiver range, and the range of these fields is determined by the size and shape of the transmitter and receiver [180]. The existence of separate electric and magnetic fields in the near-field region allows for power transfer via electrodes in the electric field and coils in the magnetic field [181, 182]. This technology is currently in use, with power transferred through magnetic fields using inductive coupling between metal coils over short distances [183]. Near-field transmission techniques include coupled magnetic resonance, permanent magnet coupling, and inductive.

The coupled magnetic resonance method consists of using transmitting and receiving coils alongside capacitances to facilitate compensation and PFC. This arrangement establishes a resonant condition, optimizing the wireless charging process for maximum power transfer [161]. Based on the coupling theory model, this method allows efficient power transfer over desired distances. It utilizes two antennas connecting the primary and secondary parts at the same operating frequency levels. South Korea has implemented online EVs using resonance coupling through dynamic wireless charging [184, 185]. This technology achieves an efficiency of approximately 90% within a one-meter range [186, 187]. Further enhancements in efficiency can be achieved by integrating magneto plate wires [167, 188].

The University of British Columbia has implemented a WPT technique based on permanent magnet coupling, utilizing neodymium permanent magnets that function as a magnetic coupler [189]. This technique operates on the principle of the magnetic gear effect, where the primary side's permanently magnetized rotor rotates the secondary rotor at synchronous speed. However, this approach introduces some drawbacks, including noise, vibrations, and temperature generated by numerous mechanical elements. Alignment and maintenance are particularly notable challenges associated with the permanent magnet WPT technique. In comparison to other EV charging technologies, the permanent magnet WPT is not convenient due to its bulky size, lower efficiency, and the presence of rotating mechanical parts [167]. A prototype of the permanent magnet WPT was developed by Covic et al. [190], showing a power transfer efficiency of 81% at a frequency of 150 Hz for a distance of 150 mm.

Inductive charging is being researched and tested, which transfers energy via an electromagnetic field [191]. An EV can

Table 17: Comparative analysis between conductive and inductive charging of electric vehicles.

Term	Conductive charging	Inductive charging
Energy transfer	• Through physical connection (cables, plugs)	• Through an electromagnetic field
Efficiency	• High	• Moderate to high (due to energy loss in magnetic field)
Charging time	• Faster	• Moderate (typically several hours)
Infrastructure cost	• Lower	• Higher (requires installation of charging pads)
Flexibility	• More widespread, various connectors	• Limited by alignment and coil structure
Maintenance	• Requires regular cleaning of connector pins	• Lower maintenance (no physical contact)
Vehicle compatibility	• Requires compatible charging port	• May require additional equipment depending on vehicle and system
Safety	• Requires careful handling of connector	• Lower risk of electric shock as no direct contact
Interference	• Susceptible to wear, weather, and vandalism	• Less susceptible to wear and weather
Future outlook	• Continued development of faster charging and smart features	• Potential for wider adoption in specific applications and autonomous vehicles

be charged through inductive charging technology without the need for physical connections. In comparison to conductive charging, it has a number of benefits, including automation, flexibility, reliability in adverse conditions, and safety in harsh environments. However, there are a lot of challenges with inductive chargers, including their expensive price, sensitivity to misalignments, and complex design. The majority of these issues are related to the coils in the transmitter and receiver [154]. A comparison between conductive and inductive charging for EVs is presented in Table 17. Wireless charging systems use WPT technology, which is based on inductive resonant coupling [192]. In Figure 23, a basic inductive charging system for EVs is illustrated, including essential components such as an input AC/DC converter, a DC/AC inverter, compensation networks, a magnetic coupler, and an output AC/DC converter. The AC power obtained from the utility grid is first converted to DC power by a rectifier. Subsequently, with the assistance of the inverter and the compensation network, a sinusoidal high-frequency current is delivered to the primary coil. PFC control schemes can be employed to mitigate current harmonics in the input rectifier. Moreover, the high operating frequency necessitates the use of soft-switching methods, thereby reducing inverter switching losses. The conversion of the induced voltage at the secondary coil to a constant DC value, for the purpose of charging the EV battery, is accomplished through the output rectifier. To ensure that both sides operate at the same frequency, a secondary compensation network is added to the secondary circuit [171].

The compensation circuits on both the primary and secondary sides play an essential role in an inductive power transfer (IPT) system. Their primary objective is to compensate for the impact of leakage inductances, thereby optimizing both efficiency and the power transfer capability of the system. Table 18 illustrates the different configurations of compensation circuits employed in WPT systems, including the series–series (SS), SP, parallel–series (PS), and parallel–parallel (PP) configurations. In terms of circuit equivalent impedance at resonance, SS and SP topologies exhibit minimum values, while PS and PP topologies show maximum values. The dependance of the primary compensation capacitance on load is minimal for SS and SP, but significant for PS and PP, requiring critical tuning. The type of AC source needed for transferring maximum power varies, with SS and SP requiring a voltage source, and PS and PP needing a voltage source at high voltage/current. Peak efficiency is higher for SS and PS, moderate to higher for SP, and moderate to low for PP. Efficiency percentages range from 95% to 98% for SS, 75%–85% for SP, 92%–95% for PS, and 70%–80% for PP. The tolerance of efficiency to variable frequency is lower for SS and PS, and higher for SP and PP. Conversely, the tolerance of power factor to variable frequency is higher for SS and PS, and lower for SP and PP. Each topology has its advantages and disadvantages. SS is simple, efficient, low-cost, and suitable for large power transfer. SP provides higher tuning flexibility and is good for mid-power applications. PS shares similar advantages with SP but is more suitable for near-field applications. PP, on the other hand, is complex, has lower efficiency, and is highly sensitive to misalignment.

Efficient power transfer in EV wireless charging presents challenges that need careful consideration. The process of WPT involves energy conversion, leading to a natural reduction in efficiency during conversion and transfer. Consequently, there is a critical need for optimization to enhance the overall transfer efficiency. These challenges have contributed to the hesitancy of some businesses to transition from conductive charging to wireless alternatives. The components of wireless chargers require comprehensive research. Various factors, including distance, geometry, frequency, efficiency, compensation topology, coil design, system load, volume and weight, coil position and alignment, and vehicle speed, directly or indirectly impact the practical system's performance. The description and the effect of each factor are provided in Table 19.

3.5. Challenges in EV Charging. Despite the increasing popularity of EVs, widespread adoption faces two key barriers, the high purchase cost and the limited maximum range of the vehicles [193].

Charging technology presents challenges for users. Many customers face issues while charging their EVs, leading

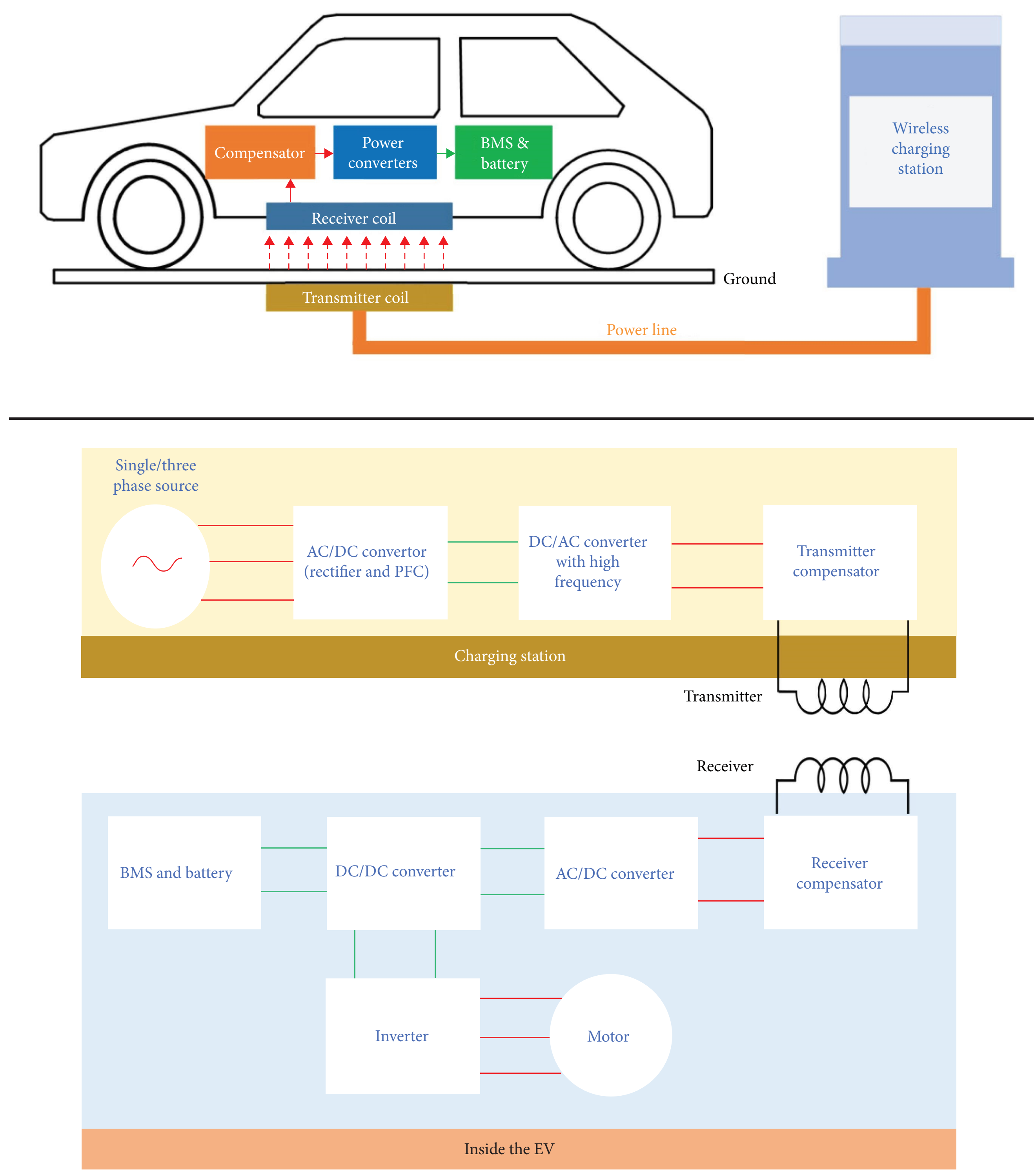


FIGURE 23: Inductive electric vehicles charging system.

automakers to explore new solutions. The EV industry confronts ongoing challenges, including the high cost of battery technology, range anxiety, and limited charging infrastructure. The primary issue is the considerable cost associated with battery technology. The manufacturing of batteries for EVs involves expensive components, often challenging to secure, as they need to store large quantities of charge to make EVs functional for the majority of consumers. Consumers are unwilling to purchase EVs due to the high cost of the batteries. CV Raman, Senior Executive Director (Engineering) at Maruti Suzuki India, stated that EVs are expected to be priced at two-and-a-half times more than the same model

Table 18: Comparative analysis between configurations of compensation circuits employed in wireless power transfer systems.

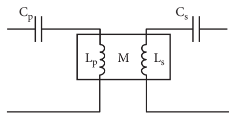
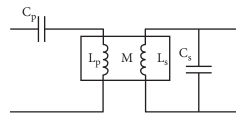
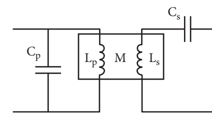
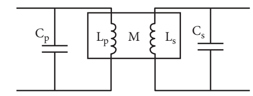
Term	SS topology	SP topology	PS topology	PP topology
Resonant circuits				
Circuit equivalent impedance at resonance	Minimum	Minimum	Maximum	Maximum
Dependance of the primary compensation capacitance on load	None	None	Affects resonant frequency (tuning needed)	Highly affects resonant frequency (tuning critical)
Type of AC source to be applied to transfer maximum power	Voltage source	Voltage source	Voltage source at high voltage/current source	Voltage source at high voltage/current source
Peak efficiency	Higher	Moderate–higher	Higher	Moderate–Low
Efficiency (%)	95%–98%	75%–85%	92%–95%	70%–80%
Tolerance of efficiency to variable frequency	Lower	Higher	Lower	Higher
Tolerance of power factor to variable frequency	Higher	Lower	Higher	Lower
Advantages	Simple, efficient, low cost, good for large power transfer	Higher tuning flexibility, good for mid-power applications	Higher tuning flexibility, good for mid-power applications	Simple, good for near-field applications
Disadvantages	High sensitivity to misalignment, limited tuning flexibility	Moderate sensitivity to misalignment, more complex	Moderate sensitivity to misalignment, more complex	High sensitivity to misalignment, complex, lower efficiency

Table 19: Factors affecting wireless charging.

Factor	Description	Effect on wireless charging
Distance	• Distance between the transmitter and receiver coils	• Efficiency decreases significantly as distance increases. This is due to a weaker magnetic field and energy dissipation across the gap
Geometry	• Shape and arrangement of the coils	• Larger coils generally offer higher efficiency. Coil shapes can also influence coupling strength and field distribution
Frequency	• Resonant frequency of the system	• Higher frequencies can result in faster charging but suffer from lower efficiency due to increased resistive losses in the coils. Conversely, lower frequencies offer better efficiency but at the cost of slower charging
Efficiency	• Energy conversion and transfer efficiency	• Reduces overall efficiency
Compensation topology	• The circuit design used to match the impedance of the transmitter and receiver coils for resonant energy transfer	• Different topologies have varying degrees of efficiency and sensitivity to misalignment. Choosing the optimal topology is essential for maximizing efficiency
Coil design	• The materials, number of turns, and winding pattern of the coils	• Coil materials with low resistance and high magnetic permeability improve efficiency. More turns generally increase efficiency but also raise inductance and self-resonant frequency considerations
System load	• The amount of power demand from the electric vehicle battery	• Efficiency typically decreases as the load increases due to higher conductor losses in the system
Volume and weight	• The physical size and weight limitations of the charging system	• Compact designs, while desirable, can restrict coil size and material choices, potentially impacting efficiency
Coil position and alignment	• The relative position and orientation of the charging pad and receiver coil	• Misalignment reduces the coupling strength and energy transfer efficiency. Precise alignment is critical, especially for higher frequencies
Vehicle speed	• Speed of the electric vehicle (applicable to dynamic charging)	• Lower efficiency with increasing speed due to changes in coupling and increased power demand

equipped with a conventional petrol or diesel-driven engine [194].

Range anxiety is considered another challenge of EVs. This term refers to the fear of running out of electrical power before reaching the desired destination [195]. The shortage of charging infrastructure in the country is a cause for concern among customers. In gasoline vehicles, the customers are not worried about running out of fuel because petrol stations are widely spread in different areas. According to Rudratej Singh, who is the president and CEO of BMW Group in India mentioned that "the infrastructure for EVs is still vague and unclear" [196]. This factor would have a significant effect on customers' acceptance when it comes to EV adoption. Customers might not accept this shift because they are uncertain about the infrastructure of EVs, and they are worried about the limited charging infrastructure. Although there are some charging stations in the testing stages, most charging must be done at home, in a garage. These challenges show the importance of focusing research and development on battery improvements, as this would not only reduce purchase costs but also enhance the maximum range of EVs.

Consumers who live in a shared house or use the same parking space are the most struggling during charging. Based on Maruti Suzuki's research, "around 60% of Indian customers don't have their own parking space" [197]. C V Raman pointed out that it is impossible for those customers to charge their vehicles.

In [198], the authors focus on the barriers to the adoption of BEVs from public perception in China. According to Egbue and Long [199], consumer acceptance is another significant barrier to the adoption of EVs. The authors highlighted three main characteristics of EV adoption barriers: financial, performance, and infrastructure. The price of EVs, the battery cost, lack of fuel cost knowledge, and maintenance costs are considered financial barriers. The high price of Li-ion batteries makes EVs more expensive. The high capacity of batteries is increasing both the driving range and purchase cost. The safety, reliability, range, battery life, charging time, and power of EVs depend on the performance barriers. Lastly, the availability of charging stations in several places, such as highways, workplaces, and public places, is an example of the infrastructure barriers. The consumers' characteristics also play a vital role in the adoption of EVs. Gender, age, income, and environmental awareness are among these characteristics [200]. For instance, consumers who are well-informed on the environmental benefits of EVs would rather choose an EV over a gasoline-powered vehicle. Based on survey results in 21 American cities, it was discovered that a majority of consumers thought that the cost of EV maintenance would be more expensive than gasoline-powered vehicles due to a lack of knowledge [201].

One of the significant challenges in EV charging is the considerable time it takes compared to refueling a gasoline vehicle. Charging an EV can take anywhere from 15 min to 8 h, depending on the charger type, whereas refueling a gasoline vehicle typically takes only 3–5 min for a full tank. Another crucial challenge in EV charging is the limited availability of charging infrastructure. Due to the novelty of EV technology, there is a shortage of charging stations globally. This issue makes EVs less suitable for long trips, resorting to charging at home due to the insufficient availability of charging stations [202, 203].

Grid capacity is also a major concern for EV charging [204]. As the adoption of EVs increases, people will rely on electric grids for charging. To accommodate these vehicles without overloading the grid, there is a need to enhance power generation capacity. This challenge emphasizes the necessity for comprehensive infrastructure development and grid capacity expansion to facilitate the widespread acceptance and practicality of EVs.

Table 20 summarizes the challenges associated with EV charging, outlining these challenges alongside proposed solutions and mitigation methods.

3.6. Smart Grid Integration With EV Charging. Significant challenges for power grid stability are introduced by the rapid expansion of EV adoption, particularly in relation to peak demand, charging coordination, and the intermittent nature of RESs. For the management of these complexities, smart grid technologies have emerged as a critical solution. Real-time monitoring, dynamic control, and load balancing capabilities are all facilitated by a smart grid, which allows for two-way interaction between utilities and EVs, thereby facilitating the integration of large-scale EVs into preexisting power systems [205].

One of the most prominent applications within this framework is V2G technology. V2G technology is one of the most well-known uses of this system. V2G facilitates EVs not only get power from the grid, but also provide power back during times of high demand. This two-way flow of power makes the grid more flexible, assists with services such as voltage and frequency regulation, and can potentially postpone the necessity for adjustments to infrastructure [206]. In consequence of this, EVs become distributed energy resources that contribute to the grid to be more reliable and efficient.

Smart charging is an essential element of grid–EV interactions. These technologies enhance charging patterns according to grid load situations, power tariffs, and the availability of renewable energy. Smart charging can be executed in either unidirectional or bidirectional formats and is frequently integrated with demand response systems that mitigate load during peak hours [207]. Smart charging minimizes grid stress and synchronizes EV charging demand with peak renewable energy supply, thereby decreasing carbon intensity and enhancing system sustainability.

Recent developments in control systems have significantly improved the performance of smart charging. Reinforcement learning techniques are widely utilized to forecast appropriate charging schedules based on user behavior, market signals, and limitations of the system [208]. These intelligent systems can independently adjust to real-time variations, enhancing energy efficiency and satisfaction among users.

While EVs provide substantial advantages for smart grids, their incorporation poses multiple challenges. Regular battery cycling in V2G systems can accelerate degradation, reducing battery lifespan and compromising performance. The lack of

Table 20: Challenges in electric vehicles charging with proposed solutions and mitigations methods.

Challenge	Description	Proposed solutions	Mitigation methods
Limited charging infrastructure	Insufficient charging stations lead to long wait times and limited access, particularly in rural areas	• Encourage private investment in charging infrastructure • Promote public–private partnerships • Invest in infrastructure development	• Address local concerns • Ensure accessibility in rural areas • Improve user experience • Encourage home charging and promote workplace charging facilities for employes
Long charging time	Current technology requires long charging times, leading to range anxiety. This affecting convenience and user satisfaction	• Implementing smarter charging systems to optimize energy transfer • Improve battery technology	• Balance charging speed and battery capacity • Manage user expectations • Invest in research and development for improved charging technologies.
Safety concerns	Concerns about the safety of electric vehicles and charging stations	• Implement safety standards, regulations, and best practices • Promote manufacturer responsibility	• Raise awareness • Enforce regulations • Collaborate with stakeholders for safe charging infrastructure.
High cost of electric vehicles	High cost of electric vehicles and charging infrastructure	• Promote government incentives, subsidies, and tax credits • Encourage innovation in battery and charging technology	• Make EV purchases and charging installations more affordable • Incentivize innovation • Invest in research and development for cost reduction.
Low range of electric vehicles	Concern about running out of charge before reaching a charging station. This hinders widespread adoption	• Increase battery capacity and efficiency • Improve battery technology • Optimize charging processes • Develop better navigation systems with real-time charging station information	• Balance performance and cost • Manage user expectations • Invest in research and development for increased battery capacity
Lack of awareness	Low awareness about electric vehicles among drivers and the public	• Educate and promote electric vehicles • Raise awareness about charging infrastructure • Encourage manufacturer-sponsored events	• Develop targeted marketing campaigns • Collaborate with stakeholders • Promote electric vehicles through various channels
Interoperability	Different charging standards and connectors can cause compatibility issues	• Establish global standards for charging technology and connectors • Develop universal adapters to bridge compatibility gaps • Implement open communication protocols for seamless charging across different networks	• Inform drivers about different charging standards and compatibility issues • Invest in charging equipment that can support multiple standards
Grid integration	Large-scale EV charging can overload the electricity grid	• Implement load management solutions • Smart grid technology • Implement smart charging and V2G technologies • Renewable energy integration	• Upgrade grid capacity • Optimize charging patterns • Manage peak load • Optimize power flow • Improve grid reliability • Encourage charging during off-peak

standardized communication standards hinders widespread adoption [209].

4. EVs Charging Standards

Numerous national and international organizations are actively involved in developing standards, guidelines, specifications, and recommended practices for EV charging infrastructure across various vehicle types and operational environments. These entities include prominent names such as the Society of Automotive Engineering, International Electrotechnical Commission (IEC), Japan Automobile Research Institute (JARI), International Organization for Standardization (ISO), Underwriters Laboratories (UL), Institute of Electrical and

FIGURE 24: Electric vehicle charging standards and protocols.

Electronics Engineers (IEEE), National Electrical Code (NEC), and the National Technical Committee of Auto Standardization (NTCAS). This collaborative effort ensures the establishment of comprehensive and universally recognized frameworks to enhance the interoperability, safety, and efficiency of EV charging systems globally. The primary standards and protocols for EV charging are shown in Figure 24 and described in Table 21.

In the United States, SAE and IEEE are the primary organizations responsible for developing EV charging standards. SAE J1772 is a widely used standard that defines the connector types and their associated requirements for EV charging. Japan has its own EV charging standards named CHAdeMO, which are published as IEEE standards. The CHAdeMO standard specifies the collaborative actions between EVs and fast chargers, referencing relevant international specifications, including SAE standards. China uses the Guobiao (GB/T) standard (issued by the Standardization Administration of China and the Chinese National Committee of ISO and IEC) for AC and DC charging. IEC standards are comparable to GB/T AC charging standards [138].

5. Conclusions

EVs have emerged as a viable alternative to conventional vehicles. This paper has provided a comprehensive review of EV

Table 21: Description of the electric vehicles' standards and protocols.

Standard	Description
Charger topology, conductive charging	
IEC 61851-1	Defines general requirements for conductive charging systems for electric vehicles, including aspects, such as system design, safety, and reliability
IEC 61851-21	Sets requirements for electric vehicle on-board chargers, including EMC requirements for conductive connection to AC/DC supply and electric vehicle requirements for conductive connection to an AC/DC supply
IEC 61851-22	Provides guidelines for the design and implementation of DC fast-charging stations, including aspects such as safety, reliability, and interoperability
IEC 61851-23	Sets requirements for DC electric vehicle charging stations, including aspects such as system design, safety, and reliability
IEC 61851-24	Defines the requirements for digital communication between a DC EV charging station and an electric vehicle for control of DC charging, including aspects such as data transfer, communication protocols, and security
IEC 61851-25	Addresses the design and implementation of DC EV supply equipment, where protection relies on electrical separation
Charger topology, wireless charging	
SAE J2954	It focuses on wireless power transfer for light-duty plug-in/electric vehicles. The standard defines acceptable criteria for interoperability, electromagnetic compatibility (EMC), and electromagnetic fields
IEC 61980-1:2020	It specifies general requirements for WPT systems for EVs, addressing safety aspects related to maintenance, WPT systems for trolley buses, rail vehicles, and vehicles designed primarily for use off-road, as well as any safety or EMC requirements for the vehicle side
IEC 61980-3:2022	It specifies requirements for magnetic field WPT (MF-WPT) systems, including the characteristics and operating conditions of the supply equipment, the required level of electrical safety, and the requirements for basic communication for safety and process matters if required by an MF-WPT system. The standard also covers the requirements for positioning to ensure efficient and safe MF-WPT power transfer
IEC/TS 61980-3	Specifies special requirements for the magnetic field produced by the wireless charging equipment
JARI G109:2001	Japanese standard that describes the use of inductive power transfer (IPT) systems to transmit power wirelessly. It also defines universal requirements for the wireless charging process
UL 9741	It defines universal requirements for the interchange charging process, considering bidirectional operation to support the power grid and feed traditional loads. It focuses on the use of IPT systems to transmit power wirelessly, emphasizing the ability to support bidirectional operation for grid support and traditional load feeding
Charging connectors	
IEC 62196-1	Establishes the specifications for plugs, socket-outlets, vehicle connectors, and vehicle inlets needed for the conductive charging of electric cars with rated operating voltages of no more than 690 V AC (50–60 Hz) at no more than 250 A in current; and no more than 1500 V DC at no more than 800 A in current
IEC 62196-2	Specifies the requirements for plugs, socket-outlets, vehicle connectors, and vehicle inlets for conductive charging of electric vehicles with a nominal rated operating voltage not exceeding 480 V AC, 50–60 Hz, and a rated current not exceeding 63 A three phase or 70 A single phase
IEC 62196-3	Specifies the requirements for vehicle couplers with pins and contact tubes of standardized configuration, intended for use in electric vehicle conductive charging systems, which incorporate control means, with rated operating voltage and current in accordance with IEC 62196-1
SAE J1772	Defines a common EV/PHEV and supply equipment vehicle conductive charging method including operational requirements and the functional and dimensional requirements for the vehicle inlet and mating connector
IEEE 1901	IEEE 1901 is a standard for power line communication (PLC) that is used for communication between an electric vehicle and a charging station. The standard specifies the physical and electrical characteristics of the connector used for communication, including aspects, such as data transfer, communication protocols, and security. The IEEE 1901 standard is used in conjunction with other standards, such as SAE J1772 and IEC 61851, to ensure interoperability and safety of electric vehicle charging systems
GB/T 20234-1/2/3	Establishes a comprehensive requirement for EV charging connectors, addressing general specifications, dimensional compatibility, and interchangeability for both AC and DC charging systems, ensuring a standardized and interoperable charging infrastructure in China. GB/T 20234 provides physical requirements for connectors and interfaces, corresponding to IEC 62196 and SAE J1772

Table 21: Continued.

Standard	Description
Charging safety	
IEC 60529	Specifies the level of protection provided by electrical equipment enclosures against the entry of solid foreign objects and the damaging effects of water intrusion
IEC 60364-7-722	Applies to circuits designed to feed electricity back from electric vehicles as well as circuits designed to supply energy to electric vehicles. This document covers circuits that terminate at the connecting point
ISO 6469-3	Specifies the safety requirements for electrically propelled road vehicles, including aspects such as electrical safety, functional safety, and protection against fire and explosion
SAE J1766	A recommended procedure for testing the crash integrity of battery systems in electric and hybrid vehicles that is applicable to all battery designs for these types of vehicles, including those outlined in SAE J1797
SAE J2464	A recommended practice guide for testing the safety and robustness of rechargeable energy storage systems (RESSs) used in electric and hybrid electric vehicles
UL 2202	This standard applies to DC conductive charging equipment intended to be supplied with a for recharging the propulsion batteries in over-the-road EV. The standard covers the requirements for DC charging equipment for EV installations intended for either dry location only or dry, wet, and damp location. The standard also specifies the requirements for electric vehicle supply equipment
ECE R100	Outlines every test that needs to be done on lithium batteries installed in four-wheel electric vehicles before they can be used to transport persons or goods. The safety of electric vehicles and their battery systems is guaranteed by the regulation
Charging communication	
OpenADR	Open ADR is intended to make it easier for utilities, energy management control systems, and customer-owned energy resources, such as EV charging infrastructure, to automatically exchange data
OCPI	OCPI functions is an open roaming protocol, encouraging communication between operators and service providers. As an internationally supported independent interface, it promotes the affordability and availability of charging infrastructure. The protocol facilitates the exchange of accurate charge station information, including location, availability, and pricing. It also manages bilateral roaming, enabling real-time billing and mobile access to charge stations
OSCP	OSCP serves as an open communication protocol facilitating communication between the charge point management system and the energy management system of the site owner or the distribution system operator (DSO). This protocol conveys a 24-h forecast of the electricity grid's available capacity. The service provider utilizes this information to align the charging profiles of electric vehicles within the confines of the available capacity
OCPP	OCPP serves as an open communication protocol facilitating interaction between the charging station and the central system of the charging station operator. This protocol manages the charging transaction and also enables the exchange of information between the vehicle and the electricity grid
SAE J2293-2	Applies to electric vehicles as well as the off-board equipment used to supply electricity to an electric vehicle from a North American electric utility power system
SAE J2847	This standard along with SAE J1772 specify the communication requirements between an EV and the charging infrastructure. SAE J2847 specifies the communication requirements
SAE J2931	The requirements for digital communication between electric vehicles, energy service interfaces (ESIs), home area networks, utilities, and EVSEs are set up in this standard. The requirements outlined by SAE J2931 must be met in order to set up a communication network for EV charging in a smart grid setting
ISO15118/IEC61850	ISO 15118 is an international standard that defines the communications protocol between the charging station and the electric vehicle, whether using AC, DC, wireless, or conductive charging. IEC61850 is an international standard for communication networks and systems used in power utility automation, particularly within electrical substations and smart grids
SAE J2836/6_201305	It specifies the communication protocols and processes needed for wireless charging
SAE J2847/6_201508	It establishes requirements and specifications for communications messages between wirelessly charged electric vehicles and wireless electric vehicle chargers
IEC/TS 61980-2	It addresses the specific requirements for communication between EVs and WPT systems. The standard focuses on the communication and activities of MF-WPT systems
GB/T 27930	It is a Chinese protocol for electric vehicle charging communication between the off-board conductive charger and the BMS of an electric vehicle

Table 21: Continued.

Standard	Description
Charging power quality	
SAE J2894	Provides guidelines for the power quality requirements of plug-in electric vehicle (PEV) chargers, whether on-board or off-board the vehicle. The standard aims to enable equipment manufacturers, vehicle manufacturers, electric utilities, and others to make reasonable design decisions regarding power quality. The standard identifies the parameters of PEV battery chargers that must be controlled to preserve the quality of the AC service
NEC 690	It covers the installation of solar photovoltaic (PV) systems, including electric vehicle charging systems. It includes requirements for the design, installation, and maintenance of PV systems to ensure the safety and quality of electric vehicle charging
IEEE 1547	Guidance on how to connect EV charging stations so that they can export power to the connected power system in both directions, either as active or reactive power exchange. It contains specifications for the quality, safety, and testing of DER systems based on inverters, which can be utilized in conjunction with infrastructure for charging electric vehicles
IEEE 1000-3-2	It is used to ensure the power quality of electric vehicle charging systems, ultimately supporting the widespread adoption of electric vehicles

technologies, including all-EVs and HEVs. The paper has also discussed the architecture of EVs, battery technologies, BMSs, electric motors, and charging technologies, including conductive and wireless charging systems. The challenges associated with EV charging, such as the lack of charging infrastructure and high production costs, were also addressed.

The paper concludes that governments should prioritize consumer education, support the construction of charging infrastructure, offer incentives for EV materials, particularly lithium, lower the cost of charging tariffs, and fund various pro-EV research projects in order to increase consumer adoption. Adoption of EVs will rise when these issues are resolved, leading to cleaner air and better mobility. The findings and recommendations presented in this paper are expected to contribute to the creation of EV and charging station designs, as well as the deployment of fast charging stations for EVs. Ultimately, the widespread use of EVs will result in lower GHG emissions and better air quality, making the future more sustainable.

This evaluation endorses progress in EV manufacturing and infrastructure development through an organized review of existing technology. The comparative analysis of electric motors, battery chemistries, and BMS offers essential insights for enhancing vehicle performance and production efficiency. The discourse on charging technologies and standards, encompassing rapid and wireless charging, informs the advancement of charging infrastructure that is both user-oriented and compatible with the grid. Moreover, the integration of EVs with smart grids and the prospects of bidirectional energy transfer (such as V2G technologies) provide significant advantages for infrastructure development, energy administration, and policy synchronization. These observations provide a basis for industrial innovation and regulatory frameworks to expedite the shift toward sustainable mobility.

Despite offering a comprehensive review of EV technologies and their integration with smart grids, this study has several limitations. This study uses secondary data from other studies and doesn't do any original research or simulations, which could make its results less reliable. Since EV technologies are evolving rapidly, some of the information looked at could soon become out of date. The analysis goes into detail about important technological issues, but it doesn't go into detail about economic factors, consumer behavior, or the effects of policy, all of which are very important for EV adoption. Concerns about the environment, such as developing batteries, obtaining raw materials, and recycling, have been raised but not fully evaluated through complete life cycle evaluations. Furthermore, the focus on mainstream technologies (e.g., lithium-ion batteries and permanent magnet motors) may overlook promising emerging alternatives, such as solid-state batteries.

Future research should investigate a variety of complementary directions. These include the creation of scalable electric motor designs that decrease dependance on rare earth materials, as well as the development of next-generation battery chemistries such as solid-state, etc. Additional research is required to improve grid integration strategies, which include advanced V2G technologies and smart charging algorithms that facilitate renewable energy utilization and demand response. To facilitate the equitable and efficient adoption of EVs on a global scale, future research should evaluate regulatory frameworks, dynamic pricing models, and infrastructure deployment strategies from a policy and planning perspective.

Data Availability Statement

Data sharing is not applicable to this article, as no datasets were generated or analyzed during the current study.

Ethics Statement

All the authors mentioned in the manuscript have confirmed that all the research meets the ethical guidelines, including adherence to the legal requirements of the study country.

Conflicts of Interest

The authors declare no conflicts of interest.

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