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Research Article

Recent Developments in EV Charging Infrastructure: Opportunities and IoE Framework Challenges

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Abstract: The increasing demand for environmentally sustainable modes of transportation has resulted in the widespread adoption of electric and plug-in hybrid vehicles, which has created significant challenges for car manufacturers and researchers globally. These challenges include the high cost of battery energy storage, limited EV range, battery lifespan, and the cost of deploying fast charging infrastructure. EV charging systems can be classified into three levels based on the output power and charging time. Furthermore, there are three types of charging systems available: inductive recharging (contactless power transfer), conductive charging systems, and battery swapping. Moreover, hydrogen-based fuel cell electric vehicles are currently undergoing extensive research and development in both academic and industrial sectors. This paper presents a detailed account of the prototype equipment and its instrumentation, along with the results of the system characterization. Furthermore, the prospects of wireless power transfer technology are deliberated upon in light of various technical and economic challenges that need to be addressed. The feasibility of integrating this technology into future road infrastructure is also examined. Finally, the paper concludes by outlining future research and demonstration steps that need to be taken to advance the technology.

Keywords: Electric Vehicles; Battery Electric Vehicles, Fuel Cell Electric Vehicles; Hybrid Vehicles, Charging Stations, Wireless Charging.

1. Introduction

Electric vehicles (EVs) have emerged as a critical technology to decarbonize the road transport sector, which accounts for 16% of global emissions. The past few years have witnessed an exponential surge in electric vehicle sales, coupled with range improvements, wider model availability, and enhanced performance. It is clear that passenger electric vehicles are increasingly becoming popular, and it is estimated that about 13% of new cars sold in 2022 will be electric. If this growth trend continues, it will pave the way for CO2 emissions from vehicles to align with the net zero emissions by 2050 scenario. However, it is worth noting that the global reach of EVs is not yet ubiquitous. In developing and emerging countries, sales have been sluggish due to higher purchase costs and the limited availability of charging infrastructure [1].

The domain of clean energy exhibits remarkable dynamism in the EV market, where sales of EVs have escalated significantly. Specifically, the sales of EVs have reached a new record of 6.6 million in 2021, which is twice the figure from the previous year. To clarify, this is a significant surge from 2012, when the worldwide sales of EVs were merely 120,000. The contemporary market, however, outpaces this previous figure, as over 120,000 EVs will be sold each week in 2021 [2]. Furthermore, the market share of EVs has witnessed a substantial surge, constituting almost 10% of global car sales in 2021. This is four times the market shares in 2019, signifying an exponential growth pattern. As a result, the total number of EVs on roads worldwide has augmented to about 16.5 million, thrice the amount in 2018. This upward trend in the sales of EVs has persisted, with global sales ascending vigorously in 2022. In the first quarter alone, 2 million electric cars were sold, reflecting an increase of 75% from the same period in 2021 [2].

The future of EVs appears to hold promise, notwithstanding a few warning signals arising from their supply chain, particularly the increase in bulk material prices that has affected the entire auto industry. In 2021, the prices of crucial materials, such as steel, aluminum, and copper, increased substantially, with a 100%, 70%, and over 33% surge, respectively. These price hikes impacted both conventional and electric vehicles, and the latter experienced further impediments due to increased prices for battery manufacturing materials [3]. Specifically, the prices of essential components like lithium carbonate, graphite, and nickel escalated by 150%, 15%, and 25% year on year, respectively. These increases underscore the challenges faced by EV manufacturers in managing the costs associated with their production and supply chain.

As the world transitions towards a more sustainable future, the demand for electric vehicles (EVs) is on the rise. The development of battery technology has made it possible for EVs to have longer driving ranges and faster charging times. However, the success of EVs is highly dependent on the availability of charging infrastructure, which has become a significant challenge for the industry. A recent paper [4] describes charging station terminologies, including different types and levels. Furthermore, it investigates various technologies that can be used to overcome charging infrastructure challenges. In addition, the paper briefly discusses lithium-ion battery charging strategies and the important role of battery management systems (BMS). Furthermore, the Indian government is committed to building an environmentally friendly ecosystem and reducing carbon emissions from the transportation sector. Moreover, another paper [5] determines and outlines charging station installation and electrical charging scheduling of activities, in addition to the global circumstances of charging infrastructure schedules. Furthermore, this work addresses the challenges and solutions related to the market for and deployment of EV charging infrastructure. The limitation of this paper is that the foreseeable scope of EV charging infrastructure is not highlighted.

One of the significant contributions of technology development in EVs is the improvement of battery technology, which offers higher energy densities and longer driving ranges. Additionally, new batteries are being developed to address the limitations of Li-ion batteries, such as safety and cost issues. However, the deployment of charging infrastructure poses several challenges. The first challenge is the lack of standardization of charging protocols, which has resulted in the proliferation of different types of charging connectors and communication protocols. This creates confusion for EV drivers and increases the cost of charging infrastructure deployment. Additionally, the deployment of charging infrastructure requires significant investments in grid infrastructure and the development of new business models, which can be a challenge for governments and private investors. Technological developments in battery technology and fast charging have significantly improved the performance of EVs. Besides that, governments, automakers, and charging infrastructure providers need to collaborate to address these challenges and promote the adoption of EVs as a sustainable mode of transportation.

This paper is structured as follows: **Section 2** focuses on the different types of EVs. **Section 3** presents the types of charging stations. **Section 4** provided a discussion of the interface of EVs and the Internet of Energy (IoE) Framework, which is categorized into three groups: charging techniques, charging procedures, communication protocols, and the IoE Framework. **Section 5** provided a discussion and opportunities for EV charging. Finally, **Section 6** summarizes the main points of the paper, emphasizing the importance of continued research and development in EV charging technologies.

2. Vehicle Technologies

Taking into consideration the presented power and energy requirements, various vehicle technologies can be contemplated. These technologies can be classified based on the type of motor employed, such as single-motor vehicles comprising internal combustion engine (ICE) vehicles, battery electric vehicles (BEVs), Fuel cell electric vehicles (FCEVs), or hybrid vehicles that utilize both ICE and electric motors [6-9]. The classification of EVs is depicted in **Figure 1**, while the advantages and limitations of electric and ICE vehicles are detailed in **Table 1**. It was important to highlight that vehicles can be categorized based on the type of fuel employed, such as gasoline tanks for ICE vehicles. Besides that, batteries can be paired with supercapacitors (SC) for BEVs and hydrogen tanks and batteries for FCEVs [10-12].

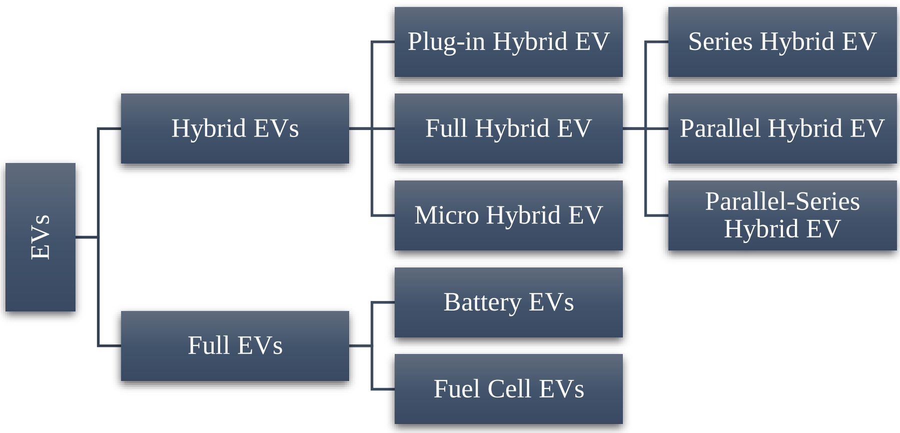


Figure 1. The classification of EVs

Table 1. Advantages and limitations of electric and ICE vehicles [13-16]

	Advantages	Limitations
EVs	▪ High torque can be generated at zero speed, making them efficient for acceleration and starting from a standstill.	▪ Limited driving range due to the low energy density of the storage system (less than 200 Wh/kg).
	▪ -EVs produce no pollutant emissions, making them environmentally friendly and suitable for use in urban areas with stringent air quality regulations.	▪ No heat source to warm the vehicle for BEV, which can be a disadvantage in cold climates.
	▪ -EVs have high efficiency due to the direct conversion of electrical energy to mechanical energy.	▪ Lack of hydrogen distribution infrastructure and fast charging stations for FCEV.
	▪ Their simple mechanical principle makes them easy to operate and maintain, leading to lower operating costs compared to ICE vehicles.	▪ Long recharging time for BEV.
ICE	▪ The storage system has a high energy density of 12 kWh/kg.	▪ Significant greenhouse gas emissions.
	▪ There is an infrastructure for energy distribution.	▪ Sophisticated and complex mechanical system.
	▪ The refueling time is very low, taking less than 5 minutes to fill 60 liters and providing several MW of power.	▪ Low overall efficiency.

A. Battery Electric Vehicles

The battery energy storage system (BESS) is responsible for providing the necessary power for traction and propulsion in battery electric vehicles (BEVs). The range of the EV is primarily determined by the battery capacity and driver behavior [17-21]. Communication can be simplified at three distinct stages in today's vehicles and charging systems: vehicle, charger, and network. Vehicle interaction is in charge of monitoring the flow of data in the vehicle, which involves the state of charge. Charger communication manages the data flow throughout the EVSE. The flow of data employed by third-party suppliers is monitored by network communication. EVSE has to satisfy specific power quality demands but has a power output that can vary for different charging scales. The power conversion system commonly used in BEVs is depicted in Figure 2. BEVs are capable of operating in two distinct modes, namely battery mode and regenerative braking mode [18-22]. In battery mode, a boost DC/DC converter is utilized to transfer power to the motor that propels the wheels via a DC/AC converter. In contrast, during regenerative braking mode, the kinetic energy of the EV is converted into electrical energy and stored in the battery [23-25].

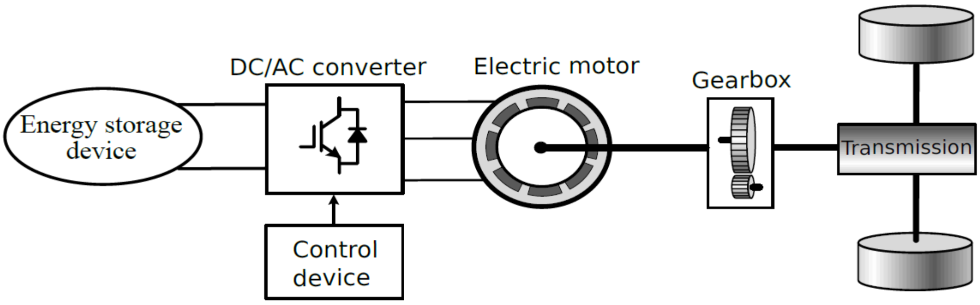


Figure 2. The diagram of battery electric vehicles.

B. Fuel cell electric vehicle

A fuel cell electric vehicle (FCEV) is an electric vehicle that employs a fuel cell in combination with a small battery or supercapacitor to power its on-board electric motor as demonstrated in Figure 3. The fuel cell is the central component of the FCEV, producing electricity through the combination of oxygen in the atmosphere and hydrogen that has been compressed and stored within tanks using focused technological advances at either 350 or 700 bar (10,000 PSI) [26-28]. FCEVs have earned a reputation as zero-emission vehicles since they produce only water and heat. Low-temperature fuel cells (80°C) are readily accessible in commerce, while high-temperature fuel cells (160°C) are presently being extensively researched by both academia and industry [29-31].

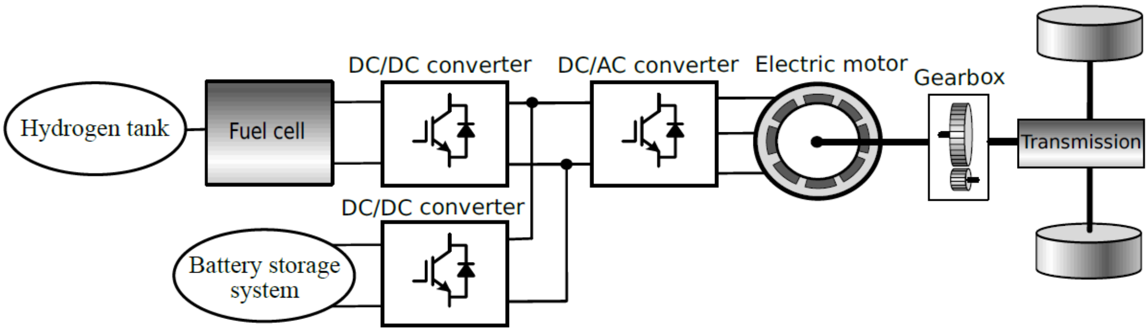


Figure 3. The diagram of fuel cell electric vehicles

Combined mode, which utilizes both fuel cell and battery to provide average and peak power to the EV, respectively. Split mode, where the fuel cell propels the vehicle and charges the battery simultaneously, Thus, in regenerative mode, the kinetic energy generated during vehicle braking is utilized to charge the battery [32-34].

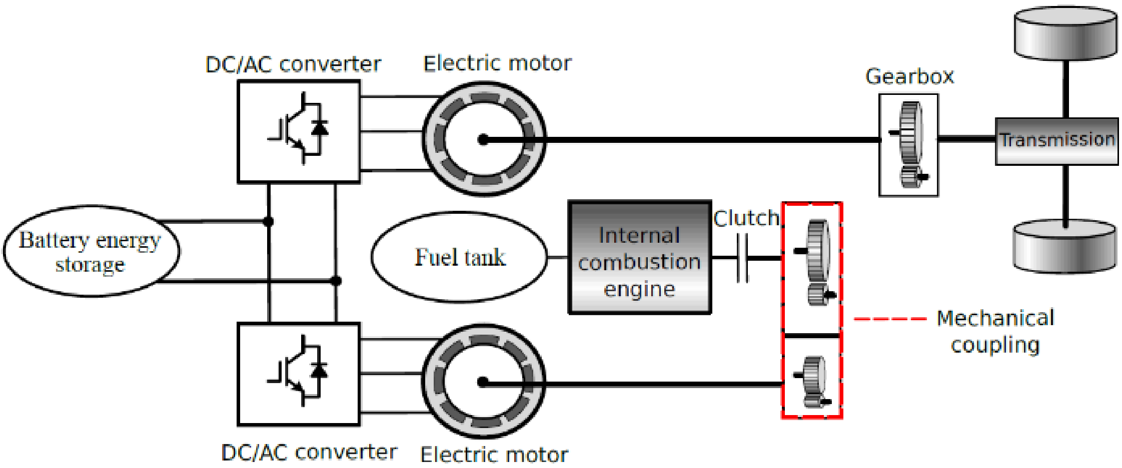
C. Internal combustion engine

The internal combustion engine (ICE) is a type of heat engine that converts the chemical energy of fuel into kinetic energy for vehicle propulsion. Natural gas, gasoline, diesel, and fuel oil are the main sources of fuel for ICEs, but they also use renewable fuels like biodiesel and bioethanol, frequently in conjunction with fossil fuels. Hydrogen, a less common fuel, is predominantly obtained from non-renewable sources (grey hydrogen) rather than renewable energy resources (green hydrogen) [35-39].

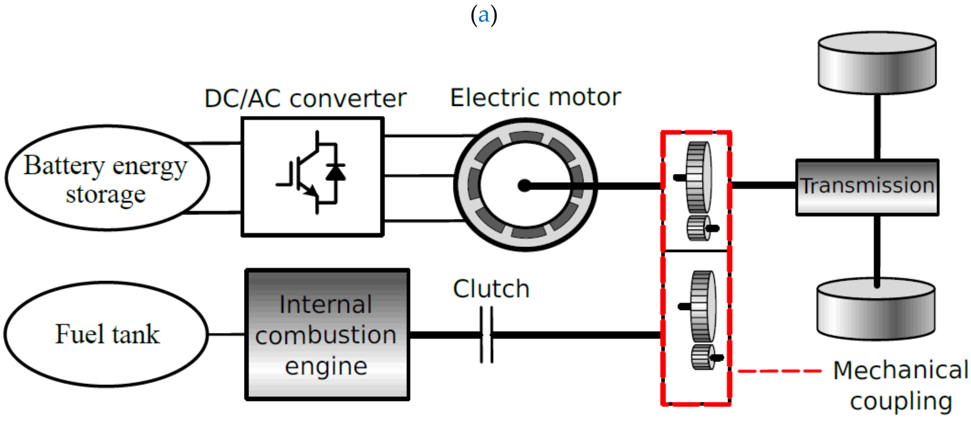
D. Hybrid and Plug-In Hybrid Vehicles

A hybrid electric vehicle (HEV) is an automobile that incorporates an additional form of reversed energy storage, including hydraulic, pressure, kinetic, or electrochemical storage spaces. along with its main power resource, which is the chemical power of the fuel. For the operation of the wheels, an HEV typically incorporates an electric motor, battery energy storage equipment, and an ICE [40-42]. Furthermore, the ICE can be operated in the most efficient band, while the electric motor aids in the acceleration stage. This is because electric motors are more productive at producing torque, whereas ICEs are more effective at ensuring high speeds. HEVs are classified into four types: micro hybrids, mild hybrids, full hybrids, and plug-in hybrids. In a series hybrid vehicle, as shown in **Figure 4(a)**, the ICE typically provides average power, while the energy storage device handles power peaks [43-45].

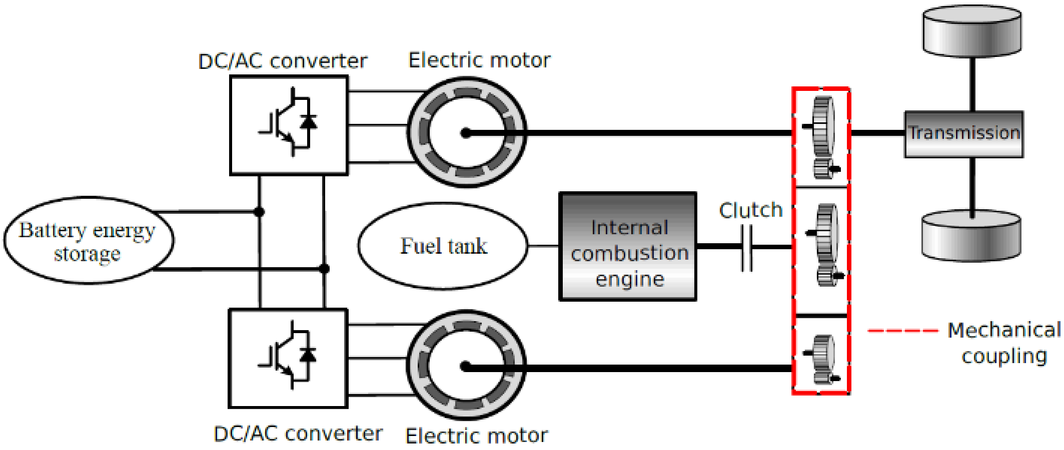
In plug-in electric vehicles, the battery can be charged from the main grid or during the energy recovery phases, such as when the vehicle is slowing down, going downhill, or braking. In a parallel hybrid configuration as shown in **Figure 4(b)**, the ICE functions similarly to that of a conventional vehicle, providing power to the wheels). The engine is mechanically coupled to an electric motor that can assist it. In consideration of the vehicle's structure and design, the mechanical coupling can take the form of either a torque addition coupling or a speed addition mechanism. The parallel-series hybrid vehicle as shown in **Figure 4(c)** integrates both principles presented earlier. This vehicle includes two electric machines and a planetary gear system that facilitates mechanical coupling with the internal combustion engine [46-53].



(a)



(b)



(c)

Figure 4. The diagram of full hybrid EV classification. (a) Series hybrid EV, (b) Parallel hybrid EV, (c) Parallel–series hybrid EV.

3. Charging Stations

Given the rapid growth of the EV market, including both electric and plug-in hybrid vehicles, the need for a reliable and safe recharging infrastructure that can meet the needs of users has become increasingly important [54-56]. To facilitate the widespread adoption of EVs, it is essential to have a well-distributed recharging infrastructure. There are three primary types of EV charging technologies, which are conductive charging, inductive charging, and battery swapping, as illustrated in Figure 5.

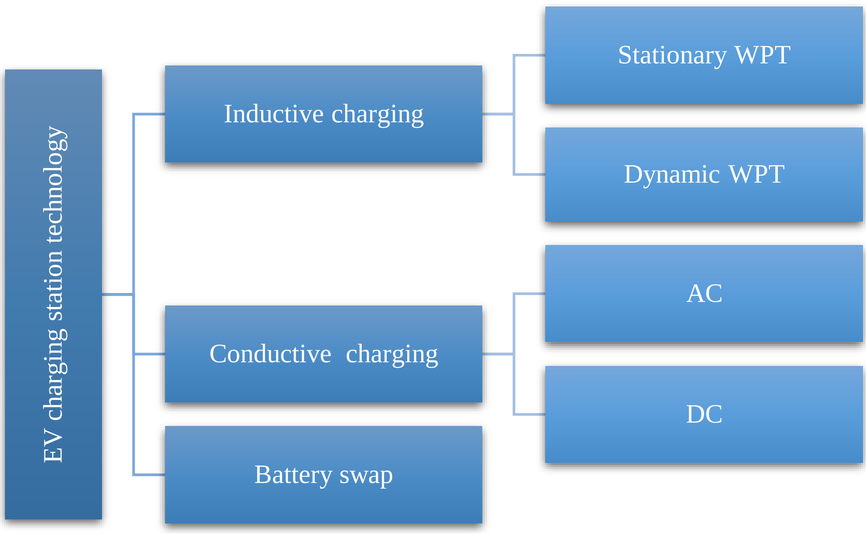


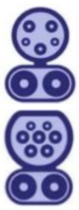
Figure 5. Three primary types of EV charging technologies

Wireless power transfer (WPT) systems designed for stationary applications have demonstrated the ability to deliver fast charging rates of up to 50 kW, reducing the charging time of EVs to as low as 15-20 minutes. On the other hand, the WPT system can provide slow charging of up to 3 kW over a period of 4 to 8 hours. Dynamic WPT enables the charging of EVs while they are moving, allowing for charging along the way. In this context, AC conductive charging offers a range of charging speeds, including fast charging (Level 3) with 3-phases up to 43 kW in 15–30 minutes, average charging (Level 2) with 3-phases up to 22 kW in 1-3 hours, and slow charging (Level 1) with 1-phase of 3.6 kW in 6–8 hours. The DC conductive charging method, categorized as Level 3 charging, is capable of delivering up to 400 kW of power at 1000V, enabling fast charging in a range of 15-20 minutes [57-60]. The battery swap is a charging method that involves replacing a depleted battery with a fully charged one. This process typically takes around five minutes to complete.

A. Electric Vehicle Supply Equipment

Electric Vehicle Supply Equipment (EVSE) is an essential component that provides electricity to EV batteries. It comprises various elements, including electrical power conductors, charge ports, and protection equipment, as well as software and communication devices that ensure an effective and secure electric power supply to recharge EV batteries [61,62]. Additionally, the EVSE facilitates communication between the EV and the charging station while managing the interactions between the charging station and the electric grid. Various standards and codes regulate the EVSE, which mainly define the connectors between the EV and EVSE and the EV and power grid, as demonstrated in Table 2. In addition, SAE J1772 is the most prevalent standard in North America, while IEC 61851/62196 is the primary standard in Europe and emerging markets. AC charging involves using power directly from the electric grid, with the EVSE functioning solely to monitor the power flow and ensure a safe operating environment, as illustrated in Figure 6.

Table 2. Different countries, symbols, connectors, charging modes, and standards of EVs.

Country	Symbol	Connectors	Charging Modes	Standards
USA Japan		Type 1/j1772	AC	IEC 62196 SAE j1772
China		GB/T	DC	GB/T 20234
UE USA		CSS/Combo	DC	DIN SPEC 70121 IEC 62196-1/2/3 SAE J2847/2 IEC 61851-1/22 ISO/IEC 15118
Tesla (EU)		Type 2/Mennekes	DC	IEC 62196
EU China		Type 2/Mennekes	AC	GB/T IEC 62196

B. EV Charging Modes and Charging Stations Level

Three main charging modes are available for electric vehicles, namely conductive charging, inductive charging, battery swapping, and wireless charging. These modes are critical for the widespread adoption of EVs. Conductive charging is the most common mode and involves the use of a cable to connect the electric vehicle supply equipment to the EVs [63,64].

C. Conductive chargers

Conductive chargers, which supply electrical power for recharging batteries for electric vehicles, are classified as on-board or off-board. Given that they use AC power to carry out the AC/DC conversion throughout the vehicle, on-board chargers have constraints in size and insignificant power. This configuration may allow the traction energy conversion mechanism to be used for battery charging. Off-board chargers, on the other hand, are DC chargers with higher output power and greater power supply flexibility. Based on the resulting power and category, conductive charging stations can be broken down into three levels: Level 1, Level 2, and DC rapid chargers [65,66].

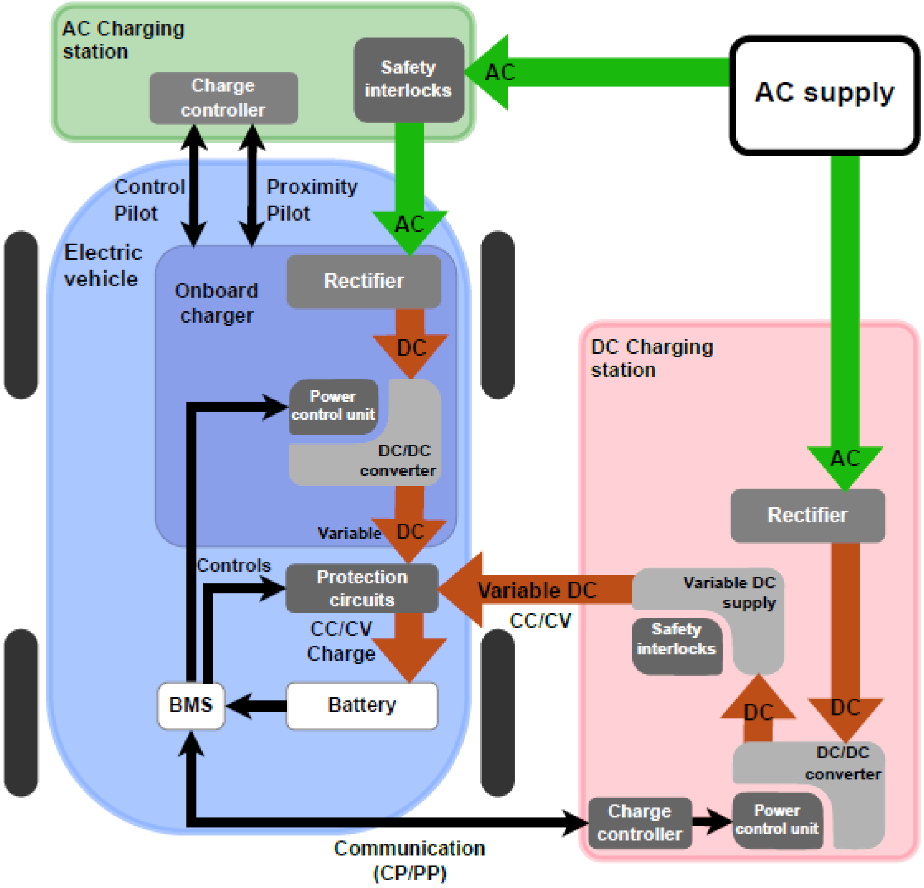


Figure 6. EV supplies equipment.

D. Inductive charger

The inductive charger is a wireless power transfer (WPT) system that facilitates battery charging through the use of electromagnetic waves. This charging method is offered in two configurations: stationary charging, which occurs when the EV is parked, and dynamic charging, which occurs when the EV is in motion and a charging device is integrated into the road. Wireless charging is a promising solution to address the issue of the diverse charging ports, which differ in their configuration, shape, and size depending on the country and electric vehicle manufacturer. By utilizing this method, all-electric vehicles can be charged using a uniform infrastructure, and the need for traditional cables is eliminated. Moreover, this method provides additional benefits, such as the integration of the charging system with the ground, thereby minimizing the risk of theft or unintentional damage by a careless driver. Furthermore, the absence of physical contact between the charging station and the electric vehicle ensures complete safety against any electric shock hazards [67-69].

E. Battery swapping

Battery swapping is a charging method that involves exchanging a depleted battery with a fully charged, identical battery. The process entails driving into a battery switch bay, and an automated system repositions the vehicle, removes the current battery, and installs a fully charged battery. Depleted batteries are recharged in the station for future use. The business model for this method assumes that the EV user owns the vehicle, not the battery. Battery swapping remains the fastest charging option, comparable to the time required to refuel a conventional vehicle. Nevertheless, this method presents significant challenges in implementation, particularly in achieving battery standardization across multiple EV manufacturers [70-72].

F. Wireless charging

Wireless charging of electric vehicles involves the use of galvanic isolation between the input and output circuitry, which allows for safe power transfer. While this technology has traditionally been used for low-power applications, recent advancements in power electronics and semiconductor materials have enabled higher power levels for wireless power transfer, making it a viable option for EV charging. The use of wireless charging for EVs offers several advantages over traditional wired charging methods. Firstly, it provides an uncomplicated, safe, and user-friendly charging process with low maintenance costs because there are no mechanical parts involved. Secondly, it eliminates potential risks associated with cable use, such as using worn cables in rainy or snowy conditions, by providing galvanic isolation between the vehicle and the power source. Thirdly, the charging transmitter can be installed underground, thus preventing exposure to unfavorable environmental conditions, significantly extending the charging infrastructure's lifespan, and preventing any vandalism such as cable theft or the removal of other components [73].

4. The Interface of EVs and the Internet of Energy (IoE) Framework

Within this section, the amalgamation of EVs and the IoE Framework is categorized into three groups: Charging Techniques, Charging Procedures and Communication Protocols, and IoE Framework [74-78].

A. Charging Techniques

EV charging can be classified into either controlled or uncontrolled charging modes. Uncontrolled charging involves plugging in the EV, and the charging process starts automatically or with a user-defined delay, continuing until the battery is fully charged or disconnected. Although this method is simple, it causes a significant challenge for the utility grid as it results in a peak in power demand, which can cause voltage irregularities and overloads in the distribution transformers and lines. As EV usage becomes more prevalent, the grid's reliability declines, making it necessary to strengthen the grid. In comparison, controlled charging involves the scheduling of EV charging profiles to mitigate the negative impacts of EV integration into electrical grids, such as increased load demand, overloaded system components, voltage and frequency imbalances, excessive harmonic distortion, and power losses. This method aims to ensure the stability of the distribution grid and delay the need for grid reinforcement. However, the convenience of EV users and economic incentives should be taken into account when implementing this charging method. Off-peak charging is a simple form of indirectly controlled charging that encourages EV charging during periods of low grid load.

Moreover, passive techniques are frequently utilized to help balance out increasing strategies throughout controlled charging; however, they may end up causing a rapid rise in load under certain grid areas if the service stations are not equitably spread. Besides that, this approach depends on consumers' ability to charge their EVs during off-hours. To obtain the legitimate goal, the aggregator collects information from each EV, such as rechargeable batteries state of charge, charging desires, and identity, and employs an algorithm that intends to accomplish one particular objective while also meeting the needs of the EV user. The main objective may be to maximize aggregator profits, minimize deviations between the aggregator's predicted demand profile and EV real-time power requirement, or reduce electricity costs or power losses in the grid. Figure 7 presents the centralized control architecture of EV charging. Figure 8 illustrates the block diagram of the decentralized control architecture. There are two control strategies for EV charging: centralized and decentralized. The process involves an aggregator controlling the charging process, whereas the latter necessitates the EV owner in decision-making. In a decentralized control strategy, each EV seeks to reduce charging costs while taking user preferences into account. Nevertheless, bidirectional information flow is required, and EVs must be intelligent to carry out the necessary instructions. This method, when compared to the centralized control scheme, seeks to impose less computation complexity and is more concerned with customer convenience. Most utilities currently use an uncontrolled charging system as well as a passive strategy known as the dual tariff strategic plan or "time of use" (TOU) pricing.

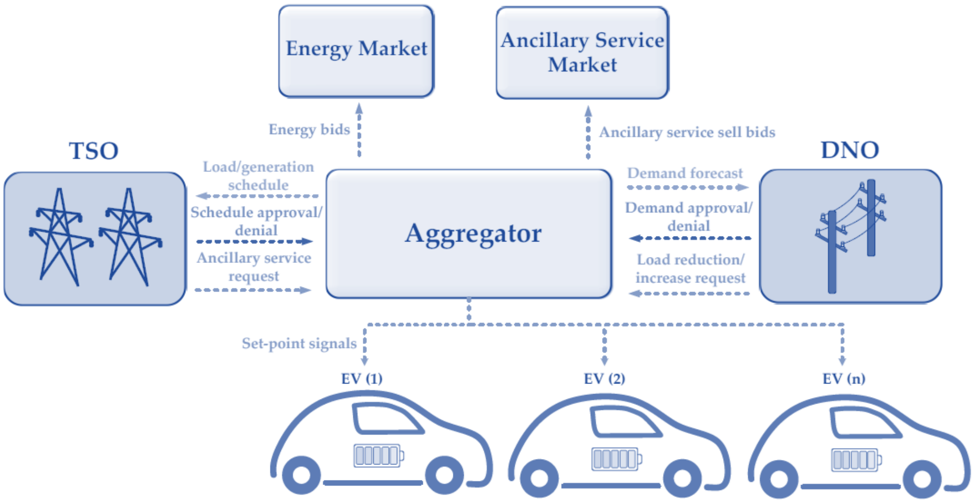


Figure 7. Centralized control architecture of EV charging

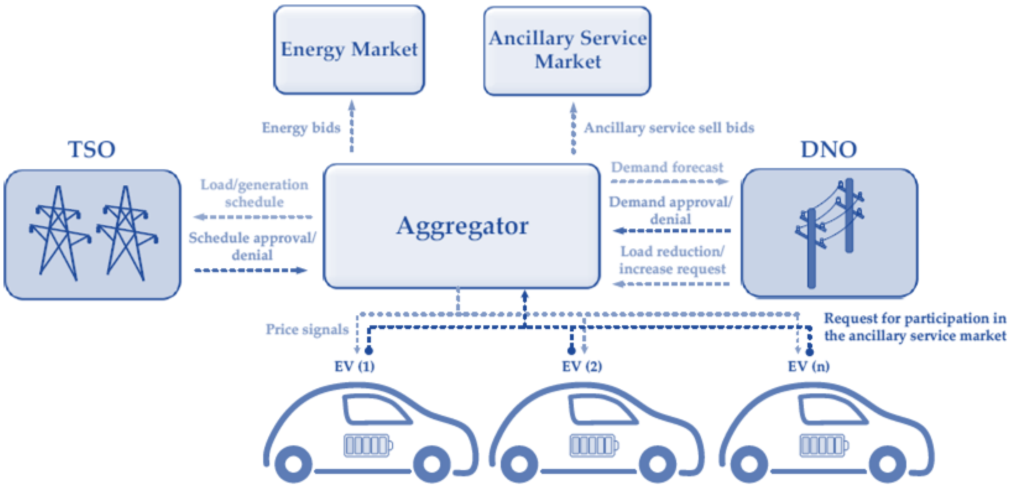


Figure 8. The block diagram of the decentralized control architecture.

B. Charging Procedure and Communication Protocols

Charging an EV involves multiple actors that are interlinked, including roaming hubs, charge point operators, and e-mobility service providers. The charge point operator is accountable for managing and operating the charging infrastructure, which encompasses technical aspects such as access control, maintenance, and data collection. Moreover, they may engage in commercial activities, as they possess the capability to purchase electricity from the supply market and offer charging services to customers. In the electric mobility ecosystem, the e-mobility service provider is a commercial entity with the responsibility of delivering e-mobility services to e-mobility customers. Their main responsibility is to make charging stations accessible to different charging station operators (CSOs). Additionally, they may offer other services such as charging station location, availability monitoring, and charging reservations. Typically, EV drivers access these services through intelligent mobile applications developed by the e-mobility service provider.

Moreover, pilot terminals allow the EVs and charging stations to talk to each other. The International Organization for Standardization (ISO)/IEC 15118 standard is used for this. This standard is widely recommended for EV communication as it enables the exchange of crucial data, including EV battery state of charge (SoC), authorized charging power, and customer identification, among other things. For the management of EV charging, the charging station management software (CSMS), which is the backend system of a charging station operator, typically employs the open charge point protocol (OCPP) to regulate the charging process remotely over the Internet. OCPP is a readily available standard based on the WebSocket communication protocol that is used as the industry-supported communication standard between the charging station and the CSMS for both AC and DC charging methods. The use of

OCPP allows for the efficient management of charging points via communication between the charging stations and the CSMS. Furthermore, the CSMS communicates with the mobile application to reserve or cancel charging slots and keep EV users informed about the progress of the charging process.

Specifically, after linking the EV to the charging point, the user can authorize the charging process using a variety of methods, including RFID (Radio Frequency Identification) cards/tokens, ISO 15118-1 Plug and Charge, payment terminals, local mechanical keys, or smartphones. The CSMS communicates with the charging station to inform the user about the transaction, language preferences, applicable tariffs, estimated costs during the charging process, and the expected end time of the charging session before the EV driver initiates the charging process.

When charging an electric EV, once the user agrees to the process, the Central System Management System (CSMS) unlocks the specific charging point connector. This gives the user full control over the charging process and keeps an eye on each EV's recharge status at all times. The CSMS also facilitates the payment procedure by accessing a database that contains comprehensive information about the available charging points, registered users, and the billing process. The OCPP has been updated to allow the CSMS to provide various schedules with different tariffs to users. This allows end-users to tailor their preferences and select the desired service, promoting time-of-use (TOU) pricing. Figure 9 depicts the communication protocols employed during the charging process.

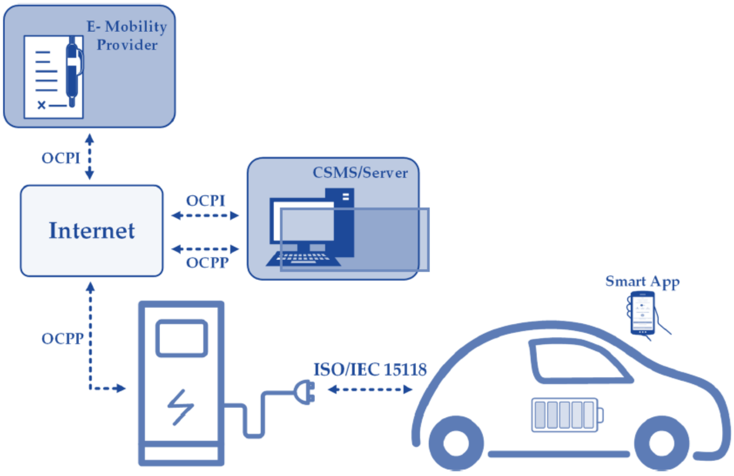


Figure 9. The communication protocols utilized during the charging procedure.

In addition, some applications provide navigation services to enhance the user experience by making it more efficient and user-friendly. Furthermore, EV drivers who need to use public charging stations that are not operated by their contracted e-mobility service provider usually depend on the OCPI roaming protocol. This protocol allows for the exchange of critical information between two service providers, either through contractual agreements or via a roaming hub that caters to all EV users. Charging point operators usually accept direct payment at their stations for users without contracts.

C. IoE Framework

In the coming years, there will be major changes to the power system structure and communication network from the current framework. The traditional centralized power generation system will be replaced by a decentralized configuration referred to as the smart grid or the Internet of Energy (IoE), which will transform the methods of distributing electric energy and information between the power system and end-users. The primary energy source will be renewable energy plants, ranging from small to large scales, and industrial and domestic consumers will have the ability to contribute power to the grid while also drawing from it, thus becoming prosumers. **Figure 10** presents the architecture of the IoE Framework.

The Internet of Energy (IoE) aims to integrate various networks, such as power, transportation, gas, and thermal systems, into a single entity. This consolidation enables the exchange of energy between different sources and loads, including renewable energy sources, distributed energy storage, thermal systems, electric vehicles, and prosumers. The IoE framework promotes the use of renewable energy sources while reducing reliance on large-scale power plants. Furthermore, each participant is connected to the physical power system in a plug-and-play manner, similar to how a computer detects and connects with a USB device, without requiring reengineering. The decision to source or absorb power depends on several variables, including the state of the grid, the ratio of local power generation to consumption, and the individual benefit or profit.

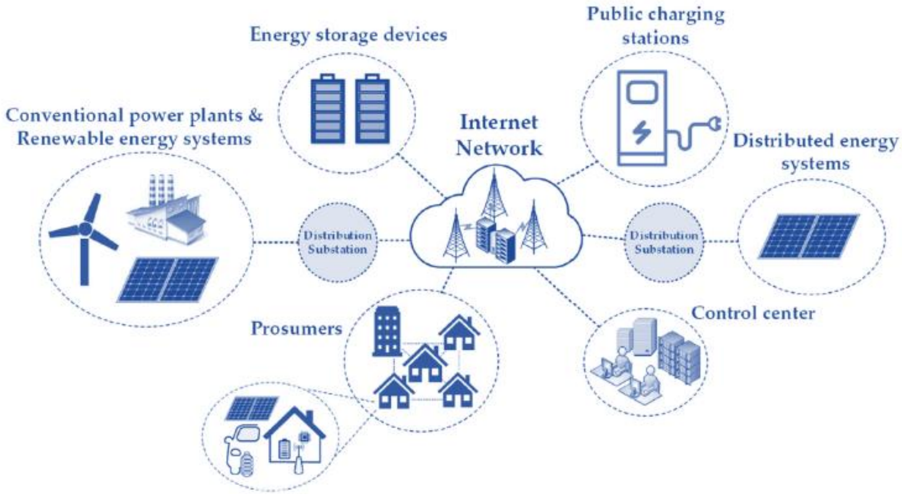


Figure 10. The architecture of the IoE framework

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5. Discussion and Opportunities for EV charging

The consistent growth in EV sales reflects the consistent progress in charging infrastructure. In recent years, high-voltage DC chargers with sophisticated power electronic devices with an increased power density as well as effectiveness have been deployed. As a result, greater amounts of charging power can be delivered while maintaining acceptable current values and the associated stress on grid and charger components. As a result, as previously reported in research findings, the needed holdup time for a full battery has been drastically decreased. Besides that, it is expected to fall further shortly because of developments in semiconductor and battery innovation.

Despite the recent advancements in EV charging infrastructure, several issues remain regarding their impact on the power system. Globally accepted standards for EV charging do not yet exist, resulting in varying regulations by country. While wireless charging presents benefits, such as the prominent feature of unplugged charging transactions and the potential to reduce battery capacity requirements, technical obstacles and the lack of established practices continue to hinder its commercialization.

Moreover, the uncontrolled integration strategy used by most utilities for wireless charging presents an additional burden on the distribution grid.As a result, smart charging methods and technologies such as Vehicle-to-Grid (V2G), Quasi-Dynamic Wireless Charging (QDWC), and Dynamic Wireless Charging (DWC) will be able to be deployed (DWC). Furthermore, the anticipated increase in EV adoption and the related surge in energy consumption will necessarily require greater use of renewable energy sources (RESs), as decarburization of the transport industry necessitates the production of more zero-carbon energy.

6. Conclusion

Electric vehicles (EVs) have emerged as a promising solution to the challenges posed by climate change and air pollution in the transportation sector. As the world transitions to a low-carbon economy, EVs offer an efficient and eco-friendly mode of transportation that reduces greenhouse gas emissions and air pollution. This article provides a comprehensive review of the current state of EV technologies, which encompass hybrid EVs, plug-in hybrid EVs, battery EVs, and fuel cell EVs, with a particular focus on the related power electronics and energy conversion system components. Furthermore, the study compares and contrasts conventional ICE vehicles, hybrids, and full EVs. Additionally, this paper offers a brief overview and analysis of various on-board and off-board battery chargers, based on EV charger specifications. The present article emphasizes the significance of electric vehicle supply equipment (EVSE) as a critical constituent for delivering electric energy to EV batteries. This complex system encompasses diverse components, such as electrical power conductors, charge ports, and protective devices, in conjunction with software and communication apparatus to ensure an efficient and secure electric power supply for recharging EV batteries. Furthermore, the act of battery swapping involves the replacement of a depleted battery with a fully charged equivalent battery as a means of recharging an EV. Battery swapping is a charging technique that entails exchanging a depleted battery with a fully charged one and typically takes around five minutes to complete. The prospective commercialization of EVs is predicted to instigate the development of an intelligent grid empowered with sophisticated capabilities for real-time information dissemination and power flow regulation. The realization of this objective will facilitate the adoption of intelligent charging strategies and technologies, including vehicle-to-grid (V2G), quasi-dynamic wireless charging (QDWC), and dynamic wireless charging (DWC). Furthermore, the anticipated rise in EV usage and the corresponding upsurge in energy requirements will mandate the increased harnessing of renewable energy sources (RESs), as the decarbonization of the transportation sector necessitates the generation of greater amounts of carbon-neutral electricity.

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