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A Comprehensive Review on Electric Vehicle Charging Infrastructure and Standards

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Abstract: The rapid evolution of global energy systems, driven by environmental concerns and the ongoing energy crisis, has significantly accelerated the transition toward sustainable technologies, particularly in the transportation sector. Electric vehicles (EVs) have emerged as a viable alternative to conventional internal combustion engine vehicles, leading to a substantial increase in their adoption worldwide. This transition necessitates the development of efficient and reliable electric vehicle charging stations (EVCSs), which act as a critical interface between the power grid and the transportation sector. This paper presents a comprehensive review of EV charging infrastructure, focusing on various configurations of EV charging stations, including AC, DC, smart charging, and battery swapping systems. It further examines the different charging standards, connector types, communication protocols, and safety regulations adopted globally. The study also highlights advanced technologies such as bidirectional charging, vehicle-to-grid (V2G) integration, and smart energy management systems that enhance grid stability and enable renewable energy integration. Additionally, the paper identifies key research gaps related to standardization, grid integration, cybersecurity, renewable energy utilization, and optimization of EVCS planning and sizing. The findings emphasize the need for integrated, intelligent, and scalable charging solutions to support the growing EV ecosystem and ensure sustainable energy utilization.

Keywords: EV charging station, Electric vehicles, Renewable energy, Fast charging.

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1. Introduction

The global changes in the recent years such as the changes in the environment, energy crisis have transformed various sectors including, transportation system, construction and energy sector. When it comes to energy systems, this transition began with the incorporation of renewable energy into the energy generation sector [1]. It is then sustained with the advancement of energy sector in all aspects, including cyber security, artificial intelligence and other energy carriers. When it comes to the transportation sector, this transformation began with the development of batteries and the development of electric vehicles (EVs) as a substitute to vehicles powered by combustion engines [2 - 4]. The fast development rate of EVs in several nations underscores the essential for planned modifications to grid setup in order to be able to encounter the increased demand for energy that is a result of the deployment of EVs and the building of EV charging stations (EVCS). EVCSs are the point of link among the energy systems and transportation sector [5 - 6]. The number of research papers indexed in Scopus for the search word "Electrical vehicle charging stations" is presented in Fig. 1. There is a significant aspect that is contributing to the expansion of EV adoption, and that is the presence of an efficient charging infrastructure that is capable of sustaining high energy consumption and includes increased charging rates [7]. In addition, advancements such as bidirectional charging, smart charging have the potential to improve the stability of power systems, facilitate the incorporation of renewable energy sources, generate additional money, and cut expenses. Over the course of the past few years, a great number of scholars have examined site-selection research related to the EVCSs. Multiple criterion decision making systems were used to conduct a systematic review of works on geographic evidence structure based EVCS site selection [8 - 9]. Additionally, essential criteria and restrictions in EVCS site selection were examined. Various methods and models for determining the most suitable locations for EVCSs, with a particular focus on environmental, social, technological, and economic considerations. EVCS location optimization was the subject, which focused on developments such as decision-making processes, synthesis practices and criteria. The impact that EV chargers have on harmonic effluence and grid hosting capacity [10 - 11]. It also talks about the several assessment methods that can be used, while also pointing out the uncertainties that exist in the placements of EVCS and charging profiles. According to the literature that has been presented, the majority of studies concentrate primarily on the optimization of the location of EVCS. They do not pay attention to the technical details of the distribution system, but rather they focus on the mathematical elements and methodologies. One other component of EVCS planning optimization is sizing, which encompasses the sizing of EVCS capacity as well as renewable energy sources in order to fulfil the necessary charging demand. It has been discovered after an exhaustive study of the available literature that there are just a few review studies on the subject of the size of EVCSs. As an illustration, the examined EVCS sizing studies concurrently with site optimization [12]. Furthermore, the sizing and siting optimization of EVCSs in distribution systems was investigated in reference [13], which involved the examination of technical issues such as power loss, voltage regulation, and power quality. It is possible that changes to power systems will be included in the planning of EVCSs. The author underlines the importance of integrating renewable energy sources, smart grid technology, and proactive steps in order to overcome power quality issues that are produced by electric vehicle charging infrastructure. The best placement of EVCS as well as the necessary improvements for power supplies that are required for the expansion of EVCS networks. Only a small number of studies particularly address the necessity of power system upgrades and the tactics that should be implemented for them [14 - 15]. This is despite the fact that a number of studies highlight the possible grid impacts that could be caused by EVCS planning.

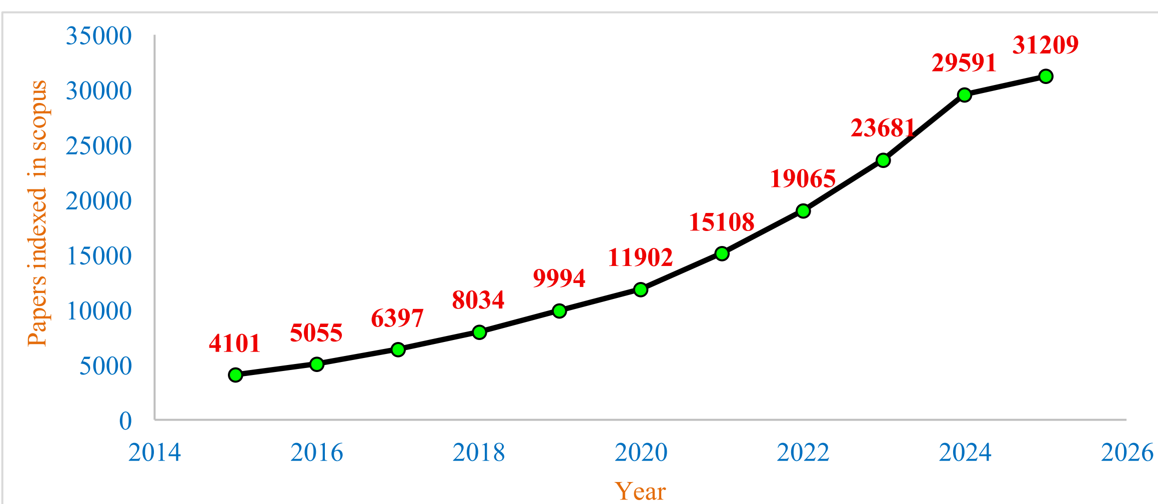

Fig. 1: Papers indexed in Scopus for the search word "Electrical vehicle charging stations".

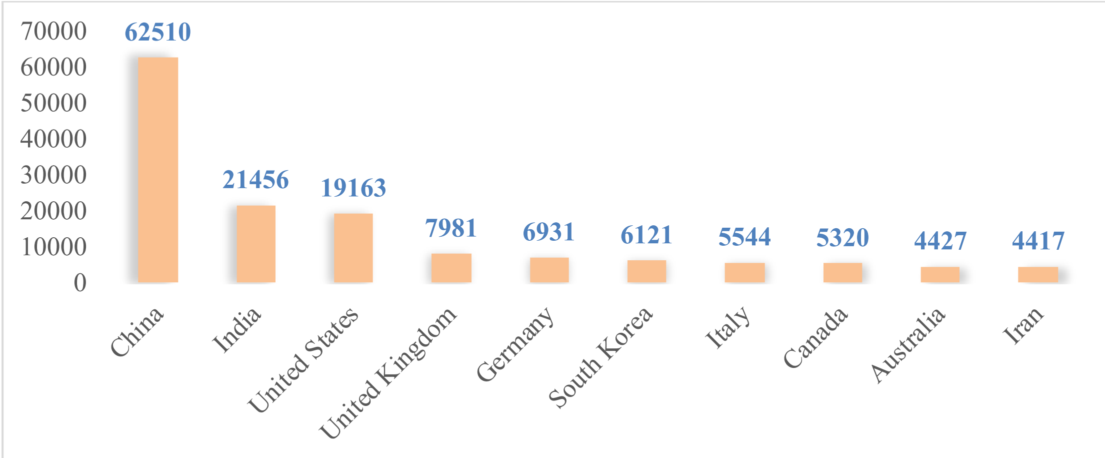

Fig. 2: The leading top 10 countries conducting research on EV charging infrastructure

Fig. 3: Top 10 institutions in the globe conducting research on EV charging infrastructure

The leading top ten countries conducting research on EV charging infrastructure is shown in Fig. 2 and Top 10 institutions in the globe conducting research on EV charging infrastructure are presented in Fig. 3. The novel contributions of this work may include,

- It presents the state-of-the-art review of different configurations of EV charging systems
- It presents the different standards used in EV charging chargers designing
- It presents the safety precautions and research gaps for the further research contributions.

The remaining paper is arranged into various sections. Section 2 presents the discussions on different configurations of EV charging stations, Section 3 presents the various standards practised in EV infrastructure, and Section 4 presents research gaps and the Section 5 discusses the conclusions.

2. EV Charging stations

The block diagram of the DC offboard charger is presented in Fig. 4. It has the DC fast charger for feeding to the EV. The transformer converts the grid voltage into required voltage level, later which is converted into DC using rectifier [16 - 17]. The architecture of the DC and AC, EV charging stations are presented in Fig. 4. DC- EV charging station representation is shown in Fig. 5 and the AC- EV charging station representation is depicted in Fig. 6.

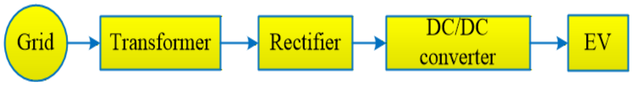

Fig. 4: Block diagram of the EV charging station

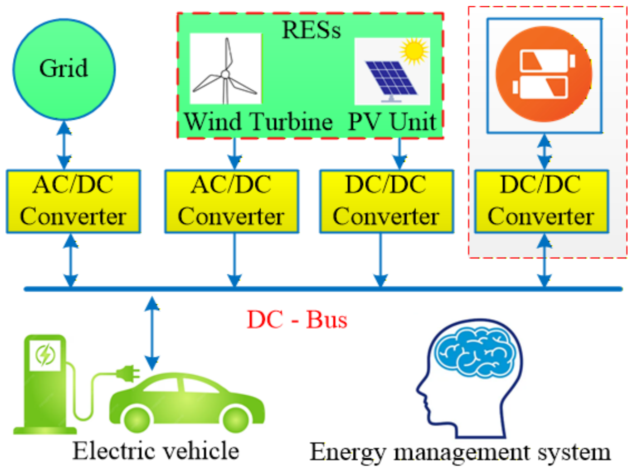

Fig. 5: DC- EV charging station representation

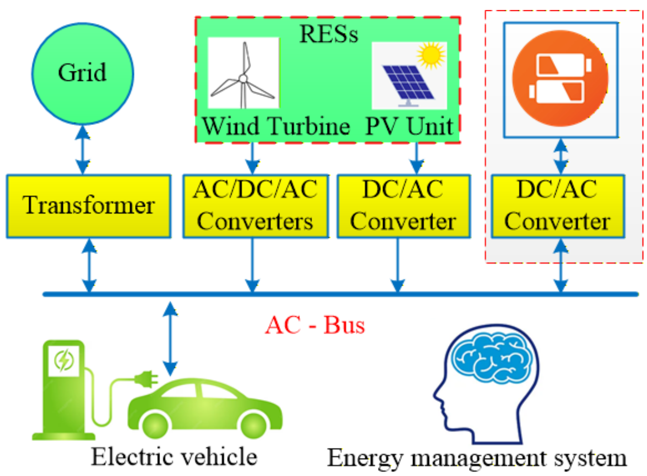

Fig. 6: AC- EV charging station representation

Smart EVCS: Ongoing research is being conducted on intelligent EVCS with the goals of achieving rapid charging, lowering the danger of power outages, and enhancing bi-directional interaction. All of these efforts are geared toward achieving zero carbon emissions, enhancing energy management, extending the lifespan of electric vehicles, and providing charging that is of high quality at a cheap cost [18]. The development of an EV smart charging system that includes an advanced master charge controller that orchestrates the entire charging process, the creation of a charging management system that includes reservation management and time slot allocation, the implementation of efficiency improvements to minimize power quality issues and reduce operational costs, and the planning of charging stations with a focus on customer behavior and low-cost charging schemes are the primary areas of research that are being conducted. RESs, a data management center, user communication interfaces (such as mobile apps and billing), and backup energy storage are all components of the smart EVCS infrastructure depicted in Fig. 7. All of these components are connected to one another through the process of cloud internet. Energy management and demand forecasting are both made possible by the monitoring of data in real time and the analysis of historical data. The development of a universal smart charger controller will be undertaken in order to manage the simultaneous charging of several vehicles and to minimize power imbalances.

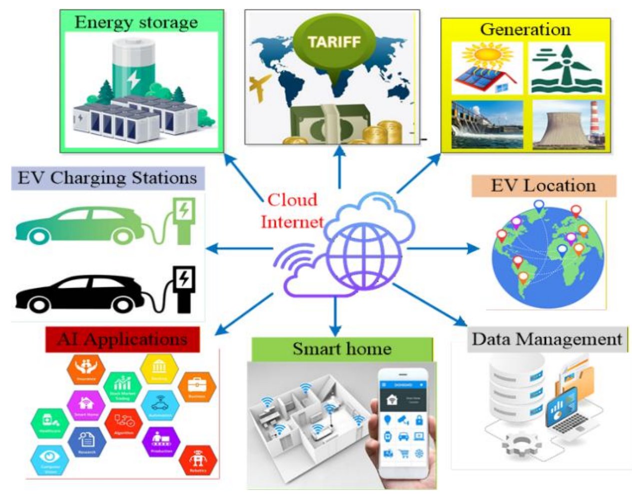

Fig. 7: Smart EV charging station

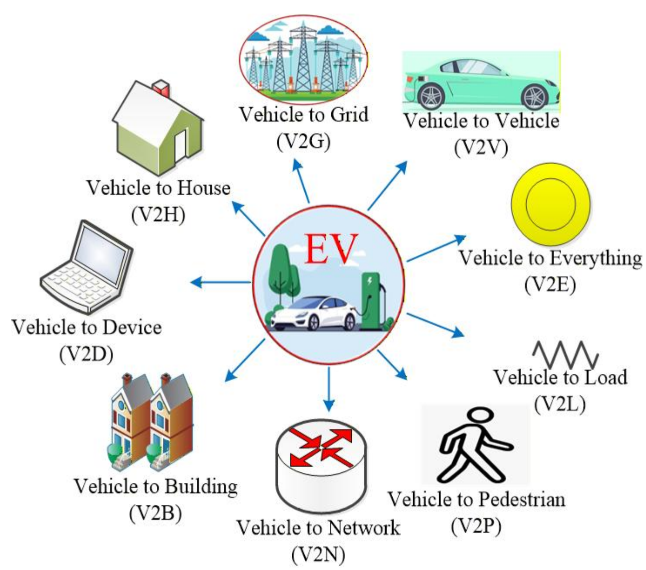

Fig. 8: Various interconnections in EV charging stations

This controller will decide the appropriate charging current depending on the grid voltage, the condition of the battery, and the requirements of the trip. This intelligent control unit will act as a communication bridge between EVs, charging systems, and power electronics. It will enable charging to be regulated according to the requirements of the user and the amount of power that is available. Additionally, smart cards will be used to provide secure access to charging stations [19 - 20]. This smart EVCS provides support for the next generation of smart city planning, with a particular emphasis on the management of energy demand. Different EVCS configurations are presented in Fig. 8 and the details are described in Table. 1.

Table. 1: Various interconnection topologies of EV charging stations

Topology	Acronym	Principle
Vehicle to Grid	V2G	It allows energy transfer from vehicle to grid in discharge mode.
Vehicle to Vehicle	V2V	Transporting energy from a vehicle to another for charging purposes.
Vehicle to Home	V2H	Harnessing EVs energy to energize local appliances.
Vehicle to Device	V2D	EVs energy is transferred to electronic devices.
Vehicle to Building	V2B	EVs serve as an auxiliary power source for buildings during power outages or to enhance the self-use of on-site RE generation.
Vehicle to Network	V2N	Integrate vehicles into the wireless communication system, providing drivers with in-vehicle services like real-time traffic updates.
Vehicle to Load	V2L	Transfer energy from EVs to supply power to specific loads.
Vehicle to Pedestrian	V2P	Vehicles are collaborating to offer similar services for commercial use.

Battery swapping EVCS: Exchange of a drained battery for a fully charged battery is what is meant by the term "battery swapping" [21 - 22]. Battery switching is a method that is utilized by countries such as South Korea, China, and Japan for their electric buses. It is possible to categorize battery switching according to the position of the battery, which can be classed as follows: side for vans and trucks, top for buses, bottom for cars, or rear for cars with adequate backspace [23]. A representation of the battery-swapping EVCS layout may be found in Fig. 9. A solid data management system, cloud storage, communication interfaces, and a selection of batteries that are readily available are elements that are necessary for a successful battery-swapping station.

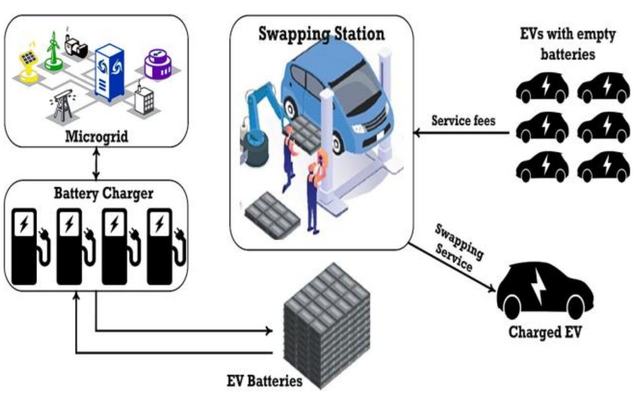

Fig. 9: Infrastructure of battery swapping EVCS

It is vital for electric vehicles, information systems, and swapping stations to maintain continuous connection with one another [24 - 25]. Using WAVE communication, an electric vehicle will send a charge request to the information system whenever the battery of the vehicle is becoming low. After that, the system works in conjunction with the swapping station to determine how to prepare a replacement battery. A robotic arm is used to replace the battery once the vehicle has been checked out to ensure that it is in good condition. In order to facilitate user notifications and tracking, the cloud is used to store various data, including payment details, battery parameters, and other information [26 - 27]. Using a mobile application, users are able to make requests for battery swaps. The application also gives station locations and real-time pricing to users. Additionally, the swapping station is able to manage payments and receive feedback, in addition to having access to information regarding the speed, location, and availability of vehicles. The quick and efficient replacement of batteries, which enables customers to continue driving without any interruptions, the bidirectional power flow, the enhancement of grid efficiency through charging during off-peak hours and supplying power during peak demand, the reduction of consumer waiting time in comparison to fast charging, the extension of battery life through longer, controlled charging, and the cost-effectiveness for both station and vehicle owners, thanks to reduced costs from recharging during low-demand periods and improved efficiencies are the primary advantages of battery swapping EVCS [28 - 30].

3. Standards and Types of EV charging

It is common practice to classify electric vehicle chargers according to their charging speed, output power and connection type. It is the physical interface that is utilized to link the electric vehicle to the charging infrastructure that is referred to as the connection type. When it comes to power levels, charging speeds, and regional norms, different connectors are designed to accommodate these variations. Level 1 chargers are the slowest mode, and they are typically utilized for charging batteries in domestic settings. Level 2, chargers, often known as rapid chargers, are generally utilized for businesses, public spaces, and residential settings. The DC fast or rapid charging type is another form of charger that is well-known. This type of charger is typically utilized in highway rest stops, public charging stations and business hubs respectively. The use of these three types of chargers is widespread; however, there are other types of chargers that are utilized less frequently. These include Ultra Rapid Chargers, Extreme Fast Charging, Wireless chargers or Inductive charging, and Portable EV Chargers. The Table. 2, presents a complete evaluation of the chargers that are available online [31 – 32].

Table. 2: Various types of EV chargers

Type	Charging time	Usage	Voltage and Power	Installation cost
Slow charging (AC - Level 1)	08-20 Hours	Domestic area	120V < 1.9 kW	300 to 1000 USD
Fast charging (Level 2)	03-08 Hours	Domestic, Commercial and Public	240 V 33 – 22 kW	500 to 2000 USD
DC Rapid charging (Level 3)	20-60 Minutes	Commercial, Public stations	400 -1000 V 50 – 350 kW	20000 to 50000 USD
Ultra rapid chargers	10-20 Minutes	Commercial areas, National highways	> 350 kW	100000 to 250000 USD
Wireless chargers	04-06 Hours	Domestic, Public areas	3.7 – 22 kW	3000 to 15000 USD
Portable chargers	06-12 Hours	Mobile usage, Emergency	1.4 – 7.4 kW	300 – 1500 USD

AC Level-1 (Slow Charging): A slow charging level, this level is perfect for home and business settings because it is great for slow charging. This is the most fundamental method of charging, and it normally makes use of an AC source of 120 volts. When it comes to charging a battery electric vehicle (BEV) with a system-on-chip (SoC) of 20% to 100%, level-1 charging is best suited for overnight use, with an anticipated charging period of up to 17 hours [33].

AC Level-2 (Fast Charging): Capable of reaching a peak power of 19.2 kW and a charging current of up to 80 A, this device was designed to work with a 240 V AC supply. When compared to Level 1, this level significantly cuts down on the amount of time required for charging, making it ideal for use at household, workplace, and public charging stations. It takes around twenty-two minutes for a plug-in hybrid electric vehicle (PHEV) to charge from zero to one hundred percent when using a charger that is twenty kilowatts [34].

***DC Level-1 Charging**:* With a charging current of up to 80 A and a charging power of up to 36 kW, this device offers a voltage range that extends from 200 to 450 V DC. By utilizing direct current (DC), this level indicates a rapid charging technique that greatly reduces the amount of time required for charging in comparison to AC Level-2 [35].

***DC Level-2 Charging**:* This device has the capability to deliver a voltage range of 200–450 V DC, a charging current of up to 200 A, and a maximum power output of 90 kW. This level is designed for rapid charging at public stations, and it offers charging periods that are even shorter than those of DC Level-1 [36]. Table. 3, presents the connector and regional standards comparison.

Table. 3: Connector and regional standards comparison

Standard	Connector Type	Charging Mode	Max Power	Regions Used
SAE J1772 (Type 1)	AC plug	AC	19.2 kW	USA, Japan
IEC 62196 Type 2	Mennekes	AC	43 kW	Europe, India
CCS1	Combo Type 1	DC	350 kW	North America
CCS2	Combo Type 2	DC	350 kW	Europe, India
CHAdeMO	Dedicated DC	DC	400 kW	Japan
GB/T	Separate AC/DC	AC/DC	250 kW	China
Bharat AC-001	Industrial socket	AC	3.3 kW	India
Bharat DC-001	DC plug	DC	15 kW	India

Table. 4: Communication protocol comparison

Standard	Communication Type	Key Features	Smart Charging	V2G Support
IEC 61851	EV–Charger	Basic control & safety	Limited	No
ISO 15118	EV–Charger	Plug & Charge, security	Yes	Yes
OCPP 1.6	Charger–Backend	Monitoring, billing	Yes	No
OCPP 2.0.1	Charger–Backend	Load mgmt., security	Advanced	Partial
IEEE 2030.5	Grid–EV	Smart grid integration	Yes	Yes

Table. 5: Safety and compliance standards comparison

Standard	Scope	Protection Provided	Region
IEC 60364-7-722	Electrical installation	Ground fault, insulation	Global
IEC 62196	Plugs & connectors	Mechanical & thermal safety	Global
UL 2202	DC chargers	Fire & shock protection	USA
UL 2594	AC chargers	Overcurrent protection	USA
IS 17017	EV supply equipment	Electrical & user safety	India

***DC Level-3 Charging**:* Located farther from the vehicle, it has the potential to increase demand and put a burden on distribution networks during times of high demand. This kind of charging can result in significant losses for distribution transformers, variations in voltage, harmonic distortions, an increase in peak demand, and thermal strains on distribution systems [36]. Table. 4, presents the communication protocol comparison, and Table. 5, gives the information on safety and compliance standards comparison.

4. Research gaps and Discussion

This section provides the research gaps and discussion points, to continue the further research in EV charging stations. The rapid expansion of electric vehicle (EV) charging infrastructure has revealed several critical research gaps that must be addressed to ensure efficient, reliable, and scalable deployment. One of the primary challenges lies in the lack of globally unified charging standards, as the coexistence of multiple connector types and protocols such as CCS, CHAdeMO, and GB/T leads to interoperability issues and limits seamless user experience. In addition, although communication frameworks like ISO 15118 and OCPP have been developed, their practical implementation remains incomplete, particularly in enabling advanced features such as plug-and-charge and secure data exchange. From a power systems perspective, there is insufficient research on real-time adaptive load management and coordinated control strategies to handle high penetration of EVs without causing grid instability or overloading, especially in microgrid environments.

Fast charging technologies, while essential for user convenience, introduce concerns related to battery degradation, thermal management, and efficiency, which are not yet fully optimized. Furthermore, the integration of renewable energy sources into EV charging stations remains underexplored, particularly in terms of managing intermittency and designing hybrid systems that effectively combine solar, wind, and energy storage. Another significant gap exists in cybersecurity, where vulnerabilities in communication protocols expose charging infrastructure to potential cyberattacks, highlighting the need for robust authentication and data protection mechanisms. Wireless charging technology, though promising, still suffers from lower efficiency, alignment challenges, and a lack of mature standardization. Finally, economic and planning aspects such as optimal placement of charging stations, dynamic pricing strategies, and cost-effective deployment models especially in developing regions have not been sufficiently addressed, indicating a strong need for multidisciplinary research combining engineering, data analytics, and policy frameworks.

5. Conclusion

In conclusion, the rapid growth of electric vehicle adoption has made the development of efficient, reliable, and standardized charging infrastructure a critical requirement for modern power systems. This paper has presented a comprehensive review of various EV charging station configurations, including AC, DC, smart charging, and battery swapping systems, along with an overview of global charging standards, communication protocols, and safety practices. The study highlights that while significant advancements have been made in EV charging technologies, several challenges still persist, particularly in terms of interoperability, grid integration, and system optimization. The analysis of existing literature reveals that most research efforts have primarily focused on optimal placement of EV charging stations, with comparatively limited attention given to technical aspects such as sizing, power quality, and distribution system impacts. Furthermore, the integration of renewable energy sources, implementation of advanced smart charging strategies, and enhancement of cybersecurity frameworks remain key areas requiring further investigation. Addressing these challenges will require a multidisciplinary approach involving power systems engineering, data analytics, communication technologies, and policy development. Future research should focus on developing intelligent, adaptive, and secure EV charging infrastructures capable of supporting large-scale EV penetration while ensuring grid stability, economic feasibility, and environmental sustainability.

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Data Availability Statement

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Conflict of Interest

The authors declared “No conflict of interest”.

CRediT authorship contribution statement

Conceptualization, PSS and ANK; methodology, PSS; software, ANK; validation, PSS, ANR and ANK; formal analysis, NAR; investigation, PSS; resources, PSS; data curation, KSR; writing—original draft preparation, ANK; writing—review and editing, PSS; visualization, NAR; supervision, KSR; project administration, ANK; funding acquisition, ANK. All authors have read and agreed to the published version of the manuscript.

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