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Review article

A critical review of the effect of light duty electric vehicle charging on the power grid

Moshammed Nishat Tasnim [a], Shahrin Akter [a], Mohammad Shahjalal [b], Tamanna Shams [c], Pooya Davari [d], Atif Iqbal [e,*]

[a] Department of Electrical and Electronic Engineering, Chittagong University of Engineering and Technology, CUET, 4349, Bangladesh
[b] University of Greenwich, Old Royal Naval College, Park Row, London SE10 9LS, UK
[c] Department of Physics, University of Dhaka, Dhaka 1000, Bangladesh
[d] Department of Energy Technology, Aalborg University, Pontoppidanstræde 101, 2–051, 9220 Aalborg Ø, Denmark
[e] Department of Electrical Engineering, Qatar University, Doha, Qatar

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ABSTRACT

Electric vehicles (EVs) have emerged as one of the alternative solutions for reducing carbon emissions in the road transportation sector. In the near future, more and more EVs will be integrated into the electric grid. These increasing EVs, mainly light-duty EVs, are appearing as an extensive power-consuming load within the power grid system. Unplanned introduction and abrupt adoption of charging stations can hinder the smooth operation of the power distribution system and bring serious technical challenges such as power quality, voltage fluctuations, harmonic injection, battery degradation, and grid instability. Light-duty EV integration and its effects on power grids, including grid access capabilities and power system planning, are the main focus of this review. Therefore, this paper analyzes and summarizes the potential issues and solutions in terms of power system characteristics and planning, grid economy, and environment in order to explore the impact of EV charging on the power system network. Moreover, in terms of coordination and speed, several charging schemes and infrastructure configurations for EV charging are evaluated. Various implementation strategies and concepts, such as the smart charging approach and optimal location selection, are also presented. Furthermore, this paper outlines potential directions for future research studies as well as additional suggestions for improving grid infrastructure and achieving win-win outcomes for both grid operators and customers.

1. Introduction

Today's global energy mix relies primarily on fossil fuels for electricity generation and the transportation sector. Emerging energy and environmental issues, geopolitical concerns, economic problems, energy security, and the depletion of fossil fuel supplies serve as a wake-up call for these industries to look for alternate energy sources (Ghosh, 2020). Therefore, the transportation sector is moving toward rapid electrification as an alternative to internal combustion engine (ICE) vehicles (Kapustin and Grushevenko, 2020; Bogdanov et al., 2021; Vujanović et al., 2021). This shift toward electric vehicles (EVs) is mainly due to the formulation of convenient policies regarding environmental regulations on greenhouse gas (GHG) emissions and in order to ensure the sustainability of the transportation sector (Shah et al., 2021; Ercan et al., 2022). Moreover, by incorporating EVs into the transportation industry, millions of euros in funding for environmental preservation will be saved in addition to the reduction in oil usage. Considering all these benefits of EVs, the worldwide adoption of EVs has started to pick up speed due to supportive policies such as tax reduction plans, parking and transit facilities, and toll exemptions. Additionally, as some nations have set restrictions on contaminant emissions for vehicles or are in the course of doing so, manufacturers have lessened the emissions of ICE vehicles and are developing new EVs as a way of adapting their vehicles to these new standards (Canals Casals et al., 2016).

According to the data presented in Fig. 1(a), the number of EVs climbed from 17,000 in 2010–7.2 million in 2019. Towards the end of 2020, there were 10 million EVs on the road worldwide, covering a decade of rapid development. Despite the global automobile industry collapse caused by the pandemic, which saw a 16% decline in global automobile sales, the number of EV registrations rose by 41% in 2020.

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* Corresponding author.
E-mail address: atif.iqbal@qu.edu.qa (A. Iqbal).

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At a new record of 6.6 million, EV sales in 2021 more than doubled from the previous year (Global EV Outlook, 2021). In 2021, about 10% of all new cars sold worldwide were electric, which is four times the market share in 2019. With this, there are now over 16.5 million EVs on the road worldwide, which is three times more than there were in 2018. With 2 million EV sales in the first quarter of 2022, up 75% from the same period in 2021, the market for EVs has continued to grow rapidly. With 59% of worldwide EV sales in 2022, China will continue to be the largest EV market. Fig. 1(b) shows that 3.3 million more EVs were sold in China in 2021 than throughout the entire world in 2020 (3.0 million). Germany, the largest auto market in Europe, as shown in Fig. 1(c), sold approximately 700,000 EVs in 2021, a 72% increase from 2020. With this flow, strong annual sales growth of EVs worldwide is expected over the coming years, making it possible to reach 230 million EVs on the road globally in 2030, which represents a 12% market share (Global EV Outlook, 2022).

With the increasing trend of EVs, the electrical networks are experiencing an increase in electric load and are also facing new challenges for reliable and secure operation due to EV charging (shafiei and Ghasemi-Marzbali, 2022). First of all, finding a sustainable solution for a reliable supply of electric power is the biggest problem for EVs because the EV itself may appear to be a load on the grid during charging (García-Villalobos et al., 2014). This newly added load is potentially increasing demand and putting tremendous pressure on the current capability of the grid. Modest to high EV penetrations may lead to unacceptable voltage variations and poor grid performance and power quality issues, especially during peak hours (Rodriguez-Calvo et al., 2017). For instance, it was discovered in (Haidar et al., 2014) that in a traditional grid scenario (where no steps were taken to maximize the integration of EV), 10% and 20% market shares of EV might result in 17.9% and 35.8% increases in peak demand, respectively. According to Fig. 2, approximately 10 TWh of energy was used globally in 2018 to charge the 4 million EVs that were already in use (Expansion, challenges and opportunities in the EV market and the EVSE industry - CIRCONTROL.", 2023). In 2030, the energy required to charge EVs could total 780 TWh (to charge about 230 million EVs) (Global EV Outlook, 2022). Another issue is that EV chargers typically manifest as non-linear loads and take the form of power electronic converters (Woodman et al., 2018). High non-linear loads can generate harmonically distorted

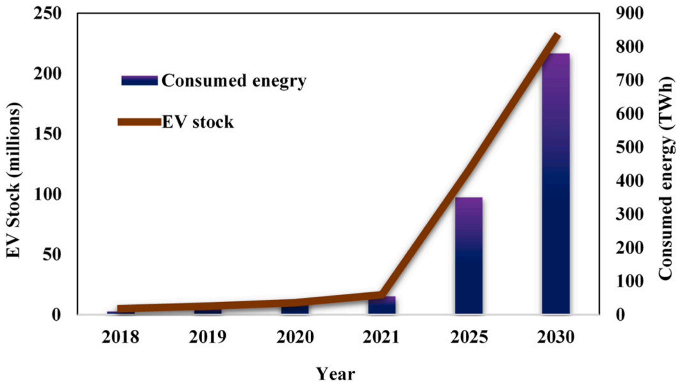
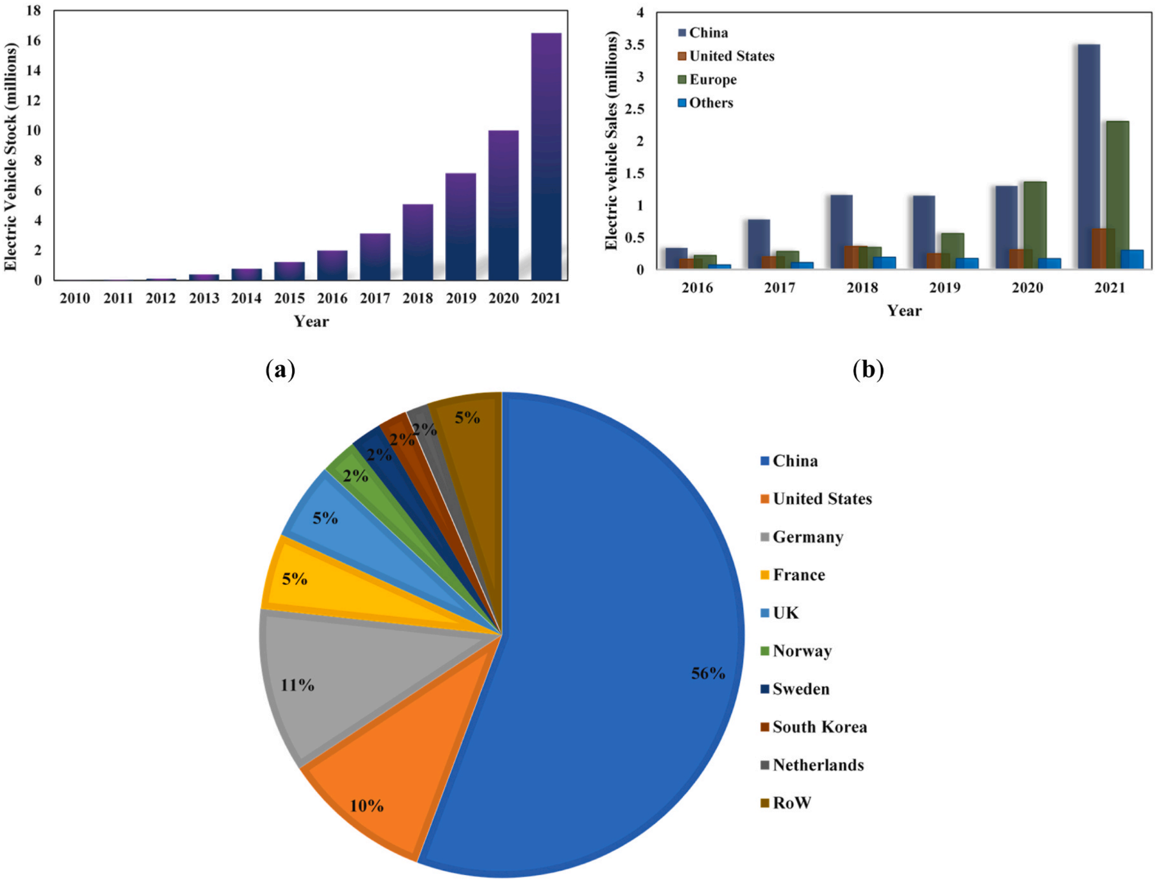


Fig. 2. Global EV stock and energy demand (Global EV Outlook, 2022).



(a)

(b)

(c)

Fig. 1. EV market share: (a) Global EV stock from 2010 to 2021 (Global EV Outlook, 2022), (b) EV sales by region from 2016 to 2021 (Global EV Outlook, 2022), (c) EV sales by country in 2021 (Global EV Outlook, 2022).

current and, in return, distort the voltage profile of the grid. Non-linear loads can also affect the performance of distribution transformers by increasing power losses in the winding and thereby reducing their power output (Godina et al., 2016). Thus, this added load in the form of EV charging may bring issues such as a dip in voltage value, a rise in the level of unbalancing, overloading of power system components like cables and transformers, a further increase in power loss, a rise in harmonic distortion, and deterioration of voltage and current transients during faults (Hussain et al., 2021). Eventually, a significant number of EVs may increase the grid's load, which may put some pressure on sustainable power sources to meet the current demand. To capitalize on the full potential of EVs, the power grid needs to be managed in an optimized manner. Second, the charging habits of EVs and the driving habits of EV owners are both more unpredictable, resulting in a form of randomness in the charging load of EVs (Vassileva and Campillo, 2017). This makes grid control further challenging and has a negative impact on the reliability of the entire power system. Therefore, it is important to research the power characteristics of EV charging because EVs, as power loads, differ from conventional ones in that their charging behavior is intermittent and unpredictable.

It is a huge challenge to integrate a large number of EVs into the electrical grid; therefore, in-depth research is required to determine the consequences, economical operation, and control benefits under optimum conditions. Moreover, the main challenges and constraints related to the charging infrastructure and their effects on the power system must be identified in order to fully comprehend the complex technological, planning, and economic issues involved in the interaction between a large number of EVs and power networks. Therefore, review papers that include significant technological and economic constraints by analysing several existing studies related to EV infrastructure and their integration are crucial. However, there are several review articles that examine the EV infrastructure and technological constraints as a result of interactions between EVs and power networks. In (Khalid et al., 2019), a review of EV fast charging stations and their effects on the current electrical grid was given. However, this study did not provide a detailed assessment of significant impacts on the grid, possible mitigation solutions, or future research initiatives in order to lessen the significant barriers to EV integration. The most recent research on EVs, their effects on the grid, the economy, and the environment, as well as the integration of renewable energy sources (RESs), was evaluated in (Richardson, 2013). A hybrid DC fast charging station with a dynamic energy management system is suggested in (Elma, 2020) in order to reduce charging times and peak demand during charging periods. An overview of the current state of EVs, international standards for EV charging and grid connectivity, various infrastructure designs, the state of the energy market, as well as difficulties and recommendations for the development of EV charging in the future, was provided in (Das et al., 2020a). Considering electricity demand, vehicle use, and network structure, the impacts that charging a sizable EV fleet would have on the power system network were examined in (Crozier et al., 2020). In (Yong et al., 2015), the latest developments in EV technologies, the impacts of EV integration, and the opportunities brought by EV deployment were reviewed. In (Rizvi et al., 2018), (Deb et al., 2018a), the authors demonstrated the key issues linked to the effects of EVs being connected to the existing power grid. In (Eltoumi et al., 2021), several charging systems and control schemes were presented, and various issues that the EV charging system must deal with were highlighted. A discussion of the effects of having many EVs linked to the power grid was also included, along with an examination of the numerous EV charging scheduling methods that are currently available. The discussions of many other published studies (Muratori, 2018)– (Manríquez et al., 2020) in this field summarize that to ensure the secure and reliable operation of the power distribution network, it is essential to evaluate how EV charging stations impact the power grid. All the aforementioned review papers lack a critical analysis of the impacts of EV integration on the power grid, short- and long-term power system planning models, and the economy, as well as possible mitigation solutions. Moreover, a defined direction for future research to identify the more critical areas with associated challenges and possible mitigation solutions in the field of large-scale EV integration is missing in many review articles. Therefore, this review paper's goal is to critically examine the ideals, strategies, and resources employed by various authors to analyze the effect of EV charging on the power grid. In this way, a researcher who is interested in this area can gain an overview of the current state of this field and spot any unexplored areas that may need further examination.

The key purpose of this study is to provide an overview of the light-duty EV charging concept in terms of charging schemes and charging infrastructure, as well as a detailed and critical explanation of the impacts of light-duty EV integration into the power grid and potential technological aspects to mitigate the negative impacts. With respect to the literature that has been discussed above, this work provides the following contributions:

I. In this paper, the most significant findings on EV charging schemes, such as coordinated and uncoordinated charging, and charging infrastructure, such as slow and fast charging, are reviewed, along with their advantages and challenges.
II. This paper reviews and assesses the impacts of EV interactions, with a major focus on technical and power system planning issues on the power grid infrastructure and possible mitigation solutions. Economic and environmental issues due to EV integration are also briefly discussed.
III. This study also discusses potential research trends, guidelines, and directions, including optimal charging station selection, smart charging infrastructure, and vehicle-to-grid (V2G) implementation.

The arrangement of this study is as follows: Section 2 introduces the structure, function, purpose, and comparison of the charging schemes of EVs in the form of uncoordinated and coordinated charging. Charging infrastructures for EVs are briefly discussed in Section 3. The consequences of future EV development on EV grid integration are examined in Section 4, along with potential strategies to reduce the impact on power and maximize potential advantages. Section 5 includes the impacts of EVs on power system planning. The impacts of EV charging on the power grid economy and environment are analyzed in Section 6. Section 7 offers some perspectives by highlighting some related findings and making some suggestions for additional or future research in this area. Lastly, Section 7 concludes the paper by summarizing the findings of this review.

2. Charging Schemes

Various charging schemes have been implemented for EVs. These charging techniques have been implemented to enhance the performance of the EVs and their performance at the distribution level. By charging EVs when and where it is most advantageous for the power grid and while ensuring that consumers' mobility demands are satisfied at an affordable price, the maximum value from integrating EVs into the power grid may be achieved (Hildermeier et al., 2019). That is, an optimal EV charging schedule can minimize load variance with a flat load profile (Gan et al., 2013). By examining the advantages of flexible EV charging on Indian power grid infrastructures, the connections between India's power and road transportation sectors were investigated in (Shu et al., 2023). The research reveals that when coupled with flexible EV charging, a number of grid infrastructure scenarios may be able to fulfill annual and hourly peak demand; however, when coupled with inflexible EV charging, particularly during the early morning, a significant amount of additional generation capacity will be required. Charging schemes can be classified into two types according to the management system: (1) user-managed charging (where the user defines the charging time of the EV based on his demand and price) and (2) supplier-managed charging (where the EV charging time is decided by the authority based on some factors such as energy consumption, production, the number of nearby charging devices at that time, etc.) (Delmonte et al., 2020). Furthermore, from the coordination point of view, it can be classified into two categories, such as coordinated charging and uncoordinated charging (Suyono et al., 2019). Table 1 lists the advantages and difficulties associated with the uncontrolled and controlled charging approaches.

2.1. Uncontrolled and Uncoordinated Charging

In an uncontrolled and uncoordinated charging system shown in Fig. 3, there is no synchronization between demand and supply of energy, i.e., this system is inconvenient for demand-supply management (Scott et al., 2021). This system is user-friendly and handy for EV proprietors, who can choose their preferred charging time. In this case, the user can charge the EV at his or her preferred time, usually during peak hours (as soon as he or she gets home or after a certain delay), without considering load pressure on the grid (Amin et al., 2020a). However, uncoordinated charging of a sizable number of EVs might result in a significant spike in peak loads, which will further affect how the power system operates. As most of the EVs arrive in the evening (peak hour), charging at that time can cause a superposition of load waves in the existing load profile. Local distribution networks may have negative effects from overloading due to unregulated EV charging, including power loss, voltage fluctuations, demand-supply imbalance, overcurrent, lower transformer lifespan, overheating in the distribution transformer and cable, and harmonic distortion (Al-Ogaili et al., 2019), (Deilami and Muyeen, 2020). Fig. 4 shows the load profile of uncontrolled charging, where most of the EVs are charged during peak hours. In (Razeghi et al., 2014), the effect of uncontrolled charging was analyzed. The results showed that uncontrolled charging of EVs causes faster aging of the transformer's winding.

Using a small-scale laboratory distribution system, insights on the effects of uncontrolled EV charging were presented in (Faddel et al., 2019). The report presents experimental findings regarding how EV charging affects system loading and voltage levels at various distribution system nodes. An architecture and control strategies for EV charging infrastructures that include both controllable and uncontrollable entities were proposed in (Qian et al., 2022), and simulations based on actual charging sessions were presented to demonstrate how the performance of various control strategies in the system architecture is impacted by the proportion of uncontrollable entities in a charging infrastructure. The electrification of road traffic would contribute roughly 7.7% of China's electricity usage by 2030, according to a case study in (Ji et al., 2020). In contrast to no EVs, uncoordinated charging may increase the peak load by 12% to 1345 GW. Peak loads by unidirectional V2G and bidirectional V2G, respectively, fall to 1236 GW and 1210 GW, respectively, with the goal of flattening the load. An EV penetration scenario for the Maldives for 2030 was examined in (Suski et al., 2021), with 30% of all EVs operating under uncoordinated and coordinated modes of charging. If EV charging is not coordinated, a relatively small increase in energy demand from EVs of 3.1% may result in a 26.1% rise in the need for generation capacity and, thus, 15.7% more investment. While coordinated charging greatly reduces the need for additional generation capacity to just 1.8%.

Table 1
An overview of controlled and uncontrolled charging procedures (Chen and Folly, 2022).

Strategies	Uncontrolled charging No control over the charge rate.No smart meter or fixed controller is used.	Controlled charging Define or limit the EV charging rate.Centralized or decentralized control.
Implementation	Easy.	Complicated because sophisticated controls are used.
Time maintenance	Immediate charging. Depends on or is adjusted by users.	Charged during low demand. Maintains optimized scheduling.
User's preference	Completely directed by the users. Don't need to maintain any schedule.	Cannot change charging profile.Degree of independence left for the owners.Decision-making by system operators is more flexible.
Effects on electrical system	Extra power losses.Voltage deviations.Thermal overloading of transformers.Reduce reliability together with cost effectiveness of the grid.Peak power increase.	Minimize distribution system losses.Minimize the power losses.Maximize the main grid load factor.Improve the reliability and safety of the grid.Peak power reduction.
Costs and profits	Compared to smart charging, charging prices might be higher.	Make electricity system operators as profitable as possible.

2.2. Controlled and coordinated charging

Coordination of charging is necessary for the integration of large EVs into the electrical grid (Wang et al., 2016). In the controlled and coordinated charging system shown in Fig. 5, energy demand and supply profiles determine EV charging time. Under this method, EV owners must instantly hand over authority to the system operators or aggregators (Ding et al., 2020). As real-time data is used in the management of energy consumption and supply, this system requires the grid to sense data continuously, which causes additional components in the grid (Zhang et al., 2014). However, in this process, by using an app, the real-time data demand curve can be flattened, which makes better use of energy. To encourage users to use controlled charging, a time-tax-tariff system can be used where the charging cost varies with the demand curve. Fig. 6 shows the load profile of the controlled charging scheme, where the charging times of the EVs are scheduled to balance the demand-supply profile.

In order to address the problems with significant EV penetrations, research investigations have developed novel controlled charging schemes and procedures. In order to transfer demand from peak period to valley period and to minimize the total peak-valley load differential, a coordinated scheduling strategy for EV charging in microgrids was developed in (Zhou et al., 2020). In order to determine the best plug-in EV (PEV) coordination strategies and predict the best daily loads with PEVs under various PEV penetration levels in both 2020 and 2030, a case study based on data collected from the Beijing-Tianjin-Tangshan Region (BTTR) in China was presented in (Luo et al., 2013). According to the simulation results, ideal PEV coordination successfully lowers the peak load and smooths the load curve. This case study is helpful for supporting PEV-related choices and policy making from a power system planning viewpoint, as well as for better understanding the costs and advantages of PEV coordination solutions. The suggested coordination strategy in (Zhang et al., 2022) incorporates a peer-to-peer (P2P) transaction model to maximize the profitability of coordinating participants and a supply-curve-based quantification method to measure the flexibility contribution of EVs. To avoid harmful and persistent over- and under-voltage circumstances in distribution networks and lessen the operational costs experienced by EV customers, a centrally coordinated EV charge-discharge scheduling technique was suggested in (Nimalsiri et al., 2021). For the precise calculation of aggregated EV charging demands in New Zealand, a probabilistic approach using EV charging characteristics and driving behavior was designed in (Su et al., 2019).

3. Charging infrastructure

The development of EVs has opened up new opportunities for the electric power and transportation sectors. Prior to acquiring the current level of popularity, EVs witnessed a number of technological

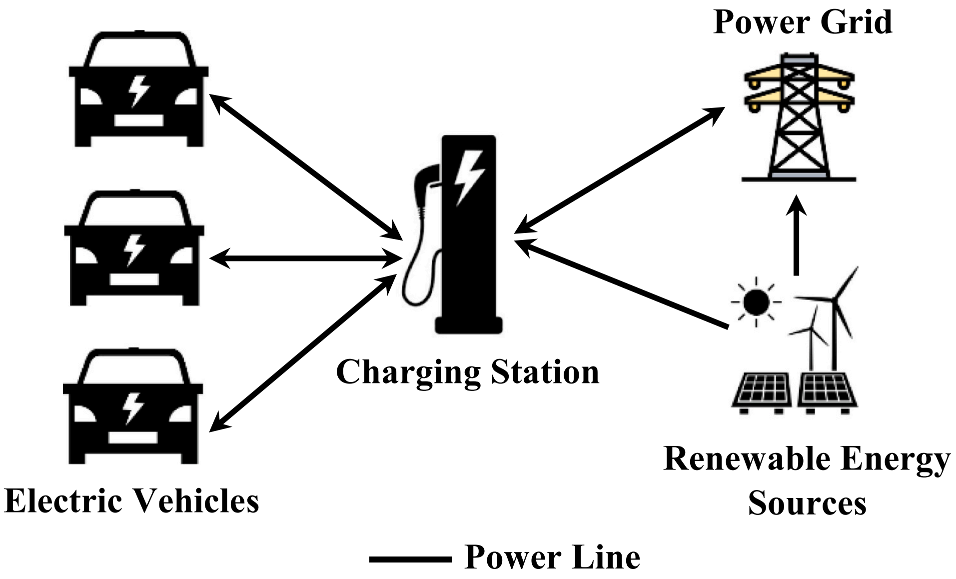


Fig. 3. Uncoordinated charging scheme (Chen and Folly, 2022).

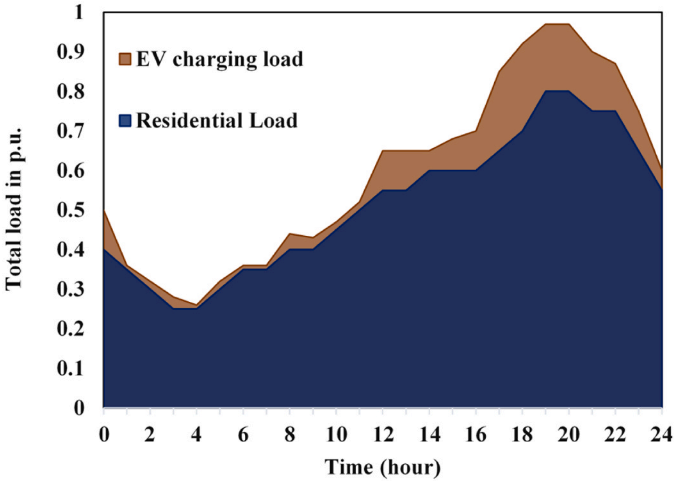


Fig. 4. Load profile of uncoordinated charging scheme (Abul'Wafa et al., 2017).

advancements. The advancement of universal charging infrastructures, related peripherals, and user-friendly control and communication systems will be essential to the successful expansion of EVs during the upcoming ten years (Rajendran et al., 2021). Most EVs have a battery-based range of about 100 kilometers, and some models have battery-based ranges of 200 kilometers to 400 kilometers (Balali and Stegen, 2021). Power infrastructure, communication infrastructure, and control infrastructure make up the total EV charging infrastructure, as shown in Fig. 7. The power infrastructure offers a circuit or system for the electric current to pass between EVs and the grid. The key components for real-time monitoring and control of EV charging are a control and communication system. The power grid, EV charging stations, and EVs are all part of the EV charging control structure. Communication systems ensure smart EV charging management between EVs and the grid (Das et al., 2020b). The flexibility of EV charging has a big impact on EV utilization and adoption. The two classifications of EV charging power levels are typically referred to as slow charging and fast charging. To specify these two power levels, a variety of charging standards are available globally. EV manufacturers in the United States utilize the Society of Automotive Engineers (SAE) and IEEE-based standards, but the International Electrotechnical Commission (IEC) is commonly used in Europe. The CHAdeMO EV charging standard is particular to Japan. The Guobiao (GB/T) standard, whose AC charging requirements are comparable to IEC requirements, is used in China (Knez et al., 2019). According to the power level and input power type (AC or DC), the charging modes are specified in IEC 61851–1 and SAE J1772. In SAE, the term "level" for the level of power is used; however, in IEC, the term "mode" is used. Four charging modes—Modes 1, 2, and 3 for AC charging and Mode 4 for DC charging—are described in IEC 61851–1 (I. Standard, ", 61851–1; Electric Vehicle Conductive Charging System—Part 1: General Requirements," IEC: Geneva, Switzerland, 2017). Additionally, fast charging is only supported by Modes 3 and 4. According to SAE J1772, there are three different levels of EV charging: Levels 1 and 2 are for slow charging using AC on-board chargers, and Level 3 is for fast charging using a DC off-board charger (Yilmaz and Krein, 2013). A summary of the voltage and current levels of IEC and SAE standards can be found in Table 2. Depending on the charging standard, different charging times are needed to charge an EV from 0% state of charge (SOC) to at least 80% SOC (Knez et al., 2019).

3.1. *Slow Charging*

Slow chargers are Level 1 and 2 on-board AC chargers that use a single-phase grid supply, and their charging power varies depending on regional standards (Rivera et al., 2021). 3.7 kW (230 V and 16 A) of power is maintained in the majority of European nations. The UK (3 kW; 230 V and 13A) and Switzerland (2.3 kW; 230 V and 10A), however, are two European nations with lower power levels (García-Villalobos et al., 2014). Fig. 8 depicts the typical setup of the Level 1 (120 V) and Level 2 (240 V) slow chargers. In such configurations, the cars should be fitted with specialized on-board chargers that can draw 1.92 kW (Level 1) and 19.2 kW (Level 2) of power from the power grid (Shahjalal et al., 2022). Level 1 and Level 2 chargers have lower capital expenses than Level 3 chargers. The energy requirement can typically be met by overnight slow charging for daily charging events due to the comparatively low power rating. It also demonstrates characteristics like a long charging time and a large distribution region, allowing distribution system operators to plan and regulate (LaMonaca and Ryan, 2022). Level 1 chargers provide the slowest charging profile. EVs with a range of 100 miles can be charged using Level 1 chargers with regular plug sockets in around 24 h. These low-power chargers are frequently utilized in residential locations. Level 2 chargers are preferred over Level 1 chargers for comparatively faster charging. An EV with a range of 100 miles may

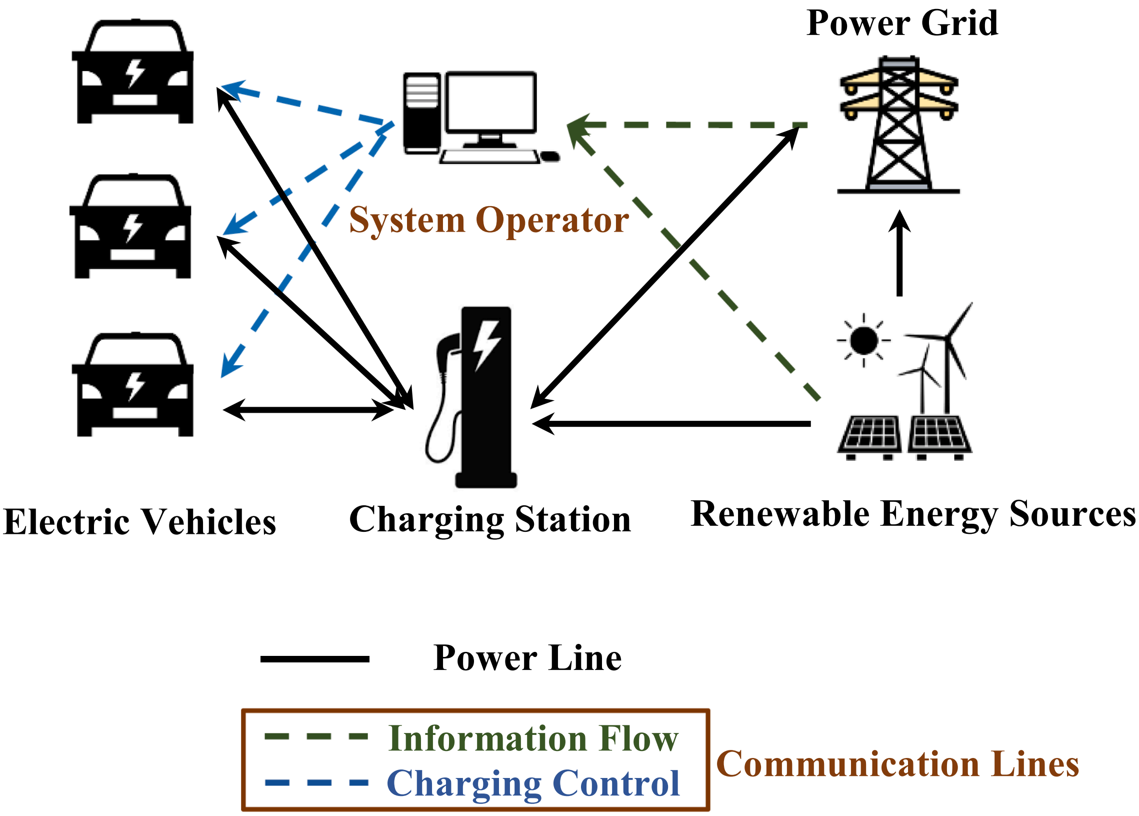


Fig. 5. Coordinated charging scheme (Chen and Folly, 2022).

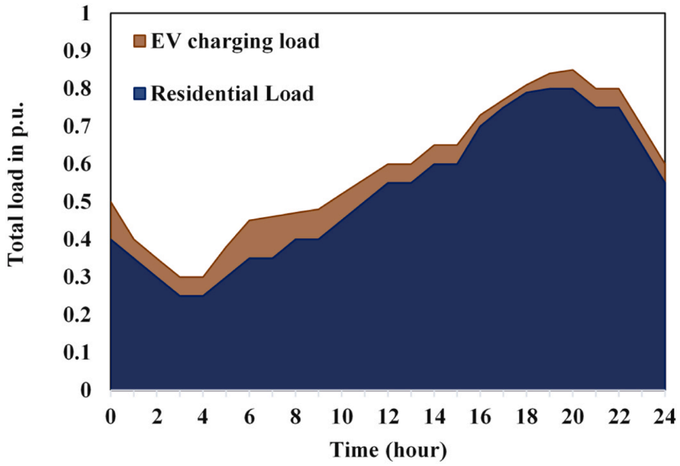


Fig. 6. Load profile of coordinated charging scheme (Abul'Wafa et al., 2017).

be charged using Level 2 infrastructure in 4–12 h (Hardman et al., 2018). Nevertheless, if utilized inside a residential building, Level 2 chargers need an increase in protection. Moreover, all these chargers typically take longer than 8 h to add 200 miles of driving range to the EV, which is not ideal for highway driving or lengthy trips.

In contrast to the frequently used valley-fill system of aggregated charging in the early morning, an intelligent scheme of EV charging using a combination of Level 1 and Level 2 charging infrastructure was proposed in (Valentine et al., 2011) that notably lessens system expenses while maintaining dependability. This study demonstrates that increasing the number of Level 2 chargers without controlling EV charging will result in a sharp rise in energy costs. If the penetration of Level 2 chargers is increased from 70/30–50/50 (Level 1/Level 2), there is a considerable reduction in system cost when using the suggested EV charging method. However, with increasing levels of Level 2 charger penetration, the system advantage is significantly reduced. In (Sears et al., 2014), the effectiveness of charging at Levels 1 and 2 was studied in terms of the proportion of grid power that is actually used by the EV battery. The outcome shows that Level 1 and Level 2 chargers both have a mean charging efficiency of 85.7%. When compared to Level 1 charging, Level 2 charging is 5.6% more efficient (89.4% vs. 83.8%). Moreover, the efficiency gap was considerably larger when the battery consumed less than 4 kWh: 87.2% for Level 2 vs. 74.2% for Level 1. In (Khan et al., 2019), the current status of a Level 2 charging system was provided, along with workable solutions, standards, and traits for smart grid operation with total safety and protection. To examine the viability of a Level 2 EV charging system on the market, a thorough overview of the existing state, socio-economic aspects, power market, and safety and control measures of EVs was also presented.

3.2. Fast Charging

Fast charging, which requires a charging period of 60 min to reach 70% battery capacity, is utilized for a variety of charging techniques defined by high charging power or quick charging times (Baumgarte et al., 2021). For medium- to large-sized EVs, this charging power is equivalent to around 50 kW. That is, fast charging requires more power than a conventional plug but may be provided in public or private spaces. Three-phase AC and DC supplies are required for fast EV charging with off-board charging systems. For EVs, there are two different infrastructures for rapid charging stations, as shown in Fig. 9: AC charging infrastructures and DC charging infrastructures. The secondary side of an MV-LV transformer serves as a common AC bus in an AC charging infrastructure, while in infrastructures for DC fast charging, a common AC/DC converter is attached to the MV-LV transformer to generate a common DC bus (Rajendran et al., 2021). However, DC charging technology is now widely utilized to manage charging powers greater than 50 kW, which is why the term "DC charging" is frequently

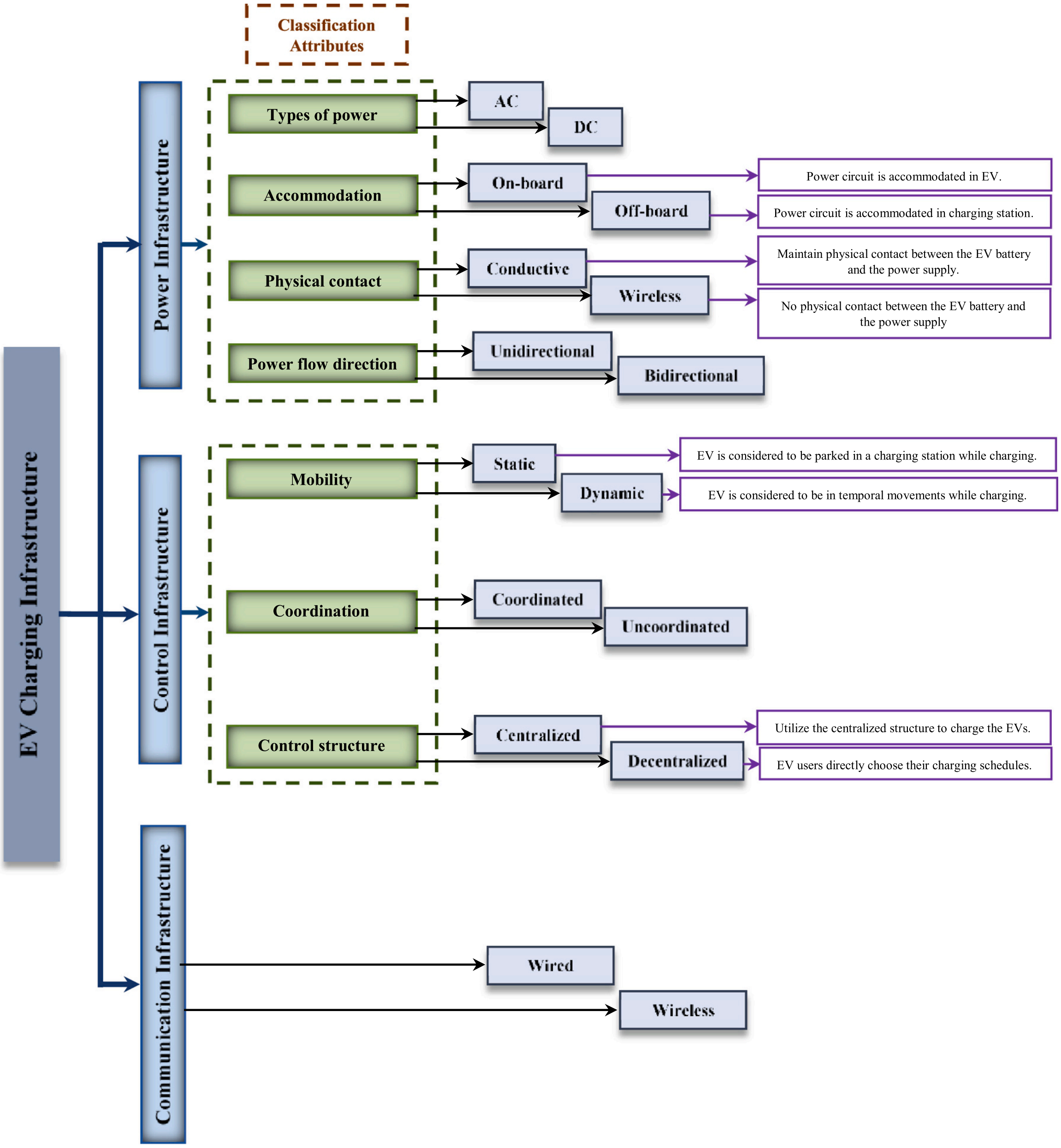


Fig. 7. EV charger infrastructure (Das et al., 2020b).

Table 2
Summary of SAE J1772 and IEC 61851 standards (Das et al., 2020b).

Standards	Organization/ Country	Source	Mode/Level	Accommodation	Voltage (V)	Phase	Maximum current (A)	Power (kW)
SAEJ1772	SAE/United States	AC	Level 1	On-board	120	Single	16	1.9
		AC	Level 2	On-board	240	Single	32	7.7
		AC	Level 3	Off-board	200–450	DC	80–200	16–90
IEC61851	IEC/Britain	AC	Mode 1	On-board	120	Single	16	1.9
		AC	Mode 2	On-board	240	Single	32	7.7
		AC	Mode 3	Off-board	250	Single/Three	32–250	8 – 62.5
		DC	Mode 4	Off-board	600	DC	400	240

used to refer to fast charging. The development of these DC fast chargers was primarily motivated by the constrained power ratings of on-board chargers. The current state of fast charging on roadways is that 150 kW is offered by default, while 350 kW is represented as a potential future option once sufficient numbers of EVs with the necessary on-board charging technology are on the road (Suarez and Martinez, 2019). DC fast chargers have the ability to offer EV consumers a reasonable charging speed by delivering DC power to the car battery through an isolated power converter placed outside the EV (Tu et al., 2019). DC fast chargers are set up as single-stall devices or as multi-stall charging stations. The 50 kW single-stall units are normally powered by an exclusive service transformer. The higher-power multi-stall charging stations, like Tesla's Supercharger stations, require additional switchgear and low-voltage metering circuits in addition to multiple chargers.

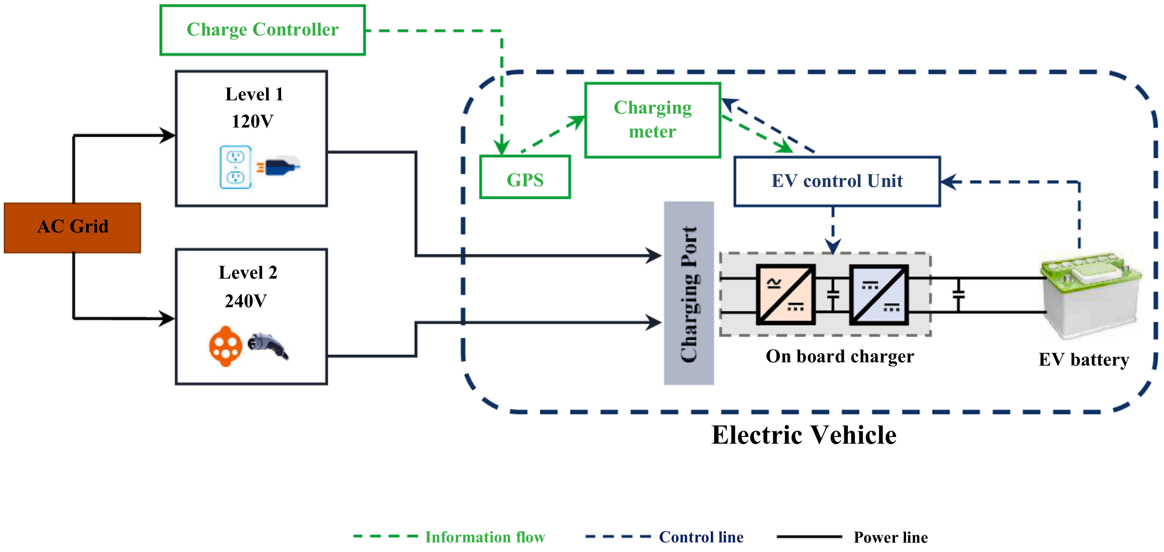


Fig. 8. AC on-board charger configuration (Ronanki et al., 2019).

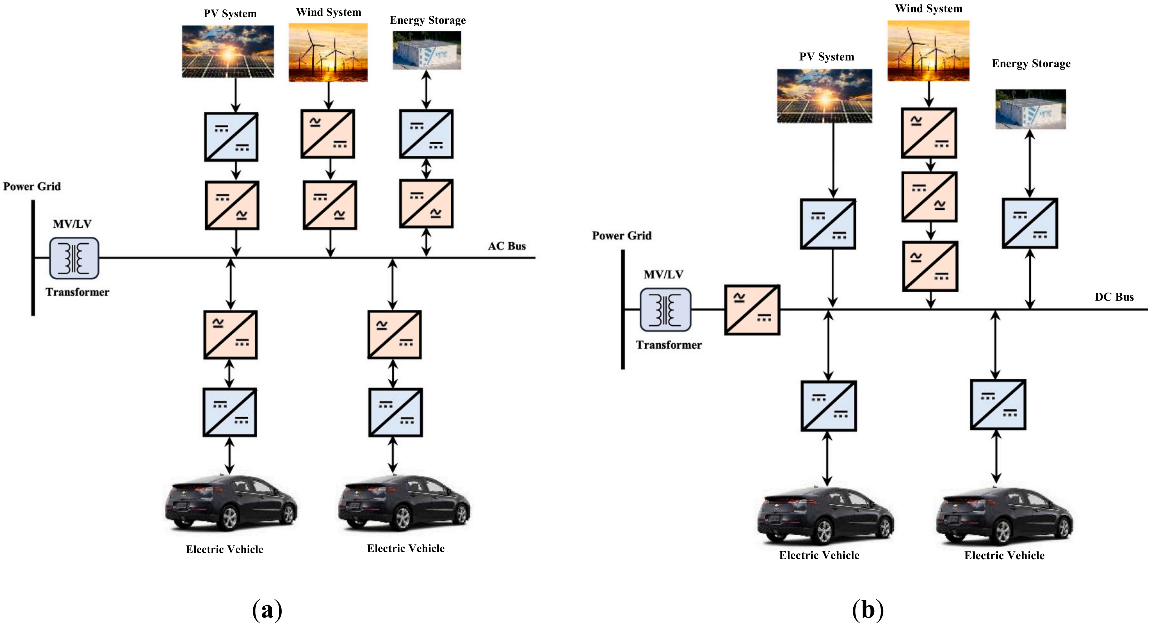


Fig. 9. Configuration of renewable energy based EV fast charging system (Rajendran et al., 2021), (Tu et al., 2019): (a) AC fast charging, (b) DC fast charging.

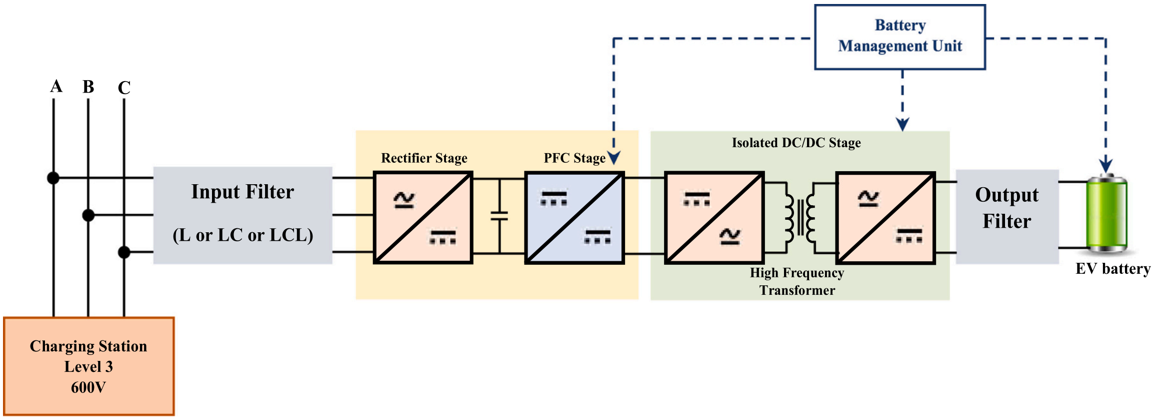


Fig. 10. Simplified diagram of a DC fast charging power infrastructure (Ronanki et al., 2019).

Fig. 10 presents a simplified diagram of a modern DC fast charger power stage. Three-phase AC voltage is converted to an intermediate DC voltage during the AC/DC rectification and power factor correction (PFC) stage, which also ensures reliable grid supply. The DC/DC stage creates the regulated DC voltage needed by the EV battery from the intermediate DC voltage and offers galvanic isolation. This galvanic isolation separates the EV from the grid and makes it simple to link the output stages of the charger (Ronanki et al., 2019).

Level 3 chargers that can fully charge an EV battery in one hour are made for commercial use. These fast-charging stations are drawing increased interest because of their shortened charging times. However, they are quite expensive, and if adequate planning is skipped, they could overload the electrical power supply. With the aid of 23 fast charging stations, the effect of their installation on the power distribution system of a Latin American intermediate city (Cuenca, Ecuador) was examined in (González et al., 2019). The findings indicate that 23 fast charging stations, with a voltage drop of no more than 0.11%, may fulfill the metropolitan area of the city for a 10% penetration of EVs (11,500 vehicles). In the line that supplies the fast charging stations, the power flowing via the feeder lines can increase by up to 7.8%, but only by less than 1% in the other lines. By incorporating renewable power (wind and solar photovoltaic (PV)) and a storage system, an EV fast-charging station was created in (Domínguez-Navarro et al., 2019) to increase the profitability of the fast-charging stations and reduce the high energy demand from the grid. The results demonstrate that the most cost-effective approach is achieved by combining renewable energies and storage solutions. With the goal of regulating the EV load effectively while reducing losses, installation costs, and transformer loading, an optimum combination of all three EV chargers (Level 1, Level 2, and Level 3) was demonstrated in (Zeb et al., 2020). The findings demonstrate that, when compared to a scenario in which Level 3 chargers are optimally placed for a 20% penetration level in commercial feeders, the proposed optimized model can significantly reduce costs from $3.55 million to $1.99 million, daily losses from 787 to 286 kWh, and distribution transformer overloading from 58% to 22%. In the case of the residential feeder, the improvement is from $2.52 to $0.81 million, from 2167 to 398 kWh, and from 106% to 14%, respectively. In (Bryden et al., 2018), two innovative strategies to support the rapid charging strategy were suggested. The time of day for fast charging stations is predicted using one approach, while the fast charging power needed to meet the needs of EV drivers is estimated using another method.

4. Impact of EV charging on power grid

The widespread electrification of transportation has significantly altered the established business strategies of electric utilities. That is, the power grid restrictions on a local or regional level may be violated by EV charging. In addition, excessive EV integration into the distribution network without prior planning may have an impact on the stability, power losses, component capacity, load profile, voltage and frequency imbalances, and harmonic injection of the distribution grid. Many possible grid effects have already been discovered by numerous system studies. This section examines how EV charging affects various parts of the electric system, and Tables 3, 4, and 6 summarize the possible impacts of EV charging on the power grid and also suggest potential mitigation approaches.

4.1. Impact on grid stability

Power system stability refers to a power system's capacity to return to its steady-state operational condition following a disturbance (Dudurych, 2021). Studies on system stability are crucial since more power system blackouts have been recorded as a result of system instability. EVs can put pressure on the power system because, while charging from the grid, they appear as non-linear loads with distinct characteristics from typical loads and consume a lot of electricity quickly (Sayed et al., 2022). As a result, a high rate of EV penetration into the main grid may raise concerns about the stability of the electrical grid, including its susceptibility to disturbances and the amount of time needed to restore it to a steady state. An analysis of the stability of the power system with and without EV charging loads was done in (Onar and Khaligh, 2010). According to this study, the system with EV charging loads was shown to be less stable than the system without EV charging loads. A peak load management model (PLM) was suggested in (Said and Mouftah, 2020) as a way to increase the rate of EV penetration while maintaining the stability of the smart grid. EVs were scheduled for charging or discharging services using the model in accordance with power consumption, timing, and location. As noted in (Tavakoli et al., 2020), the integration of RESs (such as PV systems and wind systems) and EVs individually might have a negative impact on the grid's stability because RES is intermittent and EV load is unpredictable. The effects of grid integration of EV on several forms of power system stability (Shair

Table 3
The impact of EV charging on grid stability and possible mitigation approaches.

Grid Stability Challenges	Remarks	Solutions
Voltage stability	Due to the various load characteristics, EV integration may have a negative impact on voltage stability.	Implementation of V2G systems (Zhong et al., 2014). Optimization of EV charging schedules (Hua et al., 2014). Implementation of smart EV charging.Implementation of accurate load models (de Hoog et al., 2015).
Frequency stability	System voltage deviation increases depending on the penetration level and charging rate of EVs.	Implementation of V2G systems (Zhong et al., 2014). Use of multi-objective optimum EV charging control strategies (Dechanupaprittha and Jamroen, 2021).
Rotor angle stability	Due to uncoordinated EV charging demands, uneven phase loading might significantly grow.	Coordination between EV loads and wind farms (Bhukya and Sharma, 2020). Use of power system stabilizers for damping (Bhukya et al., 2021).

Table 4
The impact of EV charging on power quality and possible mitigation approaches.

Power Quality Challenges	Remarks	Solutions
Harmonics	Harmonic pollution occurs due to the power electronics used in EV chargers during power conversion.	Use PV inverters with an active filter (Nguyen et al., 2013). Use of power factor correction devices.Use of uniformly distributed and coordinated EV charging (Deilami et al., 2010). Coordination between EV loads and wind turbines. Implementation of virtual resistance-based rectifiers (Bai and Lukic, 2013).
Voltage quality	System voltage deviation increases depending on the penetration level and charging rate of EVs.	Use of voltage-regulating devices and voltage-supporting approaches to keep the voltage deviation within tolerable limits (Yong et al., 2015). Use of smart EV charging methods (Li et al., 2012). Implementation of hybrid stand-alone renewable-based charging stations (Karmaker et al., 2019).
Phase Unbalance	Due to uncoordinated EV charging demands, uneven phase loading might significantly grow.	Appropriate management of loads.Use of PV generation (Angelim and de, 2020).

et al., 2021), such as voltage stability, frequency stability, and rotor angle stability, as shown in Fig. 11, are described in the following subsections.

4.1.1. *Voltage stability*

Voltage stability is a significant problem when assessing the stability of the power system (Modarresi et al., 2016). It is the ability of a power grid to maintain voltages at an acceptable level on all buses following disturbances, according to the IEEE power system. Voltage collapse, which is often referred to as voltage instability, is the process by which a series of events that accompany voltage instability cause abnormally low voltages or blackouts in a significant portion of the power system (Kundur et al., 2004). It is evident from the voltage stability margin shown in Fig. 12(a) that changes in load characteristics and demand (active power) can have a big impact on the grid's voltage stability. Since the characteristics of EV loads differ significantly from traditional loads due to unpredictable charging behavior, an appropriate load model is necessary to research and analyze the precise effects of EV integration on grid voltage stability. In (Das and Aliprantis, 2008), a small signal stability analysis was performed using a constant impedance load (CIL) and constant power load (CPL) model of the EV load. It demonstrates that the loading margin is smaller, as shown in Fig. 12(b), when the EV is modeled as a P load as opposed to a Z load, and also indicates that a Z load provides a better stability limit and allows for high penetration of EVs. A comparison between the ZIP model and the CPL model of the EV load was done in (Haidar and Muttaqi, 2016). The findings show that EVs that are represented using CPLs will not accurately depict how EV loads behave and how EVs affect voltage stability. By calculating the load margin and the maximum number of EVs charging that a specific grid can support in the critical situation, an optimization approach was developed in (Lyu et al., 2020) to determine the worst charging case scenario of the voltage stability limit. The negative effects of EV integration on the power grid voltage stability have been identified in (de Hoog et al., 2015), and it is suggested to do a thorough study on the grid voltage stability based on the accurate EV model, location, and capacity of EV charging stations.

4.1.2. *Frequency stability*

The ability of a power system to maintain its allowable frequency following the occurrence of a grid disturbance is referred to as frequency stability (Kundur et al., 2004). The frequency may fluctuate from its permitted value in a power system if there is an imbalance between generation and demand (Marzband et al., 2016). With a high EV penetration rate, the demand on the grid will substantially increase while they are being charged. The dynamic frequency response of a power system under a loss of generation or an increase in load is shown in Fig. 8. Depending on the size of the disturbance and the system's inertia, the frequency initially decreases rapidly from point A to point B. Point B is defined as the critical frequency, which is the lowest frequency value obtained during the transient phase. Also, as shown in Fig. 13, the frequency difference between points A and C establishes the maximum frequency deviation prior to the frequency beginning to recover to point B (the settling frequency). Therefore, in order to satisfy the increased demand, power output must be boosted or the power balance between generation and load must be swiftly restored to keep the system frequency within allowable limits (Bastida-Molina et al., 2020). The provision of system frequency response following a loss-generating incident was evaluated in (Sanchez et al., 2018) with regard to the effects of EV clusters connected to frequency-responsive charging stations. A model based on the Bessel-Legendre (B-L) inequality was created in (Zhou et al., 2020) to study the stability of time-delayed load frequency control (LFC) systems with EV aggregators. A single-area LFC system's stability areas and stability delay margins were examined in (Naveed et al., 2021) to determine the qualitative impact of an EV aggregator with communication time delay.

4.1.3. *Rotor angle stability*

Rotor angle stability determines how long the synchronous generators in a power grid can continue to operate in synchronism following the occurrence of a disturbance (Kundur et al., 2004). The rotor angle stability of the grid is anticipated to be influenced by the widespread integration of EVs into the power grid. The impacts of newly included EV loads on transient and small-signal stability were analysed in (Bhukya and Sharma, 2020). Through careful penetration of the EV battery charging station, small-signal stability was examined using eigenvalue analysis. A three-phase fault and a significant disturbance were used to assess the transient stability. An increased EV power load causes more oscillations and noticeably less stability. As a result of the similarities between wind and EV charging, the study further suggested that system stability is enhanced with wind farms. In order to evaluate the effects of commercial fast charging stations on power system dynamic stability due to changes in charging demand, an uncertainty quantification algorithm was suggested in (Jiang et al., 2022). In (Bhukya, 2023), it was examined how intermittent power flow from wind farms and erratic EV charging behavior affect rotor angle stability.

4.2. *Impact on power quality*

The term "power quality" of an electrical system describes the system's capacity to deliver a steady and pure power supply with sinusoidal

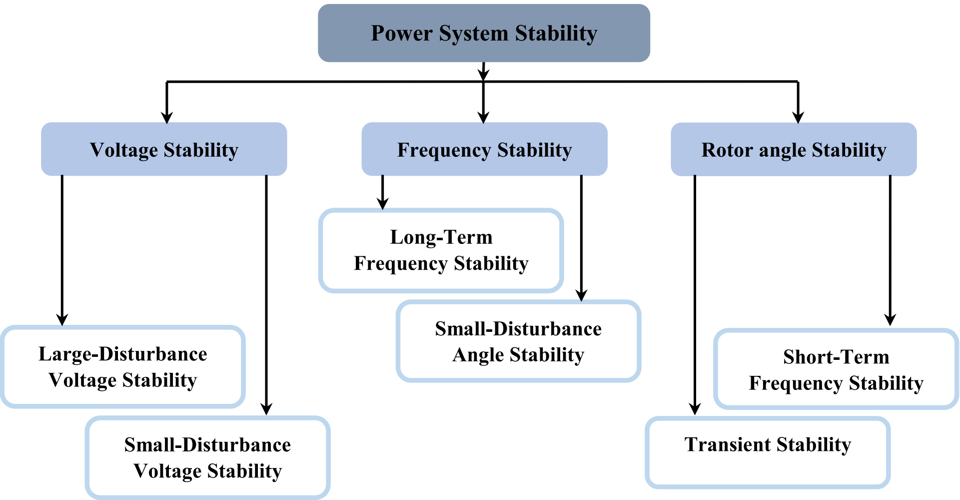
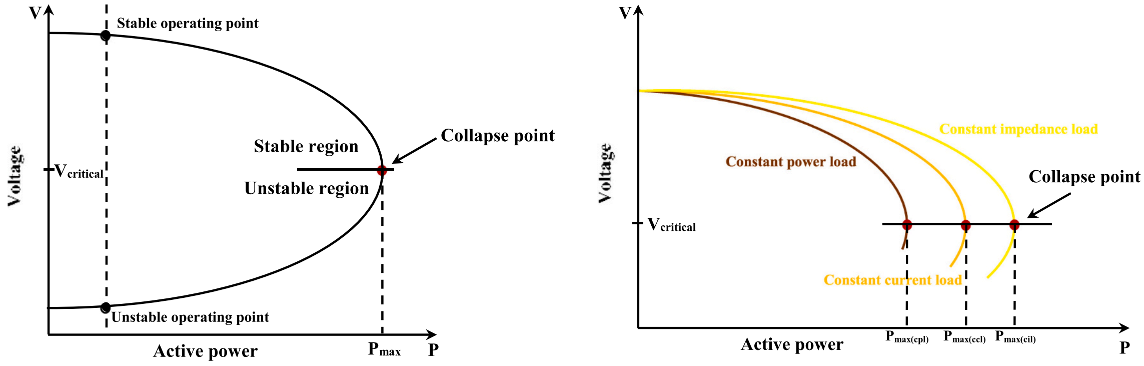


Fig. 11. IEEE power system stability classifications (Shair et al., 2021).



(a) (b)

Fig. 12. Power system voltage stability: (a) Voltage stability margin (Ashraf et al., 2017). (b) Voltage stability margin for three different types of EV charging loads (Hosseinzadeh et al., 2021).

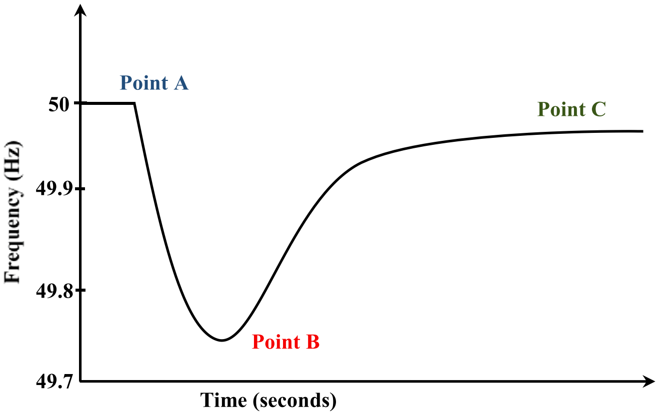


Fig. 13. Power system's frequency response under rising demand (Yakout et al., 2022).

waveforms and harmonic-free voltage and current. Three common problems with power quality are harmonics, voltage fluctuation or unbalance, and phase unbalance. When a huge number of charging stations for EVs are integrated with the grid system, harmonics are produced, which impact the voltage profile and ultimately the quality of the power. Therefore, in order to address the power-quality challenges of the power system due to EV charging, the chargers must be able to maintain IEEE-519 requirements. Also, the charger system's input power factor needs to be high to get the most real power possible from the utility. In (Sivaraman and Sharmeela, 2021), the negative effects of highly variable EV charging characteristics on the distribution network were examined. These effects included overloading, harmonic issues, poor voltage profiles with other users connected to the same distribution network, etc. As nonlinear loads and EVs are being integrated into low-voltage residential networks, a probabilistic methodology to quantify the impact on power quality, such as harmonics and voltage imbalance levels, was given in (Rodríguez-Pajarón et al., 2021). The impacts of grid integration of EVs on power quality are described in the following subsections, and potential solutions are listed in Table 4.

4.2.1. Harmonics

The term "harmonics" refers to voltages or currents having frequency components that are integer multiples of the basic power frequency. Harmonics alter the voltage and current waveforms, which has an impact on the quality of the power. Total harmonic distortion (THD) of voltage and current, as stated in Eq. (1), can be used to measure it.

$$THD_x = \frac{\sqrt{\sum_{h=2}^{N} X_h^2}}{X_1} \tag{1}$$

Here, h is the harmonic order; X_1 is the amplitude of the fundamental frequency (50 Hz or 60 Hz) component of voltage or current; and X_h is the amplitude of the harmonic components of voltage or current.

The power grid may experience power quality problems as a result of the switching operation of power electronics components for EV charging. The harmonic problem is of particular concern because severe harmonic distortion might result in system components being derated. THD values for up to a 69 kV power network should be below 5%, according to IEEE standard 519, in order to maintain the power quality (Ayub et al., 2014). The non-linear nature of EV chargers, i.e., the power electronics used in an EV charger, can result in harmonic currents in the power network. A study in (Karmaker et al., 2019) demonstrates that the harmonic disturbances would increase when the EV chargers were linked to the grid. THD is therefore around 4.82% for a single EV linked to the system, approximately 12.35% for three EVs, and approximately 19.69% for five EVs with various specifications. In order to examine the effects of EV charging on distribution systems, a power quality analysis approach considering the charging uncertainties of EVs was presented in (Leou et al., 2018). The analysis shows that as EV penetration goes above 60%, harmonic current distortion will surpass the IEEE standard, and THD equals 5.7% at 100% EV penetration. In (Sharma et al., 2020), the essential power quality issues were covered, along with a comparison of the common DC and AC bus architectures for grid-connected EV fast charging stations. According to FFT research, standard AC bus charging infrastructure has a very high current harmonic percentage (THD = 3.81%) compared to common DC bus design (THD = 1.12%), meaning that DC bus configuration offers better outcomes in terms of power quality. In comparison to low voltage (415 V), as mentioned in (Ahmed et al., 2021), medium voltage (11 kV) has a more robust performance in terms of THD for the penetration of EV charging stations. The THD at the low voltage side is 2.11% for a single charging station and 3.45% for multiple charging stations, while the THD at the medium voltage side is 0.33% with one EV charging station and 0.43% for many charging stations.

4.2.2. Voltage quality

This subsection focuses on the impact that EV charging has on the supply voltage. Rapid voltage change and flicker are two examples of voltage fluctuation problems. The need for electricity to charge the batteries of EVs is growing along with the number of EVs on the road. The secondary voltage experiences additional voltage deviation or voltage drop as a result of the higher demand brought on by EVs; voltage dips rise as the EV load size grows. For instance, the voltage drops caused by a 240 V/30A EV load are roughly twice as great as a 240 V/16A EV load (Dubey and Santoso, 2015). When numerous EV chargers are connected, the voltage may exceed the distribution end's safe voltage regulation limitations (Karmaker et al., 2019). This issue is brought on by overloading due to the high EV population. According to the assessments in (Richardson et al., 2010), there will be areas of the network where the voltage level has fallen below the permitted threshold for EV penetration levels larger than 42%. The quantity of EVs that can be linked to this specific network securely before the voltage levels fall below safe levels might vary significantly, from 28% to 42%, depending on the location of the points of connection. According to a study in (Dubey et al., 2013), an additional EV load next to an existing EV load will deteriorate the voltage quality by roughly twice the additional voltage drop. According to (Monteiro et al., 2011), a traditional EV charger causes a 7.3% voltage loss in a home that is further away from the distribution transformer. This voltage drop can cause other loads in the home to malfunction. In (Deb et al., 2018b), different charging rates with 20% and 80% EV penetration reveal a voltage difference of 12.7–43.38% from the rated voltage. According to a study in (Li et al., 2012), the network voltages of a 10 kV residential feeder will exceed the voltage variation tolerance of 7% when the EV penetration rate is 50% or higher.

4.2.3. Phase unbalance

Phase unbalance, which is a result of single-phase AC charging, is another effect of EV charging on the power quality of the electrical system. In particular, the inherent issue of phase unbalance caused by uneven loading of phases can be significantly worsened by uncontrolled EV charging (Kandpal et al., 2022). If home-based EV slow charging is not distributed evenly across all three supply phases, it could result in significant phase unbalance issues. All EVs are connected to phase "a" to examine how AC single-phase EV charging affects the phase unbalance problem in (Richardson et al., 2010). The result shows a significant phase imbalance because phase "a" has a much larger voltage drop while phases "b" and "c" have a voltage rise. Using V2G power transmission, an EV scheduling method was put forth in (Kandpal et al., 2022) to reduce phase load unbalance by reducing the demand for single-phase EV charging. An analysis in (Liu et al., 2011) found that the integration of several EV chargers on the distribution network had a negligible effect on the imbalance of current and voltage. Throughout a broad range of evaluated settings, the phase imbalance stays within acceptable bounds. In (Leemput et al., 2014), it was examined how single-phase on-board charging schemes for EVs affected the performance of a highly loaded, unbalanced three-phase low-voltage residential grid. In (Angelim and de, 2020), it was reported that connecting 7 EVs to a two-phase connection for Level 2 charging creates voltage unbalance. According to PV size and EV demand, this study also reveals that PV generation can be a good way to minimize technical issues caused by EV charging demand in a building with a commercial profile.

4.3. Impact on load profile

Due to EV charging requirements, a high EV penetration might place additional stress on the power supply. Moreover, as EV owners frequently start charging their EVs as soon as they get home from work, it is highly likely that EVs will be charged during residential peak hours (Lojowska et al., 2011). The peak load of the grid's load profile will rise as a result of large EV charging fleets. The load profile of commercially available EVs from various manufacturers is shown in Table 5. The table shows the approximate charging time and power consumption needed to charge the EV from 0% to at least 80% using three different charging standards. Many studies have been conducted to determine how EV deployment will affect the supply and demand profile on the grid. In (Qian et al., 2011), a method was presented for modelling and assessing the demand in a distribution system brought on by EV battery charging. Findings indicate that in the case of uncontrolled residential charging, a 10% market penetration of EVs would result in a rise in daily peak demand of up to 17.9%, while a 20% level of EV penetration would result in a 35.8% increase in peak load. A daily EV charging load profile that takes into account people's social and demographic traits, such as age, gender, and education level, was proposed in (Zhang et al., 2020). The outcome demonstrates that, particularly for the workplace and workdays, the demographics of EV users have a substantial impact on the

Table 6
The impacts of EV charging on power grid and possible mitigation approaches.

Other Power Grid Challenges	Remarks	Solutions
Supply and demand imbalance	EVs are connected to the electricity grid as additional loads in order to get charged. Uncoordinated EV charging increases peak load.	Implementation of time of use (TOU) tariff systems (Merrington et al., 2022). Implementation of appropriate charging management infrastructure (Sachan et al., 2020).
Power loss	A significant quantity of real power is consumed as EVs become more and more integrated into the grid, which results in distribution system power loss.	Implementation of coordinated charging (Clement-Nyns et al., 2010). Utilizing nearby distributed generators to supply EV loads (Dharmakeerthi et al., 2011). An optimum combination of all three EV chargers (Level 1, Level 2, and Level 3) (Zeb et al., 2020).
Component overloading	Overloading from the charging of EVs might result in overheating, which accelerates transformer aging.	Adaptation of the smart charging concept (Mobarak and Bauman, 2019). Selecting transformers with higher k-factors (Karmaker et al., 2019).

Table 5
Specifications for the widely available commercial EV charging demand ("EV Specifications and EV Charge +, 2023).

EV Model	Manufacturer	Level 1 (120 V)		Level 2 (240 V)		Level 3 (DC fast charging)(400–800 V)	
		Demand	Time	Demand	Time	Demand	Time
Prius PEV	Toyota			3.7 kW	2 h 20 min	-	-
Leaf	Nissan	1.8 kW	35 h	3.6Kw	12 h 45 min	46 kW	43 min
Fit	Honda	1.4 kW	15 h	6.6 kW	3 h 22 min	-	-
Model Y	Tesla	-	-	11 kW	6 h 15 min	170 kW	25 min
Model 3	Tesla	-	-	11 kW	5 h 30 min	170 kW	21 min
Roadster	Tesla	1.8 W	30 h	22 kW	10 h 45 min	250 kW	40 min
Focus Electric 23 kWh	Ford	1.8 kW	20 h	6.6 kW	3 h 30 min	50 kW	32 min
i-MiEV	Mitsubishi	1.4 kW	22 h	3.6 kW	4 h 40 min	50 kW	20 min
i3 60Ah	BMW	1.76 kW	16 h	7.6 kW	3 h	47 kW	20 min
HAN	BYD	-	-	7.4 kW	13 h 30 m	120 kW	44 min
e-Soul	KIA	1.4 kW	24 h	7.2 kW	10 h 30 min	77 kW	44 min

peak time and size of the daily charging demand. In order to predict the daily load profile for many EVs at corporate premises, a study was conducted in (Islam and Mithulananthan, 2016). The findings indicate that the total load power will increase in direct proportion to the EV penetration level. In (Mullan et al., 2011), it was explored how EV charging might affect the load profile of the electrical system in Western Australia. In the case of uncontrolled charging, the power grid can handle the charging demands of 200,000 EVs (10% of total EVs) during the peak hour. By moving EV charging to the night-time hours, the grid can accommodate the charging demands of 900,000 EVs (45% of total EVs) without having any detrimental effects on the system. The impact of 213,561 EVs during peak and off-peak periods on Ireland's wholesale power market was examined in (Foley et al., 2013). The findings indicated that off-peak charging is more advantageous than peak charging and that charging with a RE source also reduces emissions. In order to study the home-based load profile utilizing the IEEE-33 Bus radial distribution system and the effects on electrical utilities due to uncontrolled level 2 EV charging, a real-life assessment of multiple EV penetration rates with varied level 2 charger adoption rates was proposed in (Antoun et al., 2020). The findings indicate that a distribution network problem could occur from 50% level 2 charger deployment and 50% EV penetration. Electricity pricing based on time-of-use (TOU) is a developed method for lowering peak system loads. In (Birk Jones et al., 2022), the effects of EV charging on 10 distribution feeders were taken into account for situations where people spent more time at home or at work, with and without TOU pricing. The outcome demonstrates that without TOU rates, the system's overall load and line loading increased while all of the feeders' minimum system voltages were reduced within allowable bounds.

4.4. Impact on power loss

Transmission of active power from power plants to EV loads is necessary for EV charging. More system losses are experienced by all parts of the power grid as a result of this power transmission. Moreover, the losses in all utility system parts, including transformers, transmission lines, and other devices, increase when the EV load grows since the system current also rises. In (Pieltain Fernández et al., 2011), a method for analysing the effects of various EV penetration levels on the distribution network's energy losses was proposed. Obtained results indicate that, in a scenario where 60% of all vehicles are EVs, energy losses can increase by up to 40% during off-peak hours, and investment costs can rise by up to 15% of the total actual distribution system investment costs. The power losses of a grid-integrated vehicle system are calculated and examined experimentally by the authors in (Apostolaki-Iosifidou et al., 2017). According to the findings, electronics efficiency is lowest when low state-of-charge and low power transfer are present, and it is lower when discharging than when charging. Also, compared to the normal dispatch method, a dispatch algorithm was created that decreased losses from 7.0% to 9.7%. The coordination of EV charging was suggested and developed in (Deilami et al., 2011) on the basis of real-time optimization of the overall cost of energy generation, including energy losses.

4.5. Impact on component overloading

Massive number of EV charging stations necessitate vast amounts of power to be transferred from the power grid. This condition may overload the current system components because these components may not be built to handle the new extra EV loads. Transformer aging due to component overloading is another negative impact that incremental EVs have on the distribution system. The issue of EV charging clusters as a potential source of transformer overloading was covered in (Karmaker et al., 2019). In the transformer core, the harmonic current causes heating losses that lower the kVA rating of the transformer and raise overall power losses. According to an analysis of harmonic distortion's impact on transformer aging in (McBee, 2017), THD levels exceeding 10% will significantly speed up aging under emergency operating conditions. When things are running normally, the almost continuous energy requirement is what accelerates aging the most. In (Hilshey et al., 2013), a technique for calculating the effect of EV charging on overhead distribution transformers (25 kVA) was suggested based on thorough trip demand data. The findings show that straightforward smart charging strategies, including delaying charging until after midnight, can actually speed up rather than slow down transformer aging. Using long-range (60 kWh battery) and short-range (20 kWh battery) EV vehicles for 150 drivers over the course of a week, a smart charging concept was proposed in (Mobarak and Bauman, 2019). The outcomes demonstrate that the model lowers the transformer aging rate for EV penetration rates by up to 70% for short-range EVs and up to 60% for long-range EVs. In (Hua et al., 2014), an actual distribution system was taken into account to assess how uncoordinated EV charging during peak hours could affect cable loads. The findings indicate that only 15% of the EV penetration rate for fast charging and 25% of the EV penetration rate for standard charging can be handled by the current wires. This analysis comes to the conclusion that the current distribution infrastructure cannot support large rates of EV penetration.

5. Impact on power system planning

In the energy transition, power system models have become a crucial component of strategic planning and decision-making. The future trends of EVs make it clear that power system planning models need to include EVs in their forecasts since, depending on their charging habits and other effects, they could have a substantial impact on peak load and infrastructure investment. Due to the temporal patterns of customers' driving and heating needs, the electrification of the transportation and heating sectors could result in high demand peaks, which could in turn result in higher generation and network costs than the rise in total electrical energy consumption (Wu and Aliprantis, 2013). In order to hedge against the growth of EVs, it may be necessary to modernize power distribution networks, expand capacity, integrate renewable energy sources (RES), introduce dynamic pricing choices (i.e., promote off-peak charging to prevent the rising loads from exacerbating peak demand), and many other things (Bai et al., 2015). EVs have a significant impact on the short- and long-term plans of electrical networks and can function similarly to energy storage systems (ESSs). Planning the long-term extension of the electric power system is a challenging process that requires the modeling of social, technological, economic, and environmental factors. Therefore, in order to understand the impacts of EV in long-term power system planning, a thorough understanding of modelling methodologies is necessary. In (Kumar et al., 2023), the prospects and difficulties of simulating a long-term power system with EVs as a load were examined. An analysis of the system's effects on energy and power demand is necessary for power system planning that integrating transmission generation co-optimization with EV integration. It provides an overview of the various approaches used to simulate generation, transmission, and EV load, as well as the limitations imposed by creating power system planning models. In (Borozan et al., 2022), a model was proposed for EV operations to solve the large-scale and long-term network expansion planning problem under multi-dimensional uncertainty. The findings highlight EVs as a powerful non-network replacement for traditional reinforcement that could produce significant financial savings and function as hedging tools against uncertainty. In (Sterchele et al., 2020), two different approaches are described for the assessment of battery EVs. The findings demonstrate that realistic driving profiles may result in simultaneous EV charging, which raises peak demands and eventually necessitates power plant capacity expansion. A cost-effective system can be attained by implementing a regulated charging approach, reducing peak power demand and supply, incorporating more power from variable RESs, and lowering the total annual system expenses. The capacity expansion model in

(Quddus et al., 2019) models EVs as V2G technology. The optimal charging and discharging of EVs allow the charging station to adjust its power demand, which makes it seem like a flexible load on the microgrid. Table 7 includes the different short- and long-term expansion models in the presence of EV technology. The prediction of EV charging loads using stochastic uncertainty analysis was introduced in (Goh et al., 2022) for the safe and dependable functioning of the distribution network. The findings show that the maximum daily total load will increase to 15,532.9 MW on working days and 15,475.5 MW on rest days in 2025 as a result of the widespread charging of EVs. Additionally, the working day and rest day total load curves will exhibit a new peak load, increasing the basic daily load stage by 13.56% and 13.83%, respectively.

Integrated assessment models are frequently employed for analysing energy system transitions over the long term to assess international climate policy, achieve global climate targets, and explore approaches to decarbonize the transportation sector (McCollum et al., 2017). Six multinational modelling teams have developed novel methods to enhance the representation of power sector dynamics and variable renewable energy (VRE) integration in integrated assessment models in order to improve the effectiveness of these models in accurately representing all the specific issues of integrating VRE (Pietzcker et al., 2017). Eleven integrated assessment models—AIM/CGE, GCAM, DNE21 + , GEM-E3, IMAGE, Imaclim-R, POLES, REMIND, MESSAGE, TIAM-UCL, and WITCH—were compared in terms of modal structure, transport activity, energy intensity, and fuel mix development, with an emphasis on light-duty vehicles (Edelenbosch et al., 2017). The findings indicate that fuel substitution (toward electricity, hydrogen, and biofuels) and increased energy efficiency are the primary means of reducing emissions. Energy system models have been frequently used to offer insights to decision-makers on challenges relating to climate change, national energy planning, and energy policy (Yue et al., 2018). A comprehensive review of academic literature to identify the predominant energy systems models in the UK was carried out, and a classification scheme was proposed to provide comparisons among 22 models in (Hall and Buckley, 2016). The analysis based on the classification illustrates that MARKAL and its variations are the most prevalent models. In order to examine various energy prospects in a simplified energy system that represents the U.S. electric and light-duty transportation sectors and can exploit sector interactions through the introduction of PEVs that demand electricity to charge, TEMOA, an energy system model, was employed in (DeCarolis et al., 2016). It is essential to use tools that maximize investment in generation by considering physical limitations on the distribution network while maintaining desired reliability and characterizing the negative effects of pollutants to estimate the long-term benefits of the electric power system and the costs of proposed energy policies (Frew et al., 2016). An integrated planning model (IPM) with a carbon law, incentives for renewable-based electricity, the elimination of nuclear power plants, emissions taxes according to minimal damages, and the integration of EVs into the electric grid was described in (Taber et al., 2013) that optimizes the net anticipated advantages of electricity generation and investment in new generation by location.

6. Economic and environmental impact of EV charging

Since EVs rely on electricity from the power grid to move, the price of power generation has a significant impact on the price of EV usage. From the perspectives of the power grid (utility provider) and EV owners, respectively, the economic effects of EV penetration can be assessed (Richardson, 2013). From the perspective of the electricity network, EVs are extra loads that must be linked to the power grid in order to get charged. From the standpoint of EV owners, EVs are more expensive than ICE vehicles because of the expensive battery module. However, because of the increased efficiency of motor drives, reduced fuel consumption, and less expensive energy, EVs have lower operating and maintenance expenses than ICE vehicles. The deployment of EVs can be lucrative for the operation of the power grid and EV owners with the

Table 7
An overview of the co-optimization model considering the impacts of EV on power system.

Model	Planning year	Planning horizon	Programming tool	Objective	EV consideration
Long-term energy planning (Wu and Aliprantis, 2013)	2013	Long-term (40 years)	NETPLAN planning tool	Minimizes operational and investment costs	Considers numerous EV penetration scenarios.
Generation Expansion Planning (Wu and Aliprantis, 2013)	2015	Long-term	Mixed-integer linear programming (MILP)	Minimizes operational and investment costs	Considers smart-charging/discharging of EVs
Energy System Planning (Prebeg et al., 2016)	2015	Long-term (35 years)	Multi-objective optimization problem	Minimizes the net present value of energy systemsMaximizes RE integration	Considers EVs to be in V2G mode.
Energy System Planning (Noorollahi et al., 2020)	2019	Short-term	Aggregation model	Minimizes operational costs	Considers four EV charging scenarios, such as no EV, uncoordinated EV charging, unidirectional, and bidirectional V2G.
Short-term hourly operational decisions (Quddus et al., 2019)	2019	Short-term	Stochastic programming model	Minimizes the costs of charging EVs.	Considers the number of EV batteries charged and discharged through V2G, renewable, and grid power usage.
Generation and transmission expansion planning (Manríquez et al., 2020)	2020	Long-term (10 years)	Mixed-integer linear programming (MILP)	Minimizes both operational and investment costs	Considers hourly EV demand and the smart charging option.
Capacity expansion planning (Mehrjerdi, 2020)	2020	Long-term (6 years)	Mixed-integer linear programming (MILP)	Minimizes the investment, operational, and maintenance costs	Considers EVs to be in V2G mode.
Long-term expansion planning (Quddus et al., 2019)	2019	Long-term	Stochastic programming model	Minimizes the annualized cost of locating charging stations.	Considers decisions on EV charging station location
Long-Term Planning of an Isolated Microgrid (Clairand et al., 2020)	2020	Long-term	Aggregation model	Minimizes charging costs and maximizes the use of renewable energy	Considers EV charging strategies
Short-term expansion planning of distribution system (Baringo et al., 2020)	2020	Short-term	Mixed-integer linear programming (MILP)	Minimizes the investment and operational costs	Considers EV charging strategies
Generation and transmission expansion planning (Heuberger et al., 2020)	2020	Long-term	Mixed-integer linear programming (MILP)	Minimizes total system cost	Considers numerous EV penetration scenarios.
Network expansion planning (Borozan et al., 2022)	2022	Long-term (40 years)	Mixed-integer linear programming (MILP)	Minimizes expected system costs.	Considers Grid-to-Vehicle (G2V), V2G, and Vehicle-to-Building (V2B) operations of EVs.

implementation of energy trading, coordinated charging, and varied electricity tariff policies. Also, the efficiency of an ICE vehicle varies from 15% to 18% on average, but the efficiency of an EV varies from 60% to 70% (Ahmad et al., 2022). At first impression, the economic effects of EV deployment are negative for both the power grid and EV owners. In order to meet the increased demand for EVs, the power grid must have greater generation capacity. Also, EV owners must pay a hefty initial cost for their vehicles. But still, the deployment of EVs can be profitable for the electric power grid and EV owners with the establishment of coordinated charging, energy trading, and different electricity rate policies (Yong et al., 2015). Table 8 summarizes the possible impacts of EV charging on the power grid economy and also suggests potential mitigation approaches.

6.1. Initial purchase cost

The initial investment and purchase costs of EVs are higher than ICE vehicles because of the expensive battery modules and charging infrastructure. One of the main obstacles to the mass adoption of EVs is the greater initial cost of these vehicles. The findings in (Weldon et al., 2018) demonstrate that, when taking into account the 10-year analysis period, EVs are currently cost-competitive with ICE vehicles. However, the degree to which EVs are competitive with ICE vehicles depends on a variety of variables, including payback period assessments. There are various ways to lower the high initial cost of EVs, including mass producing them, instituting energy trading policies, and adopting appropriate charging practices. In (Song et al., 2015), it was suggested to use a dynamic design process to create a hybrid ESS (HESS) for an electric city bus that consists of a battery and a supercapacitor (SC). It is demonstrated that the HESS's life cycle cost initially falls sharply with the addition of SCs. An optimization strategy for charge scheduling was established in (Amamra and Marco, 2019), addressing the initial battery SOC, EV plug-in time, regulation prices, desired EV departure time, battery degradation cost, and vehicle charging requirements.

6.2. Operational and maintenance costs

The quiet ride, quick acceleration, and excellent energy economy of EVs are driving up consumer demand. Over conventional vehicles, operational costs are reduced because of increased efficiency, lower energy costs per mile, and lower costs of maintenance and repair. In accordance with the overall cost of ownership, a comparison between EVs and ICE vehicles was done in (Liu et al., 2021). The findings indicate that EVs' greater initial cost can be regained in less than 5 years. This is specifically valid for EVs with smaller ranges. In more detail, cost parity with a comparable ICE vehicle may be reached in 8 years or less for an EV with a driving range of under 200 miles. In order to reduce a power network's operational expenses, a stochastic model is created in (Khodayar et al., 2012) for scheduling wind thermal power systems under scenarios involving EV charging patterns. In (Yan et al., 2019), a control and optimization method for an EV charging station integrated with a commercial building, a PV unit, and fixed energy storage was suggested. The findings show that the suggested method can increase tolerability toward uncertainties while lowering operational costs. According to a study in (Moon and Lee, 2019), EVs are more cost-effective than ICE vehicles at the current level of fuel prices and will continue to be so even if the price of fuel drops another 20% in the Korean market. Also, consumer desire for EV products should rise as fuel prices become more reliable.

Table 8
The impacts of EV charging on power grid economy and possible mitigation approaches.

Economic Challenges	Remarks	Solutions
Initial purchase cost	Higher purchase costs due to the expensive battery modules and charging infrastructures.	Mass EV production (Gass et al., 2014). Implementation of energy trading (Kang et al., 2017). Implementation of appropriate charging infrastructure (Amamra and Marco, 2019). Adoption of hybrid ESS (Song et al., 2015).
Operational cost	Coordination costs between generation and demand.	Coordination between EV charging loads and RESs (Yan et al., 2019).
Electricity price	The price of power may rise if there are many EV charging stations.	Adaptation of various electricity tariff policies (Kang et al., 2017). Adaptation of smart energy trading (Erdinc et al., 2015). Implementation of smart charging infrastructure (Veldman and Verzijlbergh, 2015).
Ancillary services market	Balance rapid variations in loads and generators.	V2G technology (Sortomme and El-Sharkawi, 2012). Development of user-based smart charging models (Al-Obaidi et al., 2021).

6.3. Impacts on electricity price

EVs could play a significant role and have an impact on electricity pricing in the future if their market penetration is substantial. In order to reduce charging costs, the financial impact of various EV charging procedures on power systems was examined in (Veldman and Verzijlbergh, 2015). The findings in (Goncalves et al., 2013) showed that a significant increase in EV charging could push electricity prices beyond 17% by 2020. But by coming up with effective charging methods, the price increase can be mitigated. In (Jin et al., 2013a), it is demonstrated that, as compared to an unregulated approach, effective charging scheduling can result in significant cost savings and income increases. Furthermore, the presented dynamic charging scheduling systems offer closer to ideal solutions than static charging. In (Erdinc et al., 2015), a joint assessment of dynamic pricing and peak power limiting-based DR solutions with the potential for bi-directional EV and ESS utilization was realized. With the aid of this technique, the effects of various EV owner customer preferences, the availability of ESS, and two-way energy trading capabilities are studied with regard to the decrease in overall power prices. In (Vagropoulos et al., 2017), the constraints of the price-taking strategy were studied in relation to the varied effects of direct and smart charging on power system scheduling and energy prices. In (Gilleran et al., 2021), it was calculated how charging affected monthly peak power demand, electricity use, and annual electricity bills. The annual electricity cost is especially susceptible to major swings, with rises as high as 88% in cold-climate regions with rate structures that include high demand charges.

6.4. Impacts on ancillary services market

In order to balance rapid variations in loads and generators, auxiliary services are required. Ancillary service providers in a power grid are obliged to balance generation and demand and respond quickly to any imbalance in the grid's power consumption. Using a rule-based decision-making approach, an efficient real-time energy management strategy for photovoltaic-assisted charging stations participating in auxiliary services of the smart grid was created in (Chen et al., 2017). The outcome demonstrates that the suggested solution is practicable and efficient for real-time energy management. EV owners may gain financially from V2G, which involves the delivery of energy and related services to the grid, as well as utilities. A V2G algorithm was created in (Sortomme and El-Sharkawi, 2012) to improve the scheduling of ancillary services and energy. The findings in (Al-Obaidi et al., 2021) suggest that taking user preferences into account would increase the overall money produced by the EV scheduling model, which in turn might up-finance the cost of charging by as much as 100%. Also, the established user-centric smart charging model results in an increase of nearly 90% in peer-to-peer energy transactions among EVs and an increase of 11% in the provision of ancillary services to the grid. Another finding in (Osório et al., 2021) demonstrates that the unique approach with EV and PV presented can actively contribute to the energy system in a way that is both economically viable and respects the technological limitations of the network while also offering significant ancillary services to the system operator.

6.5. Environmental impact of EV charging

Since EVs emit no emissions, they are promoted as being environmentally beneficial and green. However, EVs utilize electricity produced by the power grid from conventional energies to charge their batteries, and this process does emit GHG (Yong et al., 2015). Moreover, EVs may produce more emissions than ICE vehicles while charging from a power grid that uses coal or other polluting fuels. "Wells-to-wheels emissions" is a parameter that is used to compare the emissions levels of EVs with regular ICE vehicles (Jose et al., 2022). The location and the most popular electricity sources are the main factors that affect how much well-to-wheel pollution your EV produces. The energy demand of EVs served by a RES-based distribution system instead of a conventional energy grid could lessen pollutant emissions. In order to lessen the reliance on EV charging on conventional energy, a daytime PV-based, PEV charging station installed in a business parking garage was taken into consideration in (Tulpule et al., 2013). The findings demonstrate that a workplace charging system based on solar energy has a beneficial influence on economics and lowers emissions from the power grid. In (Li and Jenn, 2022), it is recommended that the solution to securing the environmental advantages of the widespread use of EVs is the location of charging infrastructure and the management of charging activities. According to the energy mix and generation emission method, the net carbon emissions related to the deployment of EVs in Saudi Arabia were quantified in (Elshurafa and Peerbocus, 2020). Emissions would typically decrease by 0.5% for every 1% of EVs deployed, and in the best situation, emissions would decrease by 0.9%.

7. Challenges and future research direction

Although it is still in its early stages, research on EV integration is essential. EVs can have a lot of beneficial effects on technology and the environment, but due to their availability, the impacts of large-scale EV integration, technical constraints, and cost, they are not commonly used worldwide. Moreover, the main research hurdles include a smaller share of all vehicles on the planet, early stages of development, a lack of information on EVs and charging stations, and a lack of trust in EV adoption in countries that are more dependent on fossil fuels. Therefore, in order to encourage the maximum growth of EVs and lessen the effects of widespread EV integration, further research is needed in the area of the electrification of transportation systems.

7.1. Optimal location selection for EV charging station

The development of the EV sector is based on EV charging stations, which serve as the energy source for EVs (Mastoi et al., 2022). Effective, relevant, and affordable charging stations can increase consumers' willingness to purchase and promote the growth of the sector. The optimal site selection of EV charging stations is influenced by the service quality and operational effectiveness of the EV as well as the entire life cycle of the EV battery (Hosseini and Sarder, 2019). The characteristics of the distribution system, as well as the investor's mindset because of profit and investment, may be affected by the position of the EV charging station and EV charge scheduling. Also, the location of the EV charging station affects the user's choice to charge due to the minimum travel cost, waiting time, charging time, and charging access cost (Ahmad et al., 2022). Additionally, a more dependable EV charging infrastructure with faster charging times is needed due to the rising use of EVs. Therefore, fast charging is feasible for charging an EV battery in 20–30 min (Zeb et al., 2020). The negative implications of fast charging infrastructure may be avoided with proper charging station planning. Consequently, it is crucial to develop EV charging stations while taking into account the best location and size for networks that combine transportation and distribution, the best placement for EV charging stations with RESs, the integration of EV charging stations for grid management issues, and the forecasting of EV charging loads. The location of EV charging stations can be determined using a variety of optimization techniques, including distribution network operator (DNO) approaches, charging station owner (CSO) methods, EV user approaches, and combinations of the aforementioned techniques (Ahmad et al., 2022). Therefore, research on optimal location selection methods for charging stations, considering distribution network operators, EV users, and charging station owners, is necessary to deal with the uncertainty of EV charging and the impact of charging loads on the distribution system. Table 9 lists the three approaches and their associated objectives for the optimal placement of fast EV charging stations.

7.2. Integration of renewable energy sources

The greatest significant change to the electrical system could result from EV's ability to help RESs such as solar and wind energy be integrated into the current power grid. When EVs consume power from RESs, the effects on the economy and environment are especially favourable. To lessen the detrimental effects on the utility grid, the integration of RESs such as solar energy and wind energy into the grid represents a significant potential for the construction of EV charging infrastructure (Li et al., 2022). The primary obstacles to integrating large volumes of RESs into the grids are caused by RESs' intermittent nature, which is causing problems for electricity providers (Liu et al., 2015). However, the development of quick-response power electronic converter control and energy storage devices could limit such intermittent behavior. Moreover, in addition to the changing EV deployment, RES technologies have also seen cost reductions as a result of technological advancements and production learning curves. This enabled the number of permitted wind and solar projects to rise quickly. In (Narasipuram and Mopidevi, 2021), it is indicated that including renewable energy in the charging station can lessen the high burden on the grid, particularly during peak hours. An evaluation of solar-powered EV charging stations with potential mitigation strategies for present technical limitations was presented in (Yap et al., 2022). This study also indicates that a workable way to lessen the erratic nature of solar energy is through the hybrid integration of other renewable energy sources like wind or biogas.

7.3. Trade-off between grid-scale energy storage and EVs

In recent years, both EVs and grid-scale battery energy storage have seen rapid growth due to the decarbonization of energy systems, which has enabled increased penetration of renewable energy while ensuring

Table 9
Characteristics of three main optimal location selection of EV charging stations.

Ref.	Approaches	Remarks
(Gampa et al., 2020)	DNO approach	Minimizes power losses.Minimizes bus voltage deviation.Minimizes distribution network configuration cost.Improves reliability.
(Wang et al., 2018)	CSO approach	Minimizes installation cost.Minimizes land cost. Minimizes operating cost.Minimizes maintenance cost.Maximizes the EV flow.
(Othman et al., 2020)	EV user approach	Minimizes traveling cost.Minimizes waiting time cost.Minimizes charging time cost. Minimizes charging cost.

grid stability (Parra and Patel, 2019). Even if the trade-off between these two energy storage systems involves challenges, it will increase the flexibility of the distribution system. An energy system of a commercial building, comprising its grid connection, distributed energy resources, energy storage such as fuel cells, stationary energy storage and EVs, and demand profile, is modeled in (Bozchalui and Sharma, 2012) in order to examine the potential of EVs as mobile energy storage. In (Wong et al., 2011), the stationary battery and mobile battery (EV batteries) systems for grid voltage and frequency stability control in smart grids were proposed. From the perspective of the electricity market, an optimized scheduling technique for EV charging with energy storage was studied in (Jin et al., 2013b). Another approach was suggested in (Eseye et al., 2019) with the aim of optimizing total profit and ensuring the energy flexibility of the building microgrid, employing EVs as dynamic energy storage devices and battery storage as a controlled demand facility in the day-ahead and regulated electricity markets. A novel hybrid system that actively participates in grid services by combining local battery energy storage and the EV battery as a single unit was proposed in (Yang et al., 2022). The approach provides enhanced optimal power scheduling for the microgrid's fast frequency control. A battery ESS along with wind farms in which the stored energy can be used for both stationary (reserve and arbitrage) and mobile (EV) applications was proposed in (Hayajneh et al., 2019). The techno-economic assessment based on the actual conditions of the Chapman Ranch wind farm shows that the ESS's profitability scale or investment value is increased by integrating stationary and mobile applications.

7.4. Development of smart EV charging system

Smart grids enhance power generation and distribution systems by being more efficient, flexible, dependable, and secure. The smart grid includes sophisticated communication, smart energy metering, and advanced control technologies that support EVs as dynamic loads and potential dispatchable-distributed energy sources for flexible and effective deployment in the power sector. Smart charging is a charging system with duplex communication service among EVs, charging operators, and charging stations where they share their data for optimal energy management (Mwasilu et al., 2014). This data connection system knows the energy demand and supply for any time period. By monitoring the data, the system can design an energy supply plan for flattening and spreading the peak value of the energy demand curve. In other words, a smart charger can regulate the power of charging in accordance with the grid's power supply, the needs of EV users, and the grid's support during emergencies, and it also enables EVs to serve as adaptable grid resources and offer supplementary services in emergencies (Deb et al., 2022). It attempts to reduce future network reinforcement costs by shifting EV charging loads to times when other demands are low, allowing for better integration into the larger energy system (García-Villalobos et al., 2014). It is a crucial component for the economically advantageous and environmentally responsible grid integration of EVs. Such systems have the potential to help achieve a number of objectives, including raising the availability of RESs, decreasing the operating costs of EVs, maximizing the use of current network infrastructure, and reducing the need for additional investment (Heinisch et al., 2021).

7.5. Adoption of V2G technology

Electric power systems play a significant role in EV charging stations. Since there must always be an equal balance between supply and demand, it is necessary to plan for peak demand by increasing generating, transmission, and distribution capabilities. This can be done more effectively by combining RESs with V2G services, which will allow EVs to sell any unused energy in their batteries back to the grid (Quddus et al., 2019). An essential part of managing the energy used for EV charging is the V2G technology, which enables EV batteries to serve as portable energy storage and two-way energy transfer between the grid and the EV (Sami et al., 2019). The emergence of the smart grid concept in power systems has advanced the contribution of EVs in the context of V2G technology (Tan et al., 2016). When demand is at its highest, V2G enables EVs to supply energy back into the grid, relieving the grid of some of the load (Amamra and Marco, 2019). The advancement of V2G systems has increased the significance of EVs in the transportation sector as clean, energy-integrated virtual power plants.

In order to explain the function of EVs in the V2G system and the possible benefits of this system to researchers and scientists, a thorough analysis was provided in (İnci et al., 2022). The advantages, disadvantages, and technologies of EVs in a V2G connecting system were discussed and investigated in (Hannan et al., 2022). Also, a thorough review of the V2G topologies, operations, applications, problems, control systems, key characteristics, current details, advantages, and disadvantages is done, as well as associated applications. Moreover, EV technology should enable the bidirectional wireless power transfer (WPT) to deliver a number of ancillary services to the grid as wireless charging technology advances. In order to facilitate cooperative coordination between EV owners and the power system in G2V and V2G operations, an aggregator serves as an agent between the system operators and consumers (Yang et al., 2015).

However, in a V2G operation, EV owners must be compensated for the battery degeneration caused by extra cycling beyond their transportation requirements (Harnischmacher et al., 2023). Therefore, a strategy was proposed in (Sarker et al., 2016) for the aggregator to maximize revenues from involvement in competitive energy and various regulating reserve markets while compensating EV owners for degradation. The findings demonstrate that, based on the battery cost, the aggregator divides its resources between the energy and reserves markets, and that if an aggregator employs EVs for ancillary services, the system operator achieves cost savings. In (Wenzel et al., 2018), real-time charging strategies were developed in the context of V2G technology to enable the utilization of EV batteries to provide ancillary services. In order to better understand how EVs and critical loads interact in V2G conditions, address battery degradation, and inspire people to participate in V2G, an incentive-based energy trading strategy was adopted in (Umoren et al., 2023). A novel framework was proposed in (Jin et al., 2020) for an EV aggregator that can aggregate schedulable EVs to provide auxiliary services for the power grid. Along with the growing prosperity of EVs, the penetration of EVs into the V2G trading market brings challenges and security concerns to the operation of the energy market (Luo et al., 2022).

7.6. Development of convenient charging stations and pricing schemes

The energy gap during periods of high demand and the lack of charging infrastructure due to high installation costs are the main problems with charging stations. The ESSs can fill the energy gap during periods of high demand. Therefore, establishing convenient charging access points in public locations and managing EVs as ESSs are also required to gain benefits from large-scale EV penetration (Mali et al., 2022). Moreover, by charging EVs when and where it is most advantageous for the power grid and while ensuring that consumers' mobility demands are satisfied at an affordable price, the maximum value from integrating EVs into the power grid may be achieved (Mastoi et al., 2022). The charging facility layouts of the charging stations vary since they are installed by distinct companies in various locations. Therefore, it is difficult for the users to adjust the charging facility layouts to the current grid infrastructure. The impacts of EVs on the power grid will lessen with a uniform charging facility structure compare to refuelling stations (Das et al., 2020b). Moreover, in order to satisfy the urgent charging demands, it is reasonable to ascertain whether the current grid network is ready or has to be upgraded or restructured. EV owners refuel their vehicles using electricity so that the batteries have enough energy to support their driving requirements and pay for their mobility services based on the energy volume charged and on electricity pricing rather than oil prices. Therefore, pricing mechanisms can be effective tools for adjusting EV charging demand in accordance with a specific profile (De Hoog et al., 2016). In order to design a successful electricity pricing scheme with the desired profile, the responses of grid stakeholders to rates that they broadcast to EV owners have to be considered. In order to maintain stated prices in accordance with feedback from EV owners and help grid operators ensure the grid's dependable operation, an adaptive pricing approach was proposed in (Valogianni et al., 2020). A review of EVs optimum charging and scheduling under dynamic pricing schemes was proposed in (Amin et al., 2020b).

8. Conclusions

EVs are becoming more and more popular as a result of environmental concerns and technological improvements. The increased usage of EVs and their associated charging needs, however, are raising efficiency, performance, and a number of power-quality concerns that have a negative influence on grid performance and load profiles at both small and large consumer ends. Moreover, the electricity demand for EV charging loads is increasing, and EV load characteristics differ from other traditional system loads. Therefore, it is impossible to simply forecast in advance the location, time, and length of the charging process, as well as the real and reactive power consumption of the EV loads. Ultimately, EVs have introduced both considerable challenges and benefits for the power infrastructure. Thus, to ensure the greatest benefits from EVs with distributed generators, technological developments and reorganization like the appropriate smart charging infrastructure, dependable communication systems, and controlled charging are required. The consideration of the probable use of EVs in the future and their potential effects on power system infrastructures, power system planning, economics, and the environment in this paper serves to illustrate the necessity for a review in this specific field of study. This paper examines the effects and difficulties of EV charging technologies on the electricity grid and identifies potential mitigating strategies by reviewing previous works. If the technological requirements to allow the integration of a sizable number of EVs match the necessary operational parameters for the power grid, such as grid stability, power quality, load profile, and power losses, the maximum benefits from the significant number of EVs can be realized. Finally, a number of significant issues and potential directions for future research in this area are presented. It is assumed that the researchers could gain a clear understanding of the current state of light-duty EV charging impacts and grid integration research from this review.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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