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Review

Grid Impacts of Electric Vehicle Charging: A Review of Challenges and Mitigation Strategies

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Abstract: Electric vehicles (EVs) offer a sustainable solution for reducing carbon emissions in the transportation sector. However, their increasing widespread adoption poses significant challenges for local distribution grids, many of which were not designed to accommodate the heightened and irregular power demands of EV charging. Components such as transformers and distribution networks may experience overload, voltage imbalances, and congestion—particularly during peak periods. While upgrading grid infrastructure is a potential solution, it is often costly and complex to implement. The unpredictable nature of EV charging behavior further complicates grid operations, as charging demand fluctuates throughout the day. Therefore, efficient integration into the grid—both for charging and potential discharging—is essential. This paper reviews recent studies on the impacts of high EV penetration on distribution grids and explores various strategies to enhance grid performance during peak demand. It also examines promising optimization methods aimed at mitigating negative effects, such as load shifting and smart charging, and compares their effectiveness across different grid parameters. Additionally, the paper discusses key challenges related to impact analysis and proposes approaches to improve them in order to achieve better overall grid performance.

Keywords: Electric Vehicles; Electric Vehicle Charging Stations; Distributed Generation, Battery Energy Storage; Grid Integration; Smart Charging; Renewable Energy Sources; Vehicle to Grid (V2G); Optimization Techniques

1. Introduction

Electric Vehicles (EV) have existed since the 19th century, however, their popularity declined with the introduction of internal combustion engine (ICE) vehicles. As people become more concerned about climate change and air pollution, EVs have regained their popularity. Electric batteries used to power EVs are seen as the most promising solution to totally replace ICE powered vehicles; the consistent improvements in battery technology have gradually reduced cost and increased driving range, making EVs appealing to customers. EVs have zero greenhouse gas emissions, improved performance, minimal maintenance costs, and low noise levels. Nearly one of every five automobiles sold in 2023 were electric, with over 15 new million EV registered worldwide, with China and the United States accounting for more than half of worldwide EV sales [1]. This is driven by strong growth of economies in the developed countries. Ultimately, the growing awareness about climate change and air pollution has led to increased demand for eco-friendly transportation options. Other factors that drive EV adoption include affordability, awareness, charging speed, preferred model availability, and range [2]. Several studies have highlighted the importance of government incentives in increasing EV adoption, such as subsidies and lower import duties to encourage consumers to switch to EVs.

EV charging is transforming the transportation sector, but high penetration will significantly impact the distribution grid. Some of these key effects include transformer overload, voltage fluctuations, frequency deviations, and power losses. When uncontrolled charging by large number of EVs is not properly managed, it may result in equipment damage, increased costs due to energy losses, and power outages. A study conducted on the impact of uncontrolled EV charging with industrial loads showed a significant deviation in the bus voltages and line congestion [3]; that study presents the challenges and opportunities arising from EV adoption, and how the factors above contribute to the increased demand for EVs. Firstly, a comprehensive network of EV charging infrastructure would encourage potential buyers, especially those who may be concerned with range anxiety or long-distance travel. EV sales are expected to reach 330 million by 2035, with China, United States, and Europe leading the charge; emerging markets are also expected to reach a threshold towards global mass adoption in the coming years [4]. As EV adoption continues to grow, it is essential for grid operators to develop strategies to manage the impacts of EV charging on the distribution grid.

Our paper reviews and highlights the impacts of EV charging, considering different EV models, their unique properties, and how they impact the grid when connected at Electric Vehicle Charging Stations (EVCS) using different levels of EV chargers. Various EV charging strategies adopted by EVs are discussed. Recent strategies proposed for load management during peak periods are also presented. This review aims to investigate the effects of uncontrolled EV charging on distribution grids, combining recent research findings. The key contributions include:

i. Providing a comprehensive review of technical challenges associated with large scale EV charging on distribution grids, including an evaluation of the advantages and disadvantages of unregulated charging on grid stability.
ii. Highlighting various types of EV models from multiple techno-economic perspectives, with a focus on battery capacity and key factors driving adoption
iii. Reviewing of recent optimization techniques for regulating EV charging and minimizing power losses, along with mitigation strategies for reducing the impacts and stabilizing grid components
iv. Identifying and prioritizing critical technical issues related to EV charging based on their frequency of occurrence in literature, thereby highlighting key areas of concern.
v. Conducting a comparative analysis of mitigation strategies, providing insights into their performance and applicability.
vi. Quantifying the measurable impacts of EV integration on distribution grid components, such as transformers and voltage regulators, to inform improved operation and grid planning.
vii. Identifying potential future research directions, highlighting interdisciplinary opportunities to advance the field of EV integration.

This paper is organized as follows: Section 2 provides an overview of EV technology, the current state of the EV market, and future trends in EV adoption. The rest of section 2 highlights features of EVs, such as their battery capacity and range. Section 3 briefly outlines impacts of EV charging and increased load demand on the distribution grid. Section 4 reviews studies on EV impacts, including data sources, methodology in analyzing the impacts, highlighting the priority of common technical. Section 5 reviews studies on mitigation strategies and optimization techniques, ensuring grid stability. The comparison of some mitigation strategies with respect to specific impacts are also discussed. The paper then discuss challenges and future directions of this study by considering factors necessary for analyzing future EV integration.

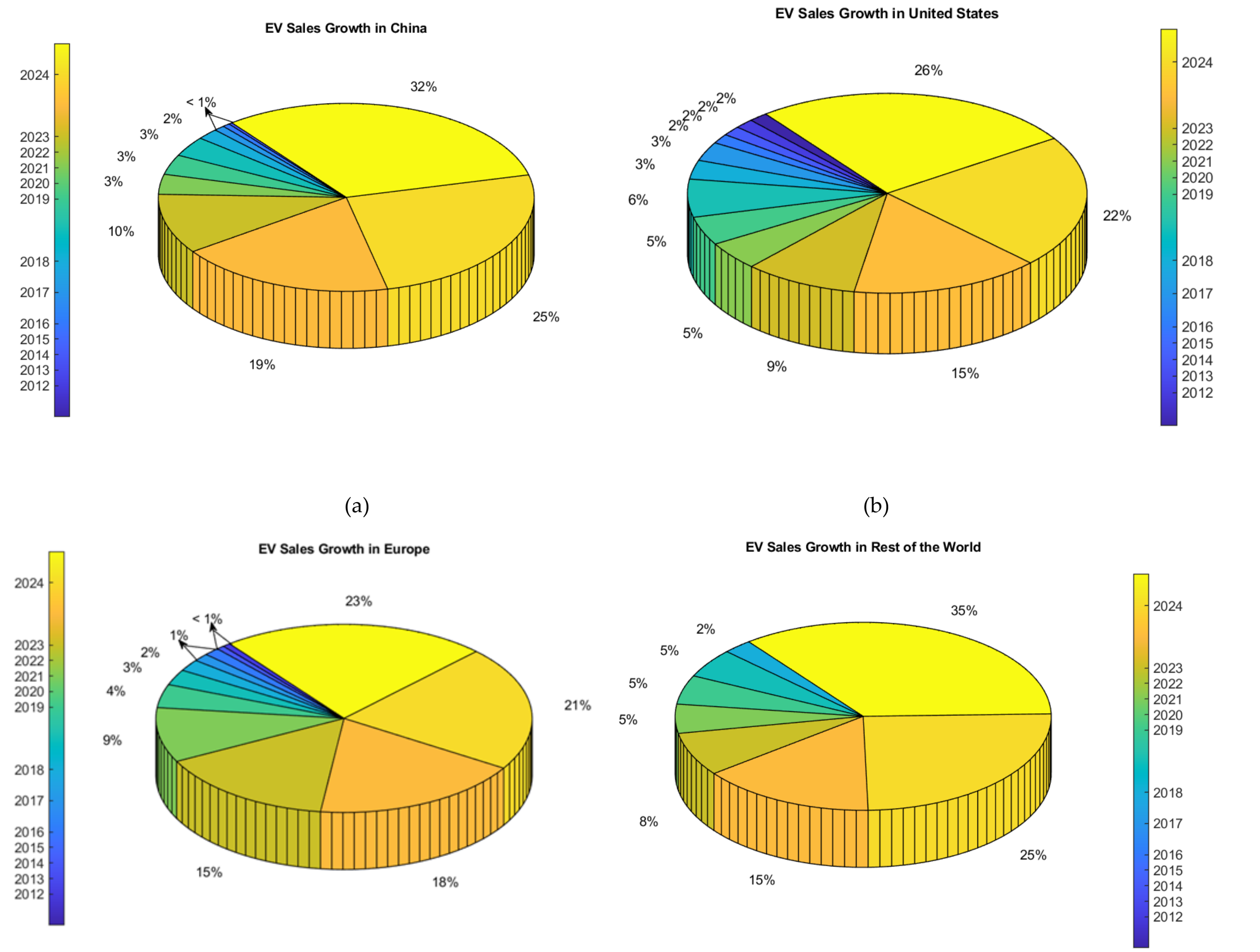
2. Electric Vehicles Technology

EVs have a rich history dating back to the 1800s. In the early beginnings, the first crude electric carriage was invented by a Scottish inventor, Robert Anderson. This was improved when the electric locomotive was developed during the late 1830s by an American inventor, Thomas Davenport. The first practical EV was developed in late 1850s, powered by lead-acid batteries; by 1890s, EVs became popular especially in big cities, due to reduced emissions and ease of driving. The concern for EV declined during the early 1900s due to high cost and limited driving range. However, from the 1960s, interests sparked up again due to government investments in EV research and development. This interest has given rise to various advances in battery technology and the introduction of hybrid vehicles in 1972, with the most popular being the Toyota Prius launched in 2000, paving the way for modern EVs [5]. Then after, various manufacturers like the Tesla, Nissan, Honda, have released a handful of EV models mostly powered by lithium-ion batteries.

Today, EV technology continues to evolve with improving battery technology, increasing range, and growing adoption worldwide. In the bid to reduce greenhouse gas emissions and the dependence on fossil fuels, many developed countries are actively working to phase out the manufacture of ICE vehicles. When EVs adoption increases, upgrades to existing distribution grids and installations of new power generators must be planned to manage the surge in electricity demand.

2.1. EV Market

The growing demand for EVs presents great opportunities for manufacturers to expand their customer base. Despite these vehicles are not so affordable by greater number of people, EV sales have continued to grow since 2016, with the United States, China, and Europe leading the charge. Figure 1a – 1d shows the growth rate for EV sales in these countries from 2012 to 2024. The sales in China and the Europe were less than 1% starting in 2012; this can be attributed to low adoption rate and the nonexistent of a strong motion for environmentally friendly solutions in the transportation sector. The global sales remained below 10% from 2012 to 2019, with the United States consistently maintaining about 2% from 2012 to 2015, and gradually increased over years until reaching 19% in 2023 due to the emerging markets in the rest of the world [6]. The figure highlights 2023 as a remarkable year for EV sales growth; this can be attributed to the increase in new EV models meeting customer preferences. Despite the charge from China, Europe and the United States in earlier years, markets in other parts of the world had a remarkable growth rate of 25% and 35% in 2023 and 2024, respectively.



(a) (b)

(c) (d)

Figure 1. EV Sales growth in China, United States, Europe, and the rest of the world [6].

2.2. EV Adoption

The adoption rate of EVs will continue to increase due to the attribute of zero gas emissions, improving the environment. According to the CARMA framework [2], the five major factors driving EV adoption include the charging rate, affordability, range, model availability, and awareness.

Charging rate: EV charging rate vary significantly, depending on the type of vehicles and chargers. The charging rate or speed is dependent on the battery capacity, air temperature, and vehicle age. Regarding charging costs, AC charging generally offers lower cost per kWh, but the DC chargers offer a higher cost because of their faster charging speeds. The DC superchargers from the Tesla network can deliver up to 350KW of power [7], enabling super-fast charging and significantly increasing driving ranges.

Affordability: This has remained the major concern for prospective customers. The cost of stacks of lithium-ion battery contributes to the rising cost; studies suggest that lower battery costs may reduce the price of the EV, making it competitive with ICE vehicles. In a bid to increase the driving range in some EV models, high-capacity batteries can be installed, making the vehicle more expensive. A sensitivity analysis conducted by [8] revealed that higher mileage would lead to greater overall cost savings for EVs, hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs).

Range: The EV range is an important factor for driving adoption. This is dependent on the battery capacity, the EV model, and weather conditions. Consumers want to know the battery's longevity and the distance they can travel on a full charge; this result can be uncertain due to lack of knowledge of battery health. A method was proposed in [9] to accurately predict the battery range and the remaining battery after the daily trip; this can help warn the users of the state of charge (SoC) of the battery and when a charge is necessary. When more investment is made in charging infrastructure and expanded throughout the cities, the anxiety over range could be reduced.

Model Availability: A customer survey was conducted in [10] to discover consumer preferences on EV model, and various options for the use of the EV. Findings show that options such as buy, battery lease, and lease be available for customers. The availability of popular models like the Nissan Leaf and the Chevrolet Bolt will drive EV adoption.

Awareness: This is crucial for driving EV adoption. The major misconceptions about EVs from consumers are the high cost and limited range; many are not familiar with the features and benefits of the EV. Investments from EV manufacturers in EV marketing and education will certainly increase the visibility and awareness. Following a general survey on increasing the awareness of EVs, the study in [11] concluded that social media is an efficient channel to spread the information about EVs. Also, government incentives and public awareness play a crucial role in increasing the acceptance of EVs.

2.3. Projected EV Sales

Global EV sales are projected to continue increasing robustly considering key trends. Observing the sales chart in figure 2, and considering present EV adoption rate 24% in 2025, it is estimated EVs reach 30% in 2027 and increase to 84.1% in 2040 [12].

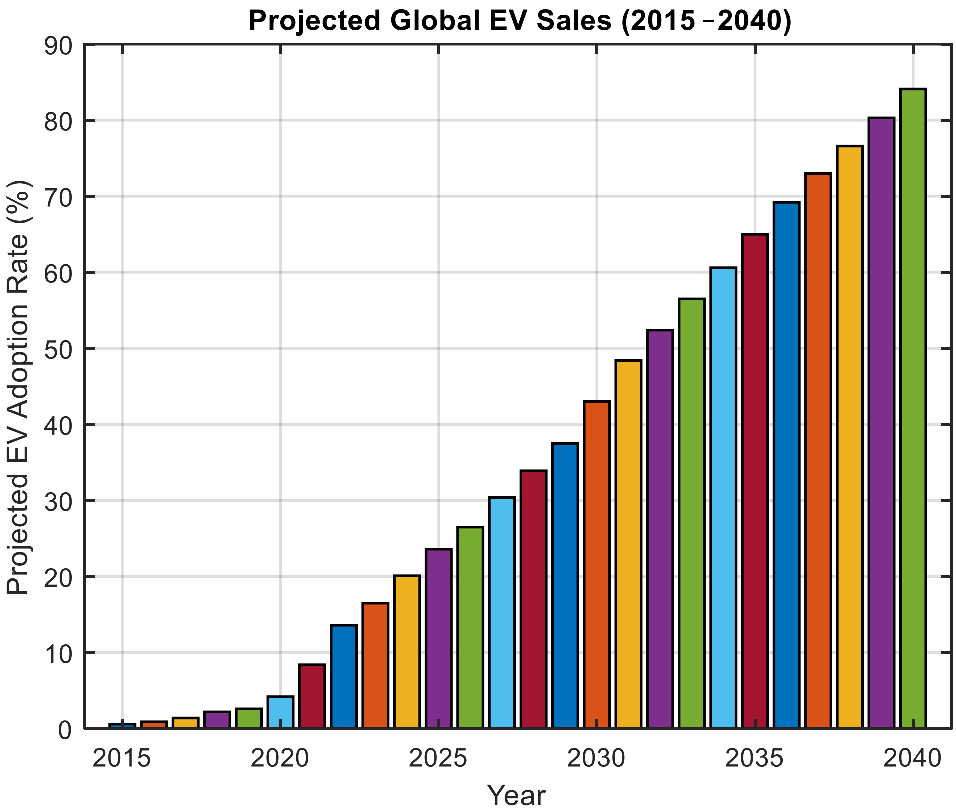


Figure 2. Global EV Sales Projection Chart (2015 – 2040) [12].

On a long-term projection, the growth of EV sales is expected to be stronger, driven by government incentives, improved battery technology aimed at reducing battery costs, making EVs affordable and available.

2.4. Types of EVs

Today, there are several types of EVs with their own unique features and characteristics. The main types are Battery Electric Vehicle (BEV), HEVs, PHEVs, Fuel Cell Electric Vehicle (FCEV), and Solar Electric Vehicles.

2.4.1. Battery Electric Vehicle

The most common type of EV is mainly powered by electric motors and batteries. Examples of the BEVs are the Tesla Model 3 and the Nissan Leaf. Table 1 shows the latest EV models, highlighting their key features and specifications [13]. The key features considered here are the battery capacity, range, motor power and overall efficiency. Generally, a larger battery capacity would result in a longer range assuming the efficiency of the motor remains constant. However, in some cases, efficiency can play a role in determining range; for example, an EV with a smaller battery capacity might have a similar range with an EV with a large battery capacity. This can be observed by comparing the Mini Aceman (with 542kWh battery capacity and 350km range) with the Kia EV3 Standard range (with 81.4kWh and 600km range). Also, larger batteries take longer time to achieve full charge, which is common in heavy duty EVs. Increased charging time will result in an increase in load on the transformer. The concern about charging time (due to battery capacity), range and limited charging infrastructure will always be factors to consider when buying an EV. Thus, there is a need to find an EV model that balances the battery capacity, range, and efficiency effectively.

Table 1. Recent BEV models and features.

Make & Models	Battery capacity (kWh) Nominal (Usable)	Range (km)	Motor power (kW)	Efficiency
Hyundai Kona Electric Long Range	68.5 (65.4)	514	150	6.35
Volvo EX30 Single Motor Extended Range	69 (64)	480	200	6.31
Ford Explorer EV Extended Range RWD	82 (77)	602	210	6.66
Kia EV3 Standard Range	81.4 (78)	600	150	6.32
Renault E-Tech EV 40 120hp	55 (52)	410	110	6.71
Mini Aceman	542 (492)	350	190	6.22
Peugeot e-3008	77 (73)	528	240	6.11
Tesla Model Y Long Range AWD	78.1 (75)	586	378	6.71
Volkswagen ID.7 Tourer Pro	82 (77)	607	210	6.44
BMW i5 Touring e-Drive 40	84.4 (81.2)	560	250	5.6
Audi A6 Avant e-tron RWD	83 (75.8)	598	240	6.44
Tesla Model 3 RWD	60 (575)	554	208	7.83
BMW i4 eDrive35	70.3 (67.1)	500	210	5.93
Mercedes EQA 250	69.7 (66.5)	528	140	6.47
BMW iX1 eDrive20	66.5 (64.7)	475	150	6.11
Audi Q8 e-tron S	114 (106)	458	370	3.61
BMW iX m70 x-drive	115 (108.9)	600	485	4.42
Audi Q4 e-tron 45 Quantro	82 (77)	524	210	5.52
Kia EV6 Long Range AWD	84 (80)	546	239	5.76
Peugeot e-5008 98 kWh FWD	101 (96.9)	668	170	5.86
Hyundai Ioniq 9 Long Range RWD	110.3 (106)	620	160	4.97
Skoda Enyaq 85	82 (77)	582	210	6.42

2.4.2. Hybrid Electric Vehicles (HEVs)

This type of vehicle combines the conventional ICE with an electric motor and battery. This combination can improve fuel efficiency and reduce the dependence on ICE, which results in low emissions; however, in most cases, fuel economy depends on user driving behavior and environmental conditions. Studies have shown that in normal conditions and proper maintenance, the batteries of the HEVs are more durable than that of the BEVs. HEVs are acclaimed to have a smooth engine operation due to the presence of the electric motor.

Unlike the BEVs and PHEVs, the hybrid vehicle need not to be plugged in to charge the battery; energy is supplied to the battery through the car’s regenerative braking system [14]. Table 2 highlights features of recent HEVs. The HEVs have smaller battery capacities due to the presence of the fuel tank in the vehicle; the battery can be considered as a secondary energy source. Despite these two sources – on a full tank and fully charged battery, the range for these vehicles are lower compared to BEV, mostly encouraged for low distance travels.

2.4.3. Plug-in Hybrid Electric Vehicles (PHEVs)

This is similar to the HEVs with the key difference that the battery can be charged from an external power source. As it does not depend on fossil fuels alone, the operational cost for the vehicle is reduced. Generally, PHEVs presents a more practical solution for consumers who desire to transition to EV driving and wish to utilize the ICE in the vehicle for longer trips. A combination of an electrical power of 70kW and an operating voltage of 200V enables the vehicle to be fuel efficient than ICE vehicles [14]. Table 2 shows the features of the recent Chrysler Pacifica PHEV model [15].

Table 2. Recent HEV/PHEV models and features.

Make & Model	Battery Capacity (kWh)	Range (mil)	Fuel Economy (mpg)
Toyota Prius Prime	13.6	45	52
Toyota RAV4 Prime	18.1	42	38
Chrysler Pacifica PHEV	12.2	32	30
Jeep Wrangler 4xe	17.3	22	20
Chevrolet Volt	16	60	42

2.4.4. Fuel Cell Electric Vehicle (FCEVs)

An FCEV uses hydrogen as an energy source to generate electricity that powers the vehicle. Electricity is generated through the electrochemical reaction that exists in the conversion process of hydrogen and oxygen. This could be a solution for long-distance travels with no emissions; however, the development of the infrastructure for hydrogen will play a crucial role in driving this EV adoption. Owing to the longer range and zero emissions, FCEVs are more expensive than BEVs or ICE vehicles although advancements in technology are reducing the costs. Examples of FCEV, which includes the Toyota Mirai, and Honda Clarity Fuel Cell, are outlined in Table 3 [16]. FCEVs achieve higher driving ranges due to their larger storage tanks, and the slower combustion rate of hydrogen. Having an EV that has no emissions, and longer range will be a win for the environment and the EV owner. However, due to the high cost and the unavailability of hydrogen refill stations, considerable effort is still required to achieve widespread adoption of FCEVs.

Table 3. Recent FCEV models and features.

Make & Model	Battery Capacity (kWh)	Range (km)	Motor power (kW)
2025 Honda CR-V Fuel Cell	17.7	434.5	130
2023 Hyundai Nexo	40	570	120
2017 Honda Clarity	25.5	143.2	120
2016 Toyota Mirai	1.6	650	134

2.5. Challenges and Opportunities for EV owners

EV owners encounter a number of challenges, but there are also numerous opportunities and benefits that far exceed these challenges. Reduced pollution, no fuel costs, a better driving experience, and more storage space are among the advantages of owning an electric vehicle. They offer driving experience unlike any others, which is economical to operate and the drivers are aware that they are contributing positively to the environment by reducing emissions and noise. Figure 3 shows major benefits and challenges for EV owners.

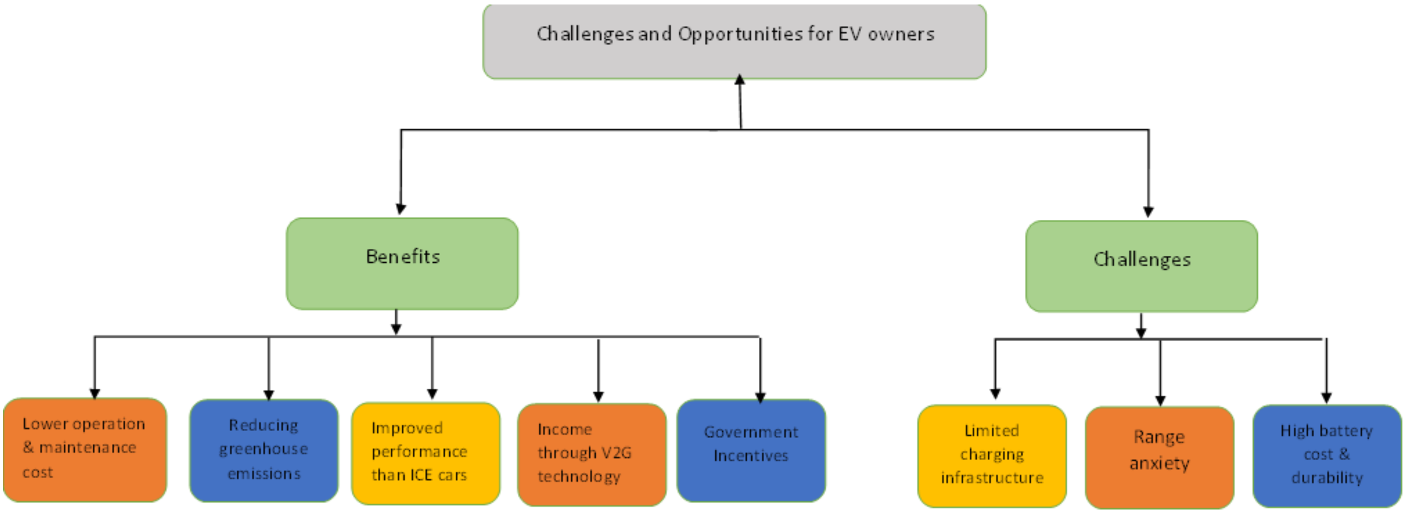


Figure 3. Benefits and Challenges for EV owners.

Furthermore, advances in smart charging technologies can assist to optimize energy consumption, minimize grid strain, and lower energy costs for EV owners [17]. The continued expansion of the EV industry, particularly the investments in an enhanced network of charging infrastructure will certainly promote EV adoption.

2.6. Types of EV Chargers

The development of a robust network of charging infrastructure has improved in many countries, which is crucial in supporting the adoption of EVs. The charging methods for EVs vary in terms of speed and accessibility; the speed is dependent on the amount of kW of power the charging outlet can supply in one hour, and the battery capacity of the EV. Primarily, EV chargers are classified into three levels:

Level 1 Chargers: These are mostly installed at homes and use the standard household 120V outlet. This is the slowest type of charging, typically providing about 2-5 miles of range per hour of charging [18].

Level 2 Chargers: These chargers require a 240V charging outlet and are mostly found at public charging stations. Level 2 Chargers are more efficient, as they can provide six times the range per hour of charging that of the level 1 chargers. Thus, level 2 chargers provide 12 – 32 miles of range per hour [17].

Level 3 Chargers: These chargers are referred to as DC-fast chargers, because power is supplied to the EV using DC technology. The buck-boost converter used in such chargers ensures their speed for full charge in a very short time. Level 3 Chargers are regarded as the fastest, as they can provide about 100 – 250 miles of range per hour of charging. These units are suitable for public charging outlets, but they are not adequately networked across many cities because they are currently expensive to construct [18]. Figure 4 shows the charging infrastructure for the three types of chargers, including the components used to achieve the required DC voltage for charging [19]. The Battery Voltage and State

Estimation (BVSE) works with the Battery Management System (BMS) to estimate the battery's SoC and health, ensuring safe and efficient charging. The AC/DC converter converts AC power to DC power for charging the EV's battery, while the BMS monitors and controls the battery's state, communicating with the charger to adjust charging rates and prevent damage. The protection circuit provides overcharge protection, over-discharge protection, and other safety features to prevent damage to the battery and ensure safe charging. The combination of these components ensures safe and efficient charging.

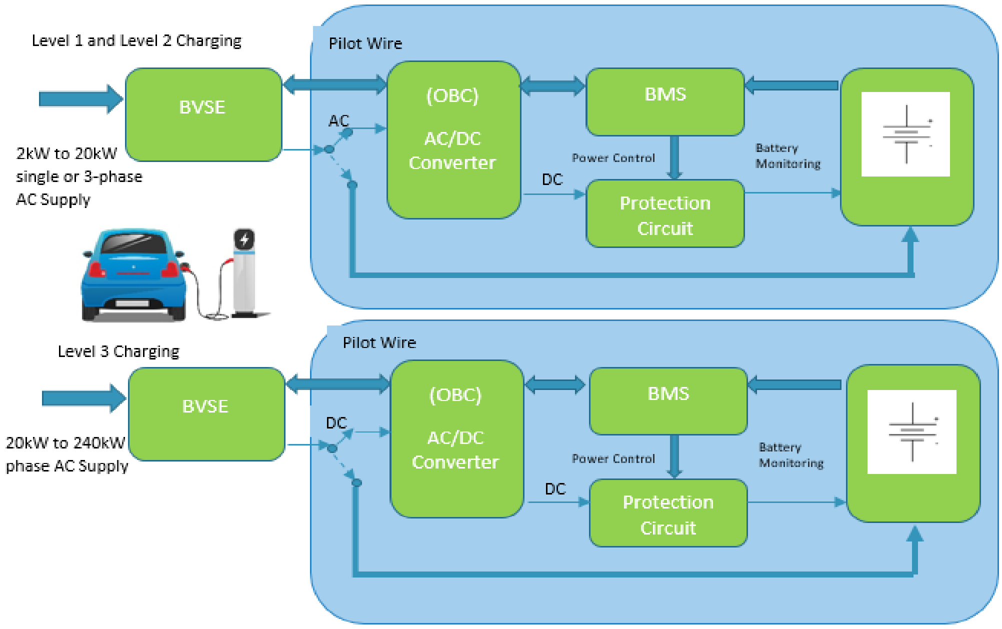


Figure 4. Charging technology for EV chargers [19].

2.7. EV Charging Methods

The three distinct methods for charging or replenishing the energy of an EV battery are conductive, inductive, and battery swapping. Each of these methods has its benefits and limitations, and the choice depends on user needs and advancement in technology.

Conductive Charging: This method is to use wired connection using a cable and connector to transfer energy to the EV battery. This method can be used by all types of chargers.

Inductive Charging: This method is to use wireless connections using electromagnetic fields of energy produced. The primary pad (transmitter) inductively transmits this energy to the vehicle mounted coil (receiver). The receiver converts this high frequency power to DC, suitable for charging the EV [20]. This method of charging eliminates the need for physical connections, thus reducing wears and tears. It is mostly applicable at public charging stations in the residential areas.

Table 4. EV charging methods and features.

Charging Method	Range (miles/hour)	Charging Time	Location	Communication
Level 1	2 - 5	8 – 20 hours	Home	None
Level 2	12 - 32	4 – 8 hours	Home, Public CS, workplace	Mode 2

DC-fast Charging	100 - 250	15 – 45 minutes	Urban areas, highways	Mode 4
Wireless (Inductive)	Slower	Longer	Developing	Developing

Table 4 shows the summary for the levels of chargers, including their communication modes. Mode 2 charging is slower and suitable for home charging, while mode 4 is faster and ideal for DC-fast charging stations. The battery is an essential component of the EV. It is important to note that the SOC dynamics also play a crucial role in influencing the core temperature and the resulting temperature gradient within lithium-ion batteries. As the battery charges and discharges, variations in SOC affect internal resistance and electrochemical activity, both of which contribute significantly to localized heat generation. This non-uniform thermal behavior not only impacts battery efficiency and longevity but also presents challenges for accurate thermal management and state estimation. To address these issues, a control-oriented enhanced electrothermal coupled framework has been proposed for the combined estimation of state-modified core temperature and temperature-corrected multi-state estimation. This framework utilizes a multi-input multi-output (MIMO) structure to capture the complex interplay between thermal and electrochemical states, enabling more accurate and robust prediction under dynamic operating conditions [21].

Battery Swapping: As the name implies, this method involves the swapping of a depleted battery with a fully charged battery. This method may include high infrastructure costs, but it reduces downtime and requires planning on battery ownership models. Using the first-in, first-out concept, and the battery swapping station prioritizes the car that arrives first for its swapping services above those that arrive later. After swapping, the batteries must be charged right away to make them available to arriving customers when they arrive subsequently [22].

3. Impact of EV Charging on the Distribution Grid

The growing adoption of EVs presents both benefits for the transportation industry but difficulties for the distribution grid. Large number of EV charging will have a complicated effect on the distribution grid. It is important to note that EV integration also presents positive impacts to the grid; however, this report only discusses the negative impacts. These impacts are caused by the growing demand for power and irregular EV charging behaviors; this may put stress on local distribution networks during peak hours due to EVs charging at the same time and result in transformer overloads due to increase in electricity demand, frequency and voltage imbalance, power quality issues, and grid congestion.

Network/transformer Overloads: An overload can occur when the load demand exceeds the rated capacity of transformer. Frequent instances of overloads can shorten the life span of the transformer and reduce the overall system efficiency of the network. Upgrading the transformers to meet the increase in load demand may be a solution, but irregular charging and consistent increase in the number of EVs in different locations still present an issue.

Frequency Distortions: Most grids are designed to operate on the operation frequency of 60Hz or 50Hz. Linear loads will function properly on the network because the current is proportional to the voltage. However, non-linear loads such as inverters which are present in EV chargers will result in total harmonic distortions (THD) in the system [23]. An increase in THD will result in malfunction of electronic controls, thermal issues, and possibly catastrophic failures of grid connected equipment [24].

Voltage Stability: Maintaining an optimal voltage profile is crucial for efficient electricity delivery. Integrating EV loads into the existing distribution system can lead to voltage drops at buses, compromising overall system efficiency [25]. Primarily, this is mostly caused by uneven load distribution across buses. The presence of high number of single-phase chargers at the residential side will create voltage imbalances if not properly distributed across the three-phase system [26]

Power Quality: High EV charging can lead to power factor issues, which can increase energy losses and reduce system efficiency. Power quality issues encompass significant and sudden events that affect various grid factors, impacting the overall quality of the electrical power supply [27].

Grid Congestion: This can happen when the distribution grid is overloaded due to an increase in EV charging. Frequent charging during peak periods can worsen grid congestion. The sensitivity analysis for EV chargers conducted in [28] shows that public charging, particularly DC fast charging, operates at higher power levels and could reduce congestion and also minimize the need for grid infrastructure upgrades in residential areas.

4. Studies on Impacts of EV on Distribution grid

The study in [29] highlights the risks and challenges of integrating EVs into the distribution system using five different cities as case studies of EV integration; the result in these smart cities show that high EV integration would result in power loss, voltage and phase imbalance, increase in load demand, frequency distortions and network overloading. A comprehensive review on the integration of renewable energy sources (RES) and EVs to the power system was conducted in [30], classifying the test studies into the mixed integer linear programming (MILP) algorithm and the particle swarm optimization. Flexible AC transmission systems (FACTSs) and voltage-source converters with intelligent dynamic controllers were utilized in [31] to analyze the impact of controlled and uncontrolled EV charging on the power quality of the distribution grid; simulation results indicate that power loss, voltage imbalance, voltage fluctuations, and harmonics would be problems for the power quality of the distribution network. Also, the power quality impact from charging station structures is discussed in [32], where studies of the impacts on RES support, grid stability, load balancing, grid voltage, frequency, infrastructure protection, and transformer losses were presented.

Various studies suggest that specialized effort is needed to overcome the challenge of EV scheduling in the power distribution system, particularly at high EV penetration levels. [33] examines the key aspects of coordinated EV charging, energy management techniques, optimal scheduling, RES-assisted charging infrastructure, and ancillary services. Analysis shows that these aspects would require optimization technique aimed at minimizing power loss, lowering load demand, regulating voltage, and decreasing overloading of the distribution network. A review is conducted in [34] of the impact of EV charging load on power quality, power system equipment, voltage profile, and load curves of the distribution system, mainly addressing issues with power quality and heating caused by the harmonic currents of EV chargers. Moreover, the influence of generalized EV load on the voltage profile and load curve of the distribution line is investigated.

Proper location of EV charging stations in large cities can encourage the rise of EV adoption, alleviate range anxiety, and promote sustainable transportation. [35] investigates numerous methods for optimal placement of EVCS, including different objective functions and constraints. The paper also discussed the charging methods in these charging stations, including efficient control and management. A study of the challenges of V2G technology, alongside the impacts of EV on integration with grid system, is presented in [36]. The study highlights the benefits of EVs participating in V2G, some of which include peak load reduction, voltage regulation and other ancillary services.

We present recent studies on the impact of EVs on distribution systems, which are illustrated in Figure 5.

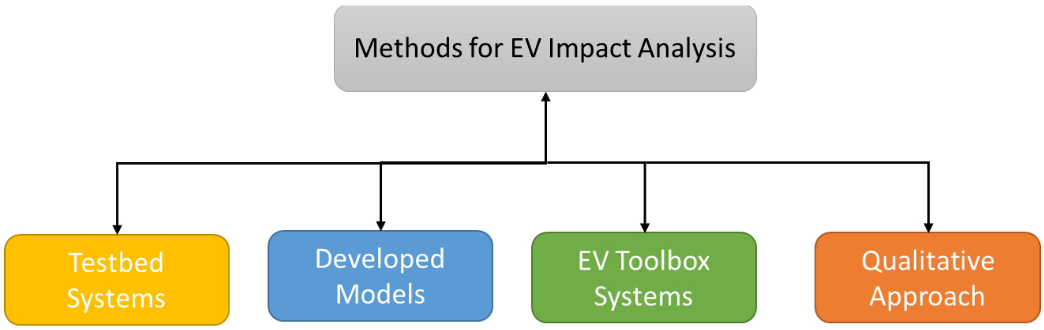


Figure 5. Methods for EV Impact Analysis.

4.1. Test-Bed Systems

IEEE radial distribution systems have been used to model, simulate, analyze and observe power flow in all buses in the electrical grid. The most popular system is the IEEE 33-bus test system. The values of the grid specifications can be modified according to the number of buses required and the specific quantity such as voltages, currents and powers to be observed. The system was developed earlier in 1989 to investigate how distribution systems are reconfigured to minimize power losses and achieve better load balancing [37]. The effect of increased load demand during peak periods on transmission lines can be observed; other grid features such as the voltage deviations and power losses can also be analyzed. Using the existing line configurations and load data, including the resistance and reactance values on each line, EV data is modelled into the distribution system. Table 5 summarizes and analyzes the recent studies of EV impact on the grid system performance using representative IEEE testbed systems. By leveraging testbed systems, researchers and engineers can design, simulate, and validate various configurations and control strategies of EV charging infrastructure, enabling the development of more efficient, reliable, and grid-friendly power systems.

Table 5. EV Impact Analysis based on the IEEE Bus Systems.

Ref.	Summary	Data Source & Preparation	Simulation type/model	Methodology	Limitations/Future Scope
[38]	Observes EV behavior at charging stations, using DC-fast charging station model.	A realistic feeder on the California distribution system. Assumed loads representing heavy-duty EVs.	MATLAB/IEEE 34-bus node test system	Using Monte Carlo simulation, a voltage impact matrix (VIM) was developed to observe the worst & best conditions of charging stations on the grid	Random charging data simulation is not realistic. Also, locations with smart charging were not considered. Distributed energy resource should be

					cited at charging locations at worst conditions.
[39]	Integrates EVs to the power grid, and observing three case studies for electrical load increase.	The transportation network of 29 nodes. The EV loads were randomly situated at five (5) nodes.	A 33-bus distribution network was utilized.	Voltage stability analysis were performed on the nodes with EV loads. This was done to ascertain the worst charging scenario.	Unreliable distribution system is presented. Real EV loads should be introduced at different nodes; especially at residential and industrial areas.
[40]	Observes the grid impact of heavy-duty EV charging stations is observed.	Energy Estimation, and Site Optimization (EVI-EnSite) was used. 72 EVs were analyzed, each with a specific battery capacity.	Open-DSS/IEEE 34-bus test system.	An impact analysis was conducted, considering the: location of charging station, number of charging ports, charging load pattern and system load pattern	The welcoming of unregistered or personal heavy duty EVs at enroute charging stations should be considered. The battery size for actual heavy duty EVs was not considered.
[41]	Analysis of EV adoption rates and its load impact on the distribution network was presented for years 2030 and 2050	Using EV projection tools - TEMPO model and EVI-Pro	PowerWorld Tool/Modified IEEE 33-bus node test system with a realistic feeder.	Voltage analysis using Newton-Raphson on buses with connected EV loads	The EV loads need to evenly distributed spread across various buses
[42]	Examines the impacts of EVs on the voltage level, power demand, and active power losses at various penetration levels and power demands.	Five (5) models of EV with their battery capacity and charging data were given.	16-bus test system was utilized.	A case study was conducted for a day, assessing the voltage level, power demand, and active power losses.	Insufficient data for impact analysis. Increasing the number of EVs and randomly placing EV loads with base loads across the network.
[43]	Determines how hacked EVs and Fast Charging DC (FCDC) stations may be used to conduct cyber-attacks on power grid.	Using data from the Toronto Parking Authority, 10 FCDC points were simulated on three busses for EV charging.	MATPOWER/ IEEE 33-bus system (distribution network) and IEEE 39-bus system (transmission network)	Identify the weakest points with the highest voltage drop.	More scenarios on how EVs and charging stations can be manipulated should be included.
[44]	Measures system reliability in normal and faulty conditions using advanced dispatch algorithms for EVs and wind turbine generators (WTG).	EV time distribution model.	RBTS/ IEEE 6-Bus system.	The sequential Monte Carlo simulation approach is used to assess the dependability of the distribution network with EVs and WTGs.	The integration of EVs or WTGs into the distribution system improved the reliability of the system.
[45]	Examines the impacts of charging from the radial distribution system (RDS) to the ring main distribution system (RMDS).	RDS modified to RMDS.	MATLAB/IEEE 33-bus Distribution test system.	Power flow was done using the Newton Raphson method on 3 cases of decreasing power loss.	Studies should focus on the impact of selecting EV chargers of various sizes and turning them on and off in real time.

[46]	Analysis on residential charging demand for Light-Duty Electric Vehicles and its load impact on distribution network was presented for years 2030 and 2050	Using NREL EV projection tools	TEMPO model and EVI-Pro/Modified IEEE 33-bus node test system with 10 feeders.	Weather data and an ambient penalty factor lookup table using a powertrain simulation model FASTSim Hot.	Improved and data-driven EV charging load analysis framework, with the goal of decreasing the burden on data acquisition.
[47]	Investigates the impact of integrating of 50KW EV charger to a utility distribution network in India.	Bulk penetration of 50 KW Level 3 DC fast charger. Charging data integrated into a distribution system.	SIMULINK/18-bus distribution system. Two cases are considered: EVCS at bus 18 and EVCS at all buses.	Analysis on the Input voltage, current and voltage/current THD was done using the PQ analyzer	Detailed study of the impact of other charger capacities should be done.
[48]	Evaluates the impacts on feeder demand and grid voltage instability due to PEV uncontrolled and controlled charging	Data from 602 Nissan Leaf cars during regular weekdays, and 75,000 residential homes.	RTDS/IEEE-34 distribution feeder.	Kernel density estimation (KDE)	Issues related to commercial charging on a suitable power grid model should be considered.

4.2. Developed distribution grid Models

This is based on distribution grid modelling and/or the modelling of critical features of the distribution grid, including EV charging demand modelling. Types of models include mathematical models, simulation models, and machine learning models; these models aim to model, simulate and analyze power system behavior under various scenarios. The uniqueness of this method is that the system can be designed specifically representing the distribution grid to be studied, including actual grid features. Considering the new pattern of power system, testbed systems might be insufficient to capture the complexities of such systems in efficient transmission and distribution management [49]. Recent studies of EV impact by employing the developed grid models or the modelling feature(s) of the grid is shown in Table 6.

Table 6. Recent studies of EV impact using developed distribution grid models.

Ref.	Summary	Data Source & Preparation	Simulation type/model	Methodology	Limitations/Future Scope
[50]	Assumes EV charging at a maximum charging power of 22 kW.	42 EVs connected to the distribution transformer for a year.	By random simulation of the summation of the plug-in time and connection time.	The peak load determined by the transformer power and its rated capacity.	To critically observe the impacts, fleet of EVs should be evenly distributed on nearby buses.
[51]	Proposes control schemes to withstand various penetration levels.	The MV/LV substations were	The EV demand was modeled based on user behavior, and	3 control schemes presented: on/off control, V2G control,	Effective for only 30% penetration level. Higher penetration

		modeled as an aggregated load.	observed at different penetration levels.	and V1G control- this refers to unidirectional charging.	levels would require more robust control methods
[52]	Examines how more EVCs affects the steady-state voltage and THD of a distribution network during steady-state conditions.	Measured network data from the UK Distribution.	MATLAB/ Simulink.	The THD analysis was performed on EVC harmonic profiles.	Only steady state faults are examined. Phase-phase faults should also be considered.
[53]	Proposes a technique that accounts for the effective scenarios of the distribution system when charging EVs in real time.	Measured network data from the Distribution grid.	Distribution System Operator (DSO) and Charging station Owner (CSO) approach.	Real-time analysis, observing Voltage regulation, power loss and power quality.	Proper allocation from the DSO, and efficient communication with CSO, would lead to regulated charging.
[54]	Examines the effect of EV charging demand on service transformers, voltage drop, and system losses.	EV data generated from real travel data Aggregated load profile was generated in MATLAB	Open-DSS/50% and 100% EV penetration levels are done using a two-stage charging power model of EV charger.	By analyzing the yearly average daily load profile for 50%, and 100% EV penetration levels.	Effective optimization methods may be used for regulated EV charging.
[55]	Examines the effects of EVCS on the distribution network on a scenario-based basis.	A 100 MVA and 400KVA distribution transformer, and gradually increasing the number of EVCS.	MATLAB/SIMULINK	Observing the effects as the number of EVCS increased, with single phase and three-phase chargers.	The amount of EVCS suitable for to a distribution transformer can be determined.
[56]	Investigates the charging power levels, and utilization characteristics of EV charging stations	Station data from Electric Vehicle Infrastructure, Energy Estimation, and Site Optimization Tool (EVI-EnSite)	(EVI-EnSite)/An EnergyPlus building energy model was developed.	By adjusting the EV parameters to provide the electricity use, power demand, and yearly electricity cost.	The retail site utilizes 350-kW charging ports, which is expensive to construct.
[57]	Proposes a method for EV impact analysis, considering the penetration scenarios, user preferences, charging patterns, and anticipated fleet growth.	Historical data on power generation and demand from the grid and forecasting model.	ETAP software	Analysis on the power quality, transient stability, voltage stability, and short circuit analysis were done.	Future research should examine the voltage profiles and demand behavior of distribution grids during harsh operating conditions.
[58]	This study analyzes the key parameters in EV modeling on low voltage distribution grids, providing direction for assessing the impact of increased EV adoption.	An LV distribution grid model with 196-bus, serving 585 residences with 89 EV connection points.	MATPOWER/Modeling of driving pattern based on survey data.	Observing the relationship between EV charging load, penetration level and EV placement	For proper impact evaluation, these parameters should be adjusted randomly to observe different scenarios.

[59]	Developes an EV capacity forecasting model for steady-state issues on emergent power networks with large-scale EV integration.	A sample microgrid with 9-buses and predicted Northern Ireland (NI) 2020 statistics data.	MATLAB/capacity forecasting model was developed.	Using Sequence Quadratic Programming (SQP) to calculate the transmission losses at every time interval.	Insufficient statistical data. Studied area should be well defined, in terms of power system and EV charging information.
[60]	Using an actual distribution system in Finland, this study conducts an impact analysis in terms of additional energy and power.	Network grid data, with average consumption of 600 GWh & average peak power of 128 MW within the period.	Scenario generation and high-level quantitative modeling.	Using the Paul Schoemaker's scenario planning process, with the anticipatory action learning methods, to develop different future scenarios.	Complex planning process. Cannot be generally applied.
[61]	Designs an adaptive protection system for the stabilization of voltage regulation during daytime operation of a solar power plant (SPP) and random charging profiles of electric cars.	EV consumption & Solar radiation data.	ETAP software/ Model of campus network designed and simulated.	Voltage regulation analysis. Sizing and optimization studies.	SPPs could be effective in reducing the dependence on the grid for charging. However, this source is unpredictable and expensive.
[62]	This study addresses EV growth paths, including policies such as energy efficiency, demand response, and smart charging to determine the impacts and ability in shifting and lowering load demand.	For load profiles, hourly load data from different balance regions by Mexico's Energy Secretariat (SENER)	Three (3) different policies were modelled to evaluate EV impact. Energy efficiency, demand response end smart charging optimization	Based on EV growth predictions made from 2020 to 2040, and a sample hourly EV charging profile.	Unrealistic data for load profile and EV growth predictions
[63]	Observes points at which BEVs will have a significant impact on the LV grid, by identifying the level of BEV penetration.	Based on GIS Data acquired from the electric utility in Trinidad.	ETAP software/ Distribution feeder model developed.	Observing EV impact at levels of BEV penetration, from 0% to 20% in 5% increment for each period time.	Future study should prioritize actual situations for EV charging, rather than focusing solely on worst-case scenarios.
[64]	Analysis on the impact of EV charging schemes on charging delay and average charging cost; resulting to a reduced power quality.	Data collected by Hogeschool van Amsterdam (HVA) database -	PandaPower (an open-source power system analysis tool) and mosaik ecosystem software.	Co-simulation based approach.	The charging power of the EVs was assumed to be the same; however, this is not practical.
[65]	Analysis on the impact of EV adoption on residential, commercial and urban-commercial feeders.	The estimation of light electric vehicles (LEVs) was derived from the zero-emission vehicle statistics.	CYME software/3 cases considered. A residential, commercial, and a combination of both.	Observing the maximum demand at peak demand time. Also, observing the state of the transformers.	Nil

4.3. EV toolbox systems & Optimization techniques

This is based on simulations involving EV projection models and toolbox systems. There are several EV toolbox systems that can help analyze and mitigate the impacts. Using the toolbox, different EV charging scenarios can be simulated, while the optimization feature ensures a reliable grid, where the stress is greatly minimized by constantly evaluating grid capacity to accommodate the increased load demand. Table 7 highlights some recent studies using this technique.

Table 7. Review of recent studies on EV toolbox systems.

Ref.	Summary	Data Source & Preparation	Simulation type/model	Methodology	Comments/Gaps
[66]	Impacts analysis was performed by simulating the EV charging demand for several scenarios of EV adoption, up to 6 million EVs	EV adoption model - EV Toolbox.	N/A	EV toolbox.	The EV loads were not evenly spread Insufficient data for simulation.
[67]	Examines the effect of EV charging demand on the use of 56 service transformers, voltage drop, and system losses	EV data generated from actual travel data-sourced from Victorian Integrated Survey of Travel & Activity.	50% and 100% EV penetration levels was established using a two-stage EV charger model.	Analyzing system's features using the yearly average daily load profile for 50%, and 100% EV penetration levels.	Effective optimization methods may be used for regulated EV charging, staggered ToU rates, and battery storage systems.
[68]	Analysis on the effects of different levels of PHEV penetration on the LoL of the distribution transformer	The study assumes a uniform battery storage capacity of 11 kWh. Residential customer load profiles were based on a load scaling factor.	Monte-Carlo simulation with 1000 samples is run for each charging period of typical days.	The LOL inference procedure was used.	The transformer's LOL rate may be exceeded if more PHEVs charge during peak load periods.
[69]	Considers the charging time, charging method and EV characteristics when observing the impacts.	Distribution transformer with 1000 residential loads.	MATLAB/SIMULINK/ EV model. Four charging scenarios were observed.	The open-circuit voltage (OCV)-based SOC estimation process was used.	Future studies should concentrate on driving behaviors of EV owners, as well as the complexities of the domestic EV charging network.
[70]	Provides a technique for analyzing the possible impacts of future EV charging in 2030.	Real-world data from the Portuguese National Institute for Statistics (INE), 2017.	The distribution of EV arrivals is modelled according to normal probability density function.	By predicting the Baseline Load Profile (BLP), Light-Duty Passenger (LdP) EV penetration, mobility patterns of drivers.	Fast charging during off-peak periods should be explored.
[71]	Examines the charge and discharge patterns that promote the penetration of electric cars on island grids.	Actual data collected from the Electrical Grid in Tenerife Island, with planned RES load.	OpenSolver on MS Excel. Optimization model incorporates a two-objective function	The technique evaluated valley-peak shifting, the electric system, and real data.	The projected RES integration route is highly intermittent and difficult to predict.

			for EV charging and discharging.		
[72]	Examines the functions of various charging infrastructures in a network and proposed charging infrastructure assignment methodologies.	The distribution data are extracted from the BEIJING GIS Map 2009. Parking capacity data are collected from the transport commission.	Parking lots are individually identified using Thiessen Polygons.	Uses a loop computation to identify charging demand locations, allocate infrastructure, and test charging loads.	Research should examine how home charging affects future travel and parking habits, as this might greatly impact charge assignment assumptions.
[73]	Analyisis on harmonic components, reactive power, and power factor under various operating conditions.	The charging of an electric car using a Business Line charging station with a capacity of 11kW.	Measurements were done using a BK-ELCOM power quality analyzer in ENA330 version.	Voltage and Frequency analysis	Owing to various power sources to on the grid, the reactive power to need to carefully analyzed.
[74]	Examines the potential impact of coincidental EV charging behaviors in the distribution network, considering power imbalance issue.	200 EVs charging profile is examined. EV charging data was obtained from New Zeeland Electricity system.	MATLAB/Simulink /EV charging loads and Photovoltaic (PV) generation were modelled into the distribution network.	Irregular charging examined by Monte-Carlo Simulations.	Limited data for EV charging data generation. Different EV models and their unique features should be considered.
[75]	Investigates the impact of charging Electric Buses (EBs) and presents a technique with EB aggregators, to reduce electricity prices	EB station and the data from Empresa Electrica Quito (EEQ) in Quito, Ecuador.	GAMS/CPLEX solver/Assuming MMC queuing model.	Sensitivity analysis using GAMS software and GAMS/CPLEX solver,	Further study in identifying potential issues for DSOs and TSOs owing to uncoordinated charging by EBs.
[76]	Presents an overview of tests on the behavior of EV integrated chargers at various operating points	No obtained data. Formulated data from bench system.	Laboratory test bench system	4 EV models were considered. Impact analysis observed using the bench system.	The test bench system might be reliable, assessing whether an EV is suitable for smart charging.
[77]	Investigates the geographical and temporal aspects of EV charging behavior for different seasons of the year.	Charging power from private and public charging stations.	K-means clustering algorithm and a GIS system.	By dividing residents into clusters with different charging patterns.	There is need for enhancing power system flexibility to handle the difficulties with low and high demand periods of energy pricing.
[78]	Impact assessment of EV charging by developing a probabilistic load flow algorithm on a residential distribution network.	Real-time load data of January and September of 2019 were collected.	MATLAB/ Probabilistic load flow algorithm was developed. Monte-Carlo Simulations were performed	Observes impacts at different EV penetration levels.	A 23-bus distribution system may be insufficient to model such network.
[79]	Investigates the impact of integrating of 50KW EV charger to a utility	Real charging data collected and	SIMULINK/modelled the EV charger on an	Analysis on the Input voltage, current THD	Detailed study of the impact of other charger

	distribution network in India.	integrated into a distribution system.	18-bus distribution system.	done using the PQ analyzer	capacities should be done.
[80]	Proposes a methodology to study and model the impacts of unscheduled charging on distribution systems.	National Household Travel Survey (NHTS), data set to generate load profile dataset. 601 EVs is simulated.	MATLAB/IEEE 13-Node Test Feeder.	Statistical analysis using probability distributions.	Tesla Model 3 EV is simulated. Other EV models with different battery SoC and parameters should be studied.

4.4. Qualitative Approach

Qualitative research refers to a methodological approach focused on the collection and interpretation of non-numerical data. This approach can give insights on the technical, social, and behavioral aspects on how EV charging can impact the grid; future assumptions can also be made on EV adoption based on past events. Generally, the conclusions are made from a technical point or on assumptions. A review analysis in [81] shows that qualitative approach can help grid operators and policy planners to understand the rate of EV adoption in energy communities. Table 8 highlights studies conducted using this method.

Table 8. Recent studies on EV impact using qualitative approach.

Ref.	Summary	Data Source & Preparation	Simulation type/model	Methodology	Limitations/Future Scope
[82]	Analysis on EV impact based on supply and demand matching. Also, potential violations of voltage limits, power quality and voltage imbalance.	This load profile from After Diversity Maximum Demand (ADMD)	Substation contains four (4) 400V outgoing feeders. EV loads and 100 domestic customers connected to one feeder.	Technical analysis using charts, indicators, and EV trends.	V2G-enabled EVs could be introduced for supply/demand matching.
[83]	Considering energy forecast, this study discusses how EVs will impact on the overall energy balance.	Based on historic data from EV and ICE vehicles.	Using nonlinear regression models to predict the decline in electricity generation from fossil sources, and the growth in adoption of EVs.	The Integration of prediction models of electricity generation and consumption to verify the energy balance.	Another approach might be to analyze how power consumption is distributed throughout the day, taking into account EV charging patterns.
[84]	Examines the remarkable features of EV charging behavior and how they change over time.	Data from the Danish emobility platform provider (eMPP) Spirii. Customers equipped with 22 kW AC charger.	A realistic representation of user behavior and its impact on EV use generated using recent data from typical users.	Using various information from the EV chargers and connected EVs during a period.	Comparison between EV user behaviors in Denmark with other countries.
[85]	This research attempts to address public charging demand by studying the EV growth rate. This predicted data was then	No data	The Logistic growth model	Relies on previous data and model is used for assessing EV growth rate	With the rise in the EV, user perception may also be integrated to arrive at more precise

	used to calculate energy usage.				energy demand projections.
[86]	A security analysis of grid-integrated EV charging infrastructure, evaluating the security of communication, hardware, and software.	The distribution network is comprised of five 1MVA, 11/0.4kV transformers, 0.4kV solar battery bank, solar rooftop panels, and 670 EVs.	Power Factory's DIgSILENT Quasi Dynamic Simulation.	Generalized stochastic Pretri Nets (GSPN) and the simulations are done using GRIF software	Study not specific on number of feeders equipped with EVs and the duration of analysis.
[87]	Explores EV impacts with coordinated and uncoordinated charging patterns for 30 and 100 percent EV penetration level.	Real Grid System data in Egypt.	MATLAB/Real distribution network model was developed.	MATLAB program: finding the hourly maximum allowable number of grid-connected EVs.	More intelligent structures for future smart grids need to be developed for controlled charging of EVs.
[88]	Examines the effects of large EV adoption on low voltage distribution, considering charging speed and technique	100 EVs with residential load for 1000 households	MATLAB Simulink/OCV-based SOC estimation process	Lookup-table-based charging strategy for EVs is suggested.	Lookup table for large EV deployment may be a complex task

4.5. *Prioritization of Technical Problems*

To improve clarity and focus, the main technical problems identified have been prioritized in Table 9, based on their severity and frequency of occurrence reported in literature.

Table 9. Technical problem and frequent occurrence reported in literature.

Key References	**Impacts**	**Severity (★=Low, ★★★=High)**	**Frequency of occurrence in Literature**
[49], [58], [72], [79]	Transformer Overload	★★	Moderate
[50], [30], [52]	Grid Congestion	★★	Moderate
[38], [40], [42], [46] [52], [56], [72], [73]	Voltage Imbalance	★★★	Very frequent
[41], [44], [49], [52], [55]	Power Quality Issues	★★	Moderate
[51], [72]	Frequency Distortion	★	Less frequent

Table 9 provides a brief overview of key studies examining the impact of electric vehicles on the distribution grid. The factors considered in assessing the severity of impacts caused by EV charging include grid capacity, EV charging patterns~~ in the case studies~~, and the condition of grid infrastructure. The available grid capacity determines whether EV charging can be supported without compromising the reliability of the power system. The timing, duration, and rate of EV charging can influence peak demand, load profiles, and overall grid stability. Additionally, the age and condition of infrastructure such as transformers, power lines, and substations affect the grid's ability to accommodate increased loads from EV charging. These factors interact with one another and with the overall characteristics of the grid, collectively influencing the extent of the impacts. By understanding and addressing these factors, utilities, policymakers, and stakeholders can develop effective strategies to support the widespread adoption of EVs while maintaining grid reliability and efficiency.

While the analysis is primarily descriptive, readers can find comparative insights within the referenced literature. Moreover, studies in [84] and [86] consistently identify voltage drop as a primary concern, even though they employ different modeling approaches, including FACTS-based control and MILP optimization. These comparisons underscore not only a consensus on critical issues but also reveal methodological trade-offs that influence scalability, accuracy, and applicability across different grid configurations.

5. Mitigation Strategies to Optimize Grid Performance

The increasing adoption of EVs poses significant challenges to the distribution grid. Effective strategies can help reduce these challenges, ensuring reliable and efficient energy supply. A combination of two or more strategies based on user data of past EV charging events and the timeliness of employing these strategies is very important. Recent studies on this subject have mainly focused on data analytics, which can help grid operators to better understand EV charging patterns, predict demand based on this information, and find a suitable strategy to optimize grid operations within a period. Other studies have suggested the strategic allocation of public charging stations to regions characterized by low residential and industrial loads; this might help distribute charging demand more evenly across the power grid and mitigate the impact on existing household and industrial consumers.

High adoption of bidirectional (V2G-enabled) EVs can reduce stress on the distribution grid, thus ensuring grid stability [89]. With these EVs, energy can be stored on the batteries and supplied back to the grid when required. Several V2G projects that are already operational will be outlined in this section, while others are still in the development stage.

5.1. Vehicle to Grid (V2G) Technology

This is an emerging technology that allows EVs to discharge their batteries to the grid during peak demand periods and recharge during periods of low demand. V2G technology can help stabilize the grid. Generally, EVs are capable of operating in two different modes: grid-connected mode and stand-alone mode. Figure 6 shows the configuration of EVs in grid connected mode. In this case, the EV storage units can be synchronized with the grid to provide reserve power capacity and other ancillary services, thereby supporting the grid in a distributed vehicle-to-grid (V2G) infrastructure. The grid-connected operation mode of EVs in V2G systems will be the main focus of this review paper.

Therefore, it is reasonable to assume that grid-connected and parked EVs (by aggregators) are effectively one large battery that can absorb, store, and then release electricity back into the grid [90]. With the potential for tens of thousands of EVs to concurrently provide power back to the grid during peak demand periods, V2G might completely transform the way our power grids work.

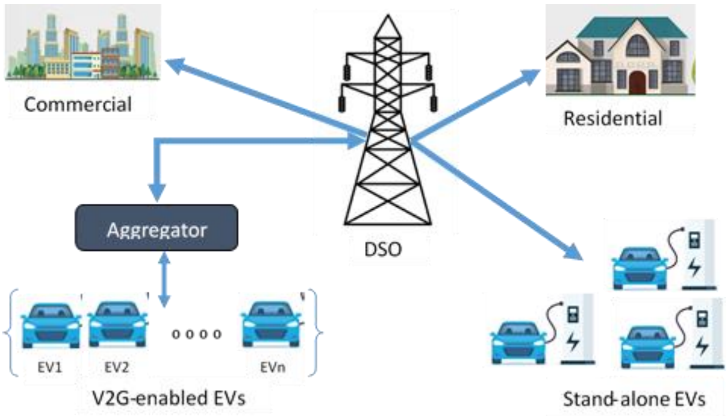


Figure 6. Direct V2G system with aggregator and other grid loads.

The traditional method requires the DSO to communicate with the EV owners directly; however, with the introduction of aggregators, shown in Figure 6, the DSO can treat the aggregator exactly as a typical provider of ancillary services. This implies that the aggregator can use the same communication system for contracting and command signals as the traditional ancillary service providers, which alleviates concerns that the DSO would be tasked with increased communication workload.

The frequency and voltage of the electricity grid can be regulated with the use of a V2G system. If the frequency is too high, either the load (number of connected EVs) must be increased, or the generation must be decreased. At the present, fast-responding generators are used to increase power generation, which is quite expensive. Alternatively, EVs can assist the grid by boosting load demand and charging their batteries. However, if the grid frequency drops too low, it indicates the electrical loads exceed generation capacity. In this case, the generation must be increased, or the load must be decreased. This can be accomplished by stopping charging or initiating discharging of some of the grid-connected EVs. Table 10 shows recent studies on V2G technology.

Table 10. Recent studies on mitigation methods using V2G technology.

Ref.	Summary	Data Source & Preparation	Simulation type/model	Feature controlled /Methodology	Limitations/Future Scope
[91]	Evaluates the feasibility of V2G in Indonesian electric grid.	Actual data received from Indonesia electric company PLN (load data) and measured data (frequency). 15 million EVs assumed in 2030.	MATLAB/SIMULINK	Frequency regulation - through load frequency control (LFC), responding to frequency change within 5–10 min.	The analysis did not consider the inconsistencies of EV operators with regards to planning their schedules.
[92]	Present a control strategy for an EV aggregator that participates in the frequency regulation of micro-grids with high RES penetration.	Historical data.	MATLAB/SIMULINK	Frequency regulation – Using coordinated sectional droop charging control (CSDCC) technique	Increased EV adoption in a microgrid improves frequency regulation rather than having a negative impact on it.
[93]	Focuses on the interaction between the convention control at the transmission system level	EV model is an adaptive control block. A static generator is considered to model	DIgSILENT Power Factory program	Frequency regulation – using Adaptive	Studying power system events for different

	and V2G at the distribution level.	the behavior of a V2G process.		droop (nonlinear multiplier) factor.	scenarios would give better conclusions
[94]	Developes a system–level design for the provision of ancillary services of frequency and voltage control	The DSO updates the prediction data on the number of EVs at charging stations from EV-sharing operator every 15 minutes.	SimPower Systems in MATLAB. A Power-Hardware in the Loop (HIL) testbed was used for validation.	Frequency and voltage control. Assess and regulate the voltage profile to the predefined value.	Numerical simulations of accurate models can also be effective for real-time data on EVs participating in a sharing service
[95]	Developes a double-loop control strategy is proposed for power grid frequency and voltage regulation.	No data were analyzed in this study.	PSIM software, implemented on a HiL emulator	Frequency and voltage control - Using a phase detector control loop and a pulse width modulation (PWM) scheme	Simulating with real data will provide more confidence in the results.
[96]	Proposes a method for observing the effects of large EV adoption on low voltage distribution, considering charging speed and technique.	Development of EV charging infrastructure for 100 EVs with a residential load profile designing for 1000.	MATLAB/SIMULINK.	Load levelling. Observes the charging profile, learning efficiency, reliability using a lookup-table-based charging strategy.	Validation with realistic EV charging profiles can be carried out in future research works.
[97]	Proposes a stable electrical grid model for studying load transients, power-sharing, and fault analysis.	No data was used in this simulation. Assumed a battery Capacity of 40kWh, nominal voltage of 350V, and initial SoC of 50 %	MATLAB/Simulink and deployed to a real-time simulation using an OPAL-RT simulator.	Voltage and frequency regulation – Using Maximum Power Point Tracking (MPPT) control method,	Simulating with real data will provide more confidence in the results.
[98]	Analysis on the island of Menorca in the auxiliary service (AS) capability of 1000 PEVs to assist solar PV grid integration.	Traffic data from Menorca island.	MATLAB.	Energy storage – Using Achievable Power Capacity (APC) model to participate in hour-ahead uni-V2G regulation services.	Additionally, this method greatly improved the predictability and controllability of PEVs for the grid operator.
[99]	Analyzes how in-vehicle batteries can provide voltage support for a high-voltage distribution grid	A practical dataset from Tokyo Electric Power Company and varies in time. The capacity of the grid is about 8:3GVA.	For the HiL test, a real-time digital simulator OPAL-RT Technologies,	Frequency/Voltage control Using Power-HIL testing.	A challenging task for future study would be a multi-domain HIL simulation of energy system with EVs.
[100]	Designs a Solar PV powered EV charging facility (EVCF) for charging EVs with ACDC converter and vector control techniques.	The PV is generating a DC power around 15kW, 400V, 35A at 700W/m^2 irradiation and 25^{0}C.	MATLAB/Simulink.	Energy storage Using MPPT controller and PV inverter controller	Future work might include the integration of control constrain in both G2V and V2G modes and how they can offer enhanced stability in distribution grids.

[101]	Performs a preliminary evaluation on the use of Vehicle-Grid Integration (VGI).	15 million EVs assumed in 2030; assuming charger capacity and battery capacity	MATLAB/SIMULINK	Load leveling frequency regulation	Data simulation with a penetration level of only 20% in not sufficient for a populated region...
[102]	Proposes a strategy for charging and discharging EVs in a typical UK low-voltage distribution network,	The daily household load profiles were evaluated in 48-time intervals, each lasting one-half hour.	MATLAB	Voltage control and reducing power loss - Optimal charging and discharging profiles computed by quadratic programming	Utility companies should devise appropriate financial incentives to encourage EV owners to engage in such smart grid initiatives.
[103]	Analyzes on the possible use of V2G for reactive power compensation in the distribution network	No data	MATLAB /Developed a mathematical model which relates V2G reactive power compensation to electrical power losses.	Power loss reduction, and increasing the battery lifespan during V2G mode.	Further study might be in observing the impact of V2G reactive power compensations on energy losses, and voltage stability.
[104]	This study analyzes the economic impact of V2G on a distribution network grid to reduce energy consumption costs and upgrade grid stability.	19 charging points were allocated. Each charging point with 5 cars charging at the same time 11kW power for each EV.	OpenDSS software	Reduce energy consumption costs and upgrade grid stability. Using linear integer Programming.	Battery degradation costs should be included in future study.
[105]	Proposes a decentralized V2G framework for primary frequency control (PFC) for fast chargers.	Residential and industrial load profiles, sun irradiation, wind speed, plug state and SoC of the battery.	MATLAB/Simulink. Alongside an AC power system with PVs and wind generators	Frequency regulation - Using Charging droop control –based on the battery SoC.	A more robust control method should be considered for decentralized frameworks, as this can be promising for further applications

5.2. Smart Charging Technology

The main concept of smart charging is the management of peak demand and load balancing. Thus, EV charging can be shifted to off-peak hours to reduce the stress on the grid during peak periods. This will ensure that EV charging is effectively distributed at different times of the day, and the loads are balanced at all locations. With the incorporation of smart charging methods, the recharging process can be effectively managed to align with grid conditions; otherwise, the uncoordinated EV charging could place significant stress on the power supply network [106]. There are two main types of smart charging technologies, namely user managed charging and supplier managed charging.

In user managed charging, the EV user decides to move charging to off-peak periods when charging cost is low. In supplier-managed charging, grid operators manage charging operations, considering factors like the SoC, real-time energy production and consumption, including V2G, V2X technologies. Recent studies on investigating the efficiency of smart charging methods are summarized and analyzed in Table 11.

Table 11. Recent studies on mitigation methods using smart charging technologies.

Ref.	Summary	Data Source & Preparation	Simulation type/model	Feature controlled/ Methodology	Limitations/Future Scope
[107]	This article investigates the implications on feeder demand and grid voltage instability due to PEV uncontrolled or controlled charging.	75,000 residential homes simulated according to actual PG&E distribution static data, and EV data from 602 privately owned Nissan Leafs.	RTDS environment/ IEEE-34 distribution feeder in a real time simulation. Charging metrics were created for each PEV using KDE.	Voltage stability By controlled charging obtained using a simple convex optimization equation	Future works could involve incorporating commercial charging limits into the grid to better understand the overall impact of PEV charging.
[108]	A study on the impact of charging a large electric car fleet, considering regional heterogeneity, electricity consumption, and network structure.	Real grid data, with EV, residential industrial load data.	OpenDSS/Random probability distribution was done using Monte Carlo simulation. 3 charging scenarios were simulated: No Charging, controlled and Uncontrolled.	A conditional probability-based method is used to model uncontrolled charging, and convex optimization is used to model smart charging.	In addition, future considerations should include an increase in distributed renewable production.
[109]	Presents a demand response system for a novel time of use (ToU) reducing the accelerated aging of transformers.	Charging data acquired from NHTS (2017), accounting for 129,696 households.	Monte Carlo Simulation is used to generate EV load for uncontrolled charging. Done using Simplicial Homology Global Optimization (SHGO) algorithm.	Reduce transformer aging. Convex optimization model is used for smart charging	Network data was not provided to observe the changes due to EV load
[110]	This paper presents a framework for reducing grid congestion using EV smart charging, using probabilistic day-ahead projections of the grid load.	Data obtained from the High-Resolution Forecast Configuration (HRES) of the Integrated Forecast System (IFS).	Python/Optimization performed using the Gurobi optimization package.	Mitigating grid congestion	This technique may be expanded by replacing the day-ahead predictions with shorter-term forecasts, lowering the number of hours with grid congestion.
[111]	Compares the conventional and fast charging of EVs with coordination, considering the effect of EVs penetration level on grid performance.	Load and line data modified from IEEE 33 standard data.	Using the backward-forward sweep approach, the load flow of the bus system is calculated for a 24-hour period	Power losses Optimizing power losses using time and location management for EV charging.	Optimal location management has been shown to produce greater benefits than time management.
[112]	Proposes an efficient strategy for charging and discharging EVs in a typical UK low-voltage distribution network, with the purpose of providing improving voltage profiles	The battery in each EV has a maximum capacity of 10 kWh.	2 case analysis are considered: several nodes, each with a group of 20 single-phase consumers. And a future analysis, with an aggregation of 30	Power quality The challenge was structured as a quadratic optimization task.	It is encouraged that utility companies establish suitable financial incentives to attract EV owners to participate in such smart grid initiatives.

	and reducing electrical power loss.		single-phase consumers.		
[113]	Highlights the potential of sophisticated optimization approaches in smart charging infrastructure to promote widespread EV adoption.	Data source not available.	Analyzed the impact of EVCS on the distribution network using two scenarios: with EVs and without EVs.	Using Genetic Algorithm (GA), Particle Swarm Optimization using (PSO), JAYA, and Teaching Learning Based Optimization (TLBO).	Studies need to show how the suitability of EV integration with renewable energy can emphasize its potential for improving system sustainability.
[114]	Proposes a period division approach for charging based on Optimal TOU Demand Response.	No data available	Three charging scenarios are simulated: uncontrolled charging, ordinary TOU price response charging, and how the best TOU reacts to charging	Power loss, Voltage variations, Minimize charging cost Using the improved GA.	Simulation with real EV data will confirm the efficacy of the strategy.
[115]	Models The Energy System Transition Model to simulate the functions of smart charging and V2G on EVs in integrated energy systems.	No data available	6 cases simulated: Considering flexible water electrolyzers, smart charging alone, V2G alone, and combination of both.	The energy system is modelled using the LUT Energy System Transition Model (LUT-ESTM).	The absence of distribution grid cost return in LUT-ESTM may result in an overestimation of smart charging.
[116]	Presents an innovative integrated charging infrastructure model for electric and hydrogen cars, considering the individual demands.	Specific model parameters and traffic data available	3 cases simulated: observing the energy cost, routing considerations, and case 3 combines aspects from Cases 1 and 2	Managing battery SoC, electrolyzer, and hydrogen tank Integrated model for fuel cells, wind turbine & PV array modelling.	Future research might look into aspects that influence battery lifespans, such as SoC, depth of discharge, charging rate, and temperature.

5.3. Energy Storage Systems

Energy storage systems (ESS) can store excess energy during off-peak periods and release it during peak periods, reducing the strain on the grid. By storing energy to manage peak demand, the need for infrastructure upgrade can be reduced. The major type of energy storage systems is classified as the battery energy storage systems (BESS), where energy is stored in batteries and released when needed, to provide a solution in managing EV demand. An advantage of using batteries is that they come in different sizes and can be easily manufactured; the cost and efficiency of batteries can determine the possibility of widespread EV adoption. Another advantage of using BESS is the scalability of these systems to meet the growing demands of EV charging and grid operations, for example, a SuperLIB battery concept is proposed in [117]. Table 12 briefly outlines and analyzes the recent studies leveraging energy storage systems to mitigate EV impacts on utility grids.

Table 12. Recent studies on mitigation methods using energy storage systems.

Ref.	Summary	Data Source & Preparation	Simulation type/model	Methodology	Limitations/Future Scope
[118]	Focuses on the optimal coordinated energy management of microgrid that includes controllable and uncontrolled power sources, battery storage units, plug-in hybrid EVs, and demand response systems.	Historical data for solar irradiance, wind speed, temperature, and load profile obtained from referenced literature.	33-bus radial distribution network. Including Price-based demand response PBDR model and Incentive-based demand response (IBDR) model.	Using the Hong's 2 m Point Estimate Method (PEM) module. Various charging scenarios are simulated.	The suggested EMS framework can be modified for an imbalanced network. Also, the EMS system might include probabilistic connections between renewable sources, conventional loads, and EV demand.
[119]	Presents an optimization framework for optimally allocating wind power generating units and Battery energy storage systems (BESS).	Real data from an Indian distribution network with 108 buses.	3 cases simulated: the base case, Wind Turbines (WTs) only, WTs and BESSs using the proposed technique.	GA is adopted; using a nature inspired meta-heuristic optimization technique	This research might be extended to a bi-level optimization framework to establish optimal energy management through inner layer optimization.
[120]	Proposes a new approach for managing a microgrid with EVs and DG units. Also, demand response was explored, as well as its impact on the overall system cost.	Data source not available	Validated on a sample microgrid model by simulating five different cases. This study considers EVs in 2 states: charge and charge/discharge	DG units and EVs are modeled as a MILP problem. Simulated using the GAMS software.	Total cost reduction strategies should be developed while employing PHEV automobiles in the microgrid.
[121]	Addresses challenges in microgrid, as well as the sizing and scheduling BESS based on system load demand, and offers a mathematical model for MG energy scheduling optimization.	DG and load profile data is obtained from other referenced literature.	33-bus grid-connected MG, with the 5 EVCSs at the different buses; The IBDR is applied to estimate the optimal load scheduling using Hong's ($2m + 1$) PEM.	Fuzzy max–min principle- based method to determine the optimal capacity of DGs.	This study may be extended to cover the optimum charging and discharging operations of EVs by engaging in pricing and incentive-based DR schemes.
[122]	Introduces a communication-based energy management system (EMS) for emergency situations.	Dataset not available.	A MG test system consisting of two diesel generators is considered for validating the proposed system.	Energy management during emergency situations (PSMS-ES) by efficient communication methods	A future work might be to developed an optimized communication strategy with reduced IEC 61850 support
[123]	This study proposes an intelligent and real-time control of BESS and On-load tap charger (OLTC) that reduces voltage	Based on the real-time data of the system, provided by PMU and SCADA network.	Implemented on the IEEE-13 bus distribution system. The OLTC is used to connect the grid and their parameters,	Using an OLTC voltage regulation control scheme.	Using real-time data is remarkable. This study will enhance voltage regulation control and reduce the size of BESS,

	fluctuations, and extends the life of BESS.		including assigning weights to the buses.		resulting in economic benefits for utilities.
[124]	Proposes an intelligent EMS-based coordinated control for PV-powered EV charging stations.	Data obtained from National Renewable Energy Laboratory database NREL: Solar, Load, and Tariff Resource Data.	Two scenarios are simulated - DG-powered EVCS with and without buffer BSS. Control scheme is validated HiL setup	ANFIS-based intelligent controller was developed	Future work might include incorporating V2G and other ancillary services into power flow control strategies.
[125]	Explores the use of EVs and their used batteries to support electricity (load leveling) in a small-scale EMS.	Experimental study based on the real data collected from the developed test-bed system.	The uncertainties brought mainly by three factors are simulated: EVs, PV, and building load.	Load leveling. By regulating the charging and discharging patterns of new and used EV batteries based on the peak-cut threshold.	Forecasting of both load and supply for future years should be considered, along with EV and battery availability forecasting.
[126]	Proposes the use of shared EVs to reduce grid congestion and evaluates its techno-economic potential.	Charging transactions are from a station-based car sharing scheme.	Python/Optimization performed using the Gurobi optimization package.	Reducing charging costs – using a mixed-integer optimization problem, based on ToU tariffs	Future study might improve the system by offering techniques for allocating the burden of reducing grid congestion among car sharing operators.

5.4. Renewable Energy Integration

Renewable energy integration plays a significant role in reducing the strain on the distribution grid. Studies have shown that integrating RES such as solar and wind power can greatly reduce the impact of EV charging load. A review conducted in [127] for utility grids in five countries shows the importance of integrating RES to make the grid more resilient. This strategy has an advantage of promoting sustainability by reducing the dependence on fossil fuels, and thus greenhouse gas emissions. The current pace of fossil fuel consumption is alarming, with predictions suggesting that these resources may be depleted by 2060, if the consumption pattern remains unchanged [128]. However, a major challenge associated with RES is their intermittent and unpredictable nature, which limits their use as primary power sources and therefore, the inclusion of energy storage systems becomes essential to buffer fluctuations and ensure a stable power supply.

Considering the economic benefits of renewables and their role in reducing the impact on the grid for EV charging, it is important that policies are created to promote the adoption of RES, alongside other energy technologies present on the network. A review study was conducted in [129] to investigate the advantages and challenges associated with incorporating EVs and RES into power grids. It is recommended that introduction of smart metering systems along with the improved communication and control strategies can effectively improve management of the EVs and RES in power grids. Table 13 highlights and analyzes recent works on integrating RES to mitigate the impact of EV charging within the grid.

Table 13. Recent studies on mitigation methods using renewable energy sources.

Ref.	Summary	Data Source & Preparation	Simulation type/model	Methodology	Limitations/Future Scope
[130]	Presents an intelligent EMS for the efficient switching between the power sources	Data contained in article (on driving distances and solar irradiance).	MATLAB/Simulink.	Using PSO	There might be need to modify the algorithm to extend the life of the energy storage device.
[131]	Examines the effects of EVs/PHEVs with V2G connection capabilities, conventional power generators, and RES employed as DGs on a power distribution grid.	Distribution grid of Manjil city in Iran modeled according as the 33-bus distribution network, with line and load data.	4 cases simulated with the introduction of power generator (CPG) and 60 EVs.	The objective function for minimizing total energy cost, power loss and voltage deviations.	Evaluating the various implications of higher number of EVs/PHEVs.
[132]	Presents an adjustable robust optimization approach for scheduling large-scale EVs with uncertainties.	MG modelled with 100 EVs. Data for capacity limits of DG units are contained in paper.	Comparison on - stochastic optimization, robust optimization, and adjustable robust optimization.	Adjustable robust optimization based on number of uncertain variables.	Emphasis should be placed on understanding the economic analysis over the types of robustness.
[133]	This paper presents a methodology for EV charging management that optimizes Renewable Energy (RE) consumption	EV parameters of and EV travel for charging load modeling are contained in paper.	3 cases simulated with regards to EVCSs and the RE consumption. Also, considering charging service fees.	Using Pearson, Spearman rank (SR), and Kendall rank (KR) correlation coefficients.	Future study might look into the bundling of RE, and how they increase total RE consumption and revenue of EV aggregators (EVA).
[134]	This paper proposes an effective energy management strategy to reduce the overlap between the residential demand and the EV charging load.	Real-time PV generation and charger occupation data from NREL PV power dataset, 2023,	Assumes 40 chargers to accommodate 60 EVs. 3 Stage optimization performed - energy costs, charging power to EVCS, and implementing real-time control using energy storage system (ESS) capabilities.	Self-sustained transportation energy system (STES) and Ensemble Temporal Convolution Network bidirectional LSTM (ETCN-BiLSTM)	This study did not account for ESS deployment.
[135]	Designes a stochastic model to maximize the integration of EVs into load response systems, with uncertainties in supply from RES, load demand, and EV behavior.	Hourly load demand data contained in paper.	Modified IEEE 6-bus microgrid model with 3 CPGs and aggregator station capacity of 200 EVs.	Modified artificial flora optimization (MAFO) algorithm to effectively manage G2V and V2G services.	The model could be expanded to include dispersed charging situations, where EV owners can choose their own charging and discharging schedules.
[136]	Proposes a novel automatic charging mechanism (ACM) for Full Electric Vehicles (FEV) to	Technical data from EV manufacturers.	PV array is modeled using Simscape	Automatic renewable recharging mechanism for FEVs	Future electrical energy storage systems must be

	increase the traveling distance, eliminating the need for recharging stations.	Electric car charging-Power Across the Nation [Online] Available		based on DC-DC converter.	integrated with different control algorithms.
[137]	Presents a method to reduce minimum congestion charges and power loss, during high renewable energy integration	Data not available	MATLAB/compared with Salp Swarm Optimization (SSA) and Gray Wolf Optimizer (GWO).	Combination of a Similarity-Navigated Graph Neural Network (SNGNN) and Black-Winged Kite Optimization	Establishing methods for addressing data scarcity, and looking into alternative optimization algorithms with lower computational complexity.
[138]	Investigates the interaction between rooftop solar PV systems and EVs as they integrate into the power grid.	Real-world data. 500 kVA Distribution Transformers (DTs) serving residential consumers. 100% EV penetration is considered.	Monte Carlo simulations in MATLAB.	Observing hot-spot temperature (HST) of DTs and transformer LoL Using a regression model identifying how penetration levels affect the aging of DTs.	It is necessary to examine the long-term integration of EVs and rooftop solar PV systems on DTs using a 25-year projection model.
[139]	Proposes a charging management method for EVs to support the integration of RES and DG, in order to reduce the effects of the intermittency of the energy sources.	Data from China National Renewable Energy Centre (CNREC), Energy - 2018.	The microgrid consists of 32 nodes, 24 DG units and 218 consumers.	Using an estimation of EV battery's SoC evolution	It is necessary to improve the charge management system as RES are fully adapted.
[140]	Develops an approach to address the actual power loss in grid systems.	No data used	Compares with 3 optimization techniques - Cuckoo Search Algorithm (CSA), Bat algorithm (BA), and African vulture optimization algorithm (AVOA)	For improving voltage stability and bus voltage profiles Slime Mould Algorithm (SMA)	To modify the model to include dynamic load forecasting models, particularly those capable of accommodating the growing use of renewable energy and EVs.
[141]	Presents a two-stage stochastic optimization approach for renewable energy planning in a distribution system with integrated EVs.	Network data contained in paper.	Simulated on modified 33-bus RDS – 300 EVs simulated. PV and WT placed at far nodes, including parking lots with EV clusters.	Scenarios generation-reduction technique was achieved using Kantorovich distance matrix (KDM)	This study can be expanded by integrating seasonal fluctuations in the load and power profiles from RES.
[142]	Investigates the fast-charging impact on the grid, to provide a solution by integrating RES (such as solar PV) along with a	No data involved.	Algorithm is validated in the buck converter	With a fixed SoC of 16%, an increase in battery capacity is observed as the	Efficiency of charging management strategy needs to be evaluated on real EV data.

	battery in dc bus to reduce this effect.			simulation time is increases.	
[143]	Examines the potential for e-mobility to enhance solar PV grid integration through intermittency flattening ancillary services (AS).	Real data obtained from the Menorca region.	MATLAB.	1) Daily model for utilizable ESP of all EV types, and 2) An hour-ahead model.	The adoption of e-mobility is a promising option in touristic islands to reduce the carbon footprints.

5.5. Performance Comparison of Mitigation Strategies

Mitigation strategies addressing the impacts of EV integration on distribution grids have been widely explored in the literature. To facilitate clearer understanding and comparison, these strategies are now evaluated using a side-by-side comparative table. Table 14 summarizes their relative effectiveness, implementation cost, scalability, and the key barriers associated with each approach, providing a concise reference for both researchers and practitioners. The implementation costs of the strategies outlined in the ~~table~~Table 14 are evaluated by considering factors such as grid infrastructure, ~~—~~particularly its capacity and scale, ~~—~~and prevailing energy prices. ~~The s~~Scalability is assessed ~~based on~~by how easily these strategies can be ~~combined~~ integrated with other approaches or ~~integrated with newer~~ emerging technologies to achieve improved results.

Table 14: Comparative Analysis of Mitigation Strategies.

References	Strategy	Effectiveness	Cost	Scalability	Key Barrier
[91], [93], [97], [103], [104]	Vehicle-to-Grid	High	High	Medium	Aggregator coordination
[109], [110], [114],	Smart Charging	Medium	Low-Med	High	User engagement
[120], [123], [127]	Battery Storage	High	Very High	Low	Infrastructure cost
[132], [135], [138],	Renewable Integration	Variable	High	Medium	Intermittency, siting

5.6. Impacts and Effectiveness of Mitigation Strategies

To enhance the analytical depth of this review, performance data from selected key studies have been compiled into a quantitative comparison table. Table 15 shows measurable impacts of EV integration on distribution grid components, —such as transformer load increase and voltage deviation, under varying penetration levels and mitigation scenarios. This table complements the qualitative insights by providing a clearer picture of the effectiveness and limitations of different approaches.

Table 15. Quantitative Assessment of Impacts.

Ref	EV Penetration	Transformer Overload	Voltage Deviation (%)	Mitigation Strategy Used
[39]	<30%	45%	3.2%	V2G
[50]	60%	33%	1.8%	V2G + Smart Charging
[45], [139]	100%	85%	5.5%	Renewable Energy + Smart Charging

6. Challenges and Future Work

There are practical and academic challenges in reviewing literature that analyzes EV impacts and mitigation strategies. To have a better understanding of the subject, various solutions should be proposed to address these issues.

A. Limited Data Availability

Most research does not provide access to detailed data used in the study, such as EV charging patterns, grid infrastructure, and data on energy consumption or load demand used within the duration of the studies. Researchers frequently face challenges due to the scarcity of quality datasets that can facilitate broad reproducibility and applicability. This issue can also be expected in selecting case studies in different locations in this area, making it difficult to conduct accurate studies and provide a definitive analysis based on the results obtained.

B. Complexities of EV Charging behavior

The patterns of how EV owners charge their vehicle is a complex factor to consider. Studies have shown that understanding EV charging behavior is important for grid planning and energy management. Key factors to consider in this challenge are the charging frequency, charging duration and time, charging location, and the energy consumption by an EV on full charge. The uncontrolled charging nature of EVs needs to be carefully analyzed, which would enable researchers and policy makers to develop more effective solutions to support the widespread adoption of EVs.

C. Uncertainty and Variability

Most research collected data based on assumptions and it will be challenging to give accurate predictions based on assumed data. As there are many EV models available, each with its unique features, it would be difficult to generalize models, which are not scalable to observe future EV models. Most studies used a fleet of one EV model and assumed a SoC for all EVs; this type of analysis is unrealistic in the real world. Thus, models proposed are limited to a particular EV and for a particular location of study. The variability in the percentage of residential and industrial load in a location is also a factor to consider in EV impact analysis. For example, the impact caused by a fleet of Kia EV3 Standard Range will be different from the impact caused by a fleet of Tesla Model 3 RWD.

D. Technological Advancements

The development of unified theoretical EV frameworks is essential for advancing research across various fields. To create such frameworks, researchers need to diligently follow a series of steps, from identifying the research question to developing and validating the framework. By integrating the proposed framework with existing knowledge and theories, researchers can clearly demonstrate the contribution to the EV framework and ensure that it is both comprehensive and robust.

Modeling heterogeneity and evolution is also essential for capturing the complexities of real-world systems. By incorporating these elements into system modeling, researchers can develop more accurate and robust EV models that account for the diverse characteristics and behaviors of complex systems. This approach enables the creation of models better equipped to handle real-world intricacies, leading to more accurate predictions and deeper insights.

The integration of multi-scale models is a critical aspect of system modeling, as it enables researchers to capture the interactions across different scales and levels of complexity. To achieve this, researchers must identify relevant scales, such as component-level, system-level, network-level, and grid-level models, and develop EV models tailored to each scale, using appropriate tools and techniques. By incorporating these scale-specific models into a unified framework, researchers can more effectively capture the interactions between scales and gain a deeper understanding of complex systems.

Academic research should consider the ethical and policy dimensions of its findings, including factors such as equity, environmental justice, and long-term effects on society. These factors are often overlooked in technical EV models, yet they are essential for ensuring that research is socially responsible and beneficial. By integrating these dimensions into their work, researchers can develop more comprehensive and sustainable solutions that benefit both individuals and society as a whole.

Future work addressing these research gaps includes developing models to predict EV charging demand and designing effective charging management systems, which are essential for mitigating the impacts of EVs on the power grid. By accurately predicting EV charging patterns at different times of the day, grid operators can prepare for and manage these impacts more efficiently. A well-designed charging management system can minimize grid stress and optimize EV charging, ensuring a stable and reliable power supply network.

Presently, most optimization strategies in literature require significant processing time, which can hinder their effectiveness in real-world applications. To address this challenge, it is essential to develop mitigation strategies that can reduce computation time and enable rapid responses to changing grid conditions. By doing so, grid operators can more efficiently manage the impacts of EV charging.

In-depth research on ESS is necessary to fully understand their potential in mitigating the impacts of EV charging on the power grid. By leveraging communication technologies to enable real-time monitoring of energy storage levels and EV charging demand, ESS can be optimized to deliver maximum benefits. Predictive analysis based on historical data and past events and forecasts of EV charging demand can further enhance the efficient optimization of ESS.

Despite growing research on the impacts of EVs on distribution grids, several critical gaps still exist. One of the most pressing issues is the lack of real-world, high-resolution EV charging datasets, which constraints the accuracy and applicability of current simulation-based studies. Additionally, integrated investigations that combine V2G and smart charging strategies are limited, particularly in mixed residential and commercial load environments. These gaps raise key open questions, such as determining the optimal combination of mitigation strategies tailored to different grid types, and assessing how cybersecurity threats may compromise the integrity and reliability of EV-grid interactions. Addressing these challenges will require interdisciplinary collaboration. Cybersecurity experts must develop secure communication frameworks for EV charging systems, while economists and policymakers should work together to design dynamic pricing models that encourage grid-friendly charging behavior and support widespread technology adoption.

7. Conclusion

There is continuous growth in EV adoption; thus, understanding the impact of EVs at higher adoption rates on the power grid system is crucial. This review highlights key findings of the EV impact on transformer overload, frequency deviations, voltage variations, power quality, and energy losses, which are sectioned based on the strategy for impact analysis. To mitigate these impacts, various studies have explored strategies in V2G technology, smart charging, energy storage, and renewable energy integration. In the low EV adoption, it is important to develop smart charging systems that communicate with the grid in real time by adjusting charging rates based on grid conditions. It is desirable to implement advanced optimization techniques for minimizing cost and power losses during low EV adoption. However, for the high EV adoption, V2G technology proves to be an innovative solution to ensure grid stability; studies have shown that allowing EVs to supply energy to the grid has numerous benefits, and create an income stream for the EV owners. Therefore, a clear understanding of EV impacts on the distribution grid, along with effective mitigation strategies, is essential for enabling a smooth transition to sustainable transportation.

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