

# Electric Vehicles: A Comprehensive Review of Technologies, Integration, Adoption, and Optimization

Mr Sadique H Khan<sup>1</sup>, Mrs. Pranoti S Choudhari<sup>2</sup>, Mrs. Bhagyashree S Wan<sup>3</sup>  
*Asst Professor (Electrical Engg), NMKC COET Jalgaon Maharashtra India*

**Abstract**—The transport sector has experienced a boom in electric mobility over the past decade as it moves towards a more sustainable future associated with the Sustainable Development Goals (SDGs). This paper provides a comprehensive review of the existing literature on important aspects of electric vehicle development, including technical, social, and methodological viewpoints. This paper presents an overview of electric vehicle (EV) operations, including discussions on the technology, charging modes and standards, as well as charging coordination and control. The paper also examines the potential benefits and consequences of integrating EVs into power systems. The paper thereafter presents the reader with a concise overview of the key elements and obstacles that are acknowledged as crucial to the widespread adoption and market expansion of EVs globally. Ultimately, we examine many areas of focus for improving efficiency in the operations and planning of EV integration into power grids.

**Index Terms**—Plug-in electric vehicles (PEV), smart charging, vehicle to grid (V2G).

## I. INTRODUCTION

The transport sector is increasingly solidifying its place as one of the most significant sectors in terms of energy use. Despite being influenced by multiple variables such as the COVID-19 pandemic and the energy crisis, its proportion of energy utilization reached 25% of the overall final consumption (TFC) in 2023, with fossil fuels serving as the primary energy source [1]. Transportation is responsible for 32% of direct CO<sub>2</sub> emissions from burning fuel. Specifically, road vehicles such as cars, buses, and two and three wheelers are accountable for nearly

three quarters of these emissions [2]. Consequently, there has been a continuous and increasing endeavor worldwide to promote the advancement of electric transportation as a viable solution to reduce the rise in car- bon emissions and greenhouse gases, while also decreasing reliance on fossil fuels.

The associate editor coordinating the review of this manuscript and approving it for publication was N. Prabakaran

The current prospects of the electric vehicle (EV) sector demonstrate a significant level of interest. The worldwide EV market has undergone significant expansion in recent years, as indicated by the data presented in Fig.1 [3]. In the chart, BEV refers to battery EVs while PHEV refers to plug-in hybrid vehicles. In 2023, the number of EVs in use surpassed 3.5 million, representing a growth of around 35% compared to the previous year. This increase can be attributed to the rising interest and investment from people and governments in EV technology and the necessary infrastructure to support it [3]. Figure 2 presents a comprehensive view of the EV market share distribution across various countries for the year 2023. This chart provides valuable insights into the differing levels of EV adoption worldwide and highlights the influence of national policies, infrastructure development, and consumer behavior on the penetration of EVs in the automotive market. Norway leads with over 90% of new automobile sales being electric, highlighting its robust adoption driven by significant governmental incentives and widespread

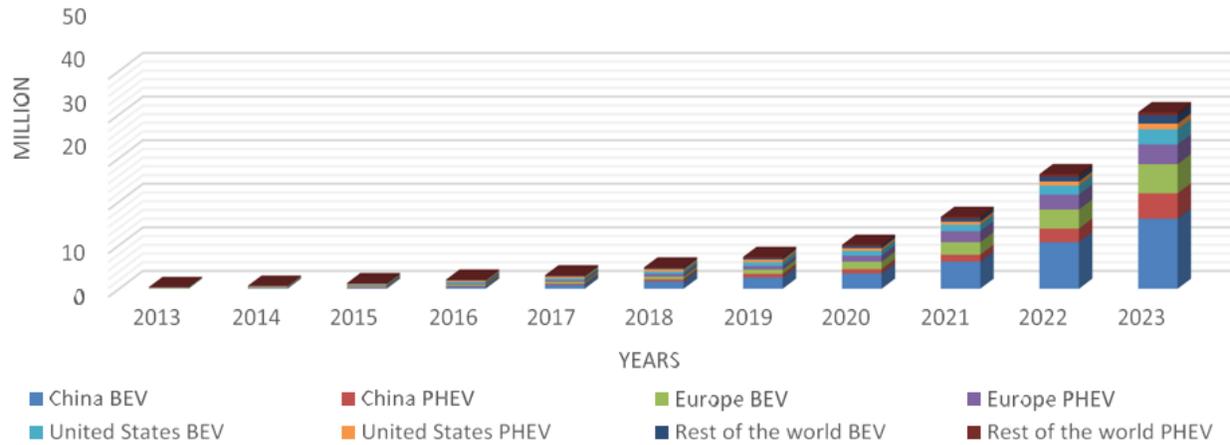


FIGURE 1. Worldwide inventory of EV, 2010-2023.

charging infrastructure. China follows with approximately 40% market share, supported by its extensive investment in EV technology and infrastructure, including a vast network of public charging stations. The chart also compares the market share of other major regions, such as the European Union (EU), the United States (US), and emerging markets. The EU shows varied levels of EV market penetration across its member states. Countries like Germany and the Netherlands are leading the charge with significant market shares, while others are still in the early stages of adoption. This variation reflects differences in national policies, economic incentives, and infrastructure development within the EU. In the US, the EV market share stands at around 18%. While this represents significant growth from previous years, the adoption rate is slower compared to Norway and China. Factors contributing to this include varying state-level incentives, differing consumer preferences, and challenges in expanding charging infrastructure across the country. The chart also depicts market shares in emerging markets and other developed nations. These regions show lower penetration rates, indicating that EV adoption is still in its nascent stages. Factors such as economic conditions, lack of infrastructure, and limited government support play significant roles in these lower adoption rates [3], [4], [5], [6], [7].

This data in Figure 2 not only reflects a substantial increase in consumer adoption rates but also indicates broader changes in the automotive industry and governmental policies favoring eco-friendly alternatives. Some factors contributing to EV market growth can be summarized as follows:

**Government Incentives and Regulations:** Governments worldwide have introduced various incentives, such as tax rebates, grants, and subsidies, to make EVs more accessible and attractive to consumers. Additionally, stringent emissions regulations have pressured automakers to increase their offerings of low-emission vehicles. For instance, the implementation of the European Union's strict CO<sub>2</sub> emissions targets has propelled significant investments in EV technology by major automotive manufacturers, contributing directly to the surge in EV numbers.

#### A. TECHNOLOGICAL ADVANCEMENTS

Technological improvements in battery technology have played a crucial role in this growth. The development of lithium-ion batteries with higher energy densities and lower costs has extended the range of EVs while reducing their price, making them a viable option for a broader consumer base. For example, the average cost of lithium-ion batteries per kilowatt-hour has decreased significantly over the past decade, correlating with the increase in EV adoption.

#### B. CONSUMER AWARENESS AND PREFERENCES

There is a growing awareness and concern about environmental issues among consumers, which has led to increased demand for sustainable alternatives. The shift in consumer preferences is reflected in the rising sales of EVs, as individuals look to reduce their carbon footprint. Surveys indicate that consumers are increasingly considering EVs as their primary or secondary vehicles, driven by both environmental

concerns and lower long-term ownership costs.

**C. EXPANSION OF CHARGING INFRASTRUCTURE**

The expansion of charging infrastructure has further supported the EV market growth. Public and private investments in charging stations have reduced range anxiety, making EVs a more practical choice for everyday use. The correlation between the availability of charging infrastructure and EV adoption rates is evident in urban areas, where increased charger density has accelerated the adoption of EVs.

This rapid growth in the EV market has profound implications for the automotive industry, energy markets, and global efforts to reduce greenhouse gas emissions. It suggests a pivotal shift towards an electrified future, promising reduced dependence on fossil fuels and lower emissions. However, it also poses challenges such as the need for increased electricity generation, potential strain on electrical grids, and the critical requirement for sustainable battery production and recycling processes.

The ACEA, the European Automobile Manufacturers' Association, represents European car manufacturers.

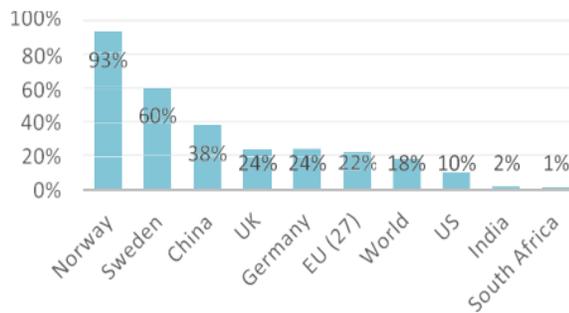


FIGURE 2. Global electric vehicle market share by country in 2023.

Electrically-chargeable vehicles, including battery electric and plug-in hybrids, make up 21.6% of new passenger cars in the EU. Hybrids, on the other hand, account for 22.6% of total car sales for the 2018-2022 timeframe [8]. China now dominates the global electric vehicle supply equipment (EVSE) market, boasting over 85% of the world's fast chargers and over 60% of slow chargers. China has already exceeded its goal for electric car sales, with a market share of over 35%, surpassing its objective for 2025. Now, China is shifting its attention to developing

charging infrastructure. The aim is to have complete coverage of charging stations in cities and highways by 2030 and expand coverage in rural areas. As of 2023, an estimated 3.5 million charging stations have been installed globally. 2023, there was a 40% increase compared to the previous year. Out of the total number of charging stations, almost 1.84 million were categorized as slow charging stations, whereas 1.4 million were classified as fast charging stations [3].

Innovative EV business models with unique benefits have both encouraged the shift to electric mobility and painted a promising future for the industry. These innovative business models, such as car sharing, battery swapping, and leasing models, are not just trends, but potential game-changers in the EV industry. They are being scrutinized to comprehend their impact on EV adoption and the generation and capture of value [9]. Furthermore, the potential to create value for EV adopters through intelligent grid technology is a significant driver in the proliferation of EV technology and its allure to potential adopters. This will be elaborated upon in the next section.

A range of advanced technologies in the Vehicle-Grid Interface (VGI) has crucially promoted EVs as a viable option for sustainable energy transition. EVs not only function as a storage system capable of supplying electricity back to the grids through a demand response service, but also have the potential to offer auxiliary services to the grid. These technologies offer significant benefits for customers, utilities, governments, and society, leading to a brighter, more sustainable future [10]. However, if the integration of EVs into power grids is not effectively managed or controlled, it could lead to significant negative consequences [9]. Therefore, it is not just a matter of optimizing the benefits, but also of limiting and preventing the undesirable impacts. Due to the complex nature of integrating EVs into the power grid, which

often requires making conflicting decisions, mathematical optimization methods are employed to determine the best decisions that achieve several objectives [11]. This underscores the critical importance of effective management in this context.

Various governments throughout the globe are implementing strategies and constructing infrastructure to facilitate the transition to EVs to meet their sustainability objectives at both national and

global levels. However, not all countries have a clear roadmap for accomplishing these goals. In order to successfully integrate EVs into the mainstream, various factors need to be considered. These include antecedents, drivers, and mediating and moderating variables, which play a crucial role in determining the widespread adoption of EVs and their positive impact on the environment and economy [12].

In order to present a clear and structured overview of the various aspects covered in this study, a block diagram (Figure 3) is provided to summarize the key elements of EV integration and its impact on power systems. This diagram outlines the main sections of the paper, guiding readers through the progression from EV market growth to the technological, operational, and grid-related challenges, and finally to the optimization strategies and future trends in the EV domain.

**EV Market Growth:** This block highlights the rapid expansion of the global EV market, driven by technological advancements and supportive government policies. EV market growth already is discussed in the Introduction Section. This growth serves as the foundation for the rest of the paper.

**EV Technologies and Operations:** This section delves into the various types of EVs, the infrastructure required to support them, and the mechanisms by which EVs interact with the power grid. It covers essential aspects such as charging modes, standards, and smart charging strategies like V1G and V2G.

**Impact on Power Grid:** As EV adoption increases, their integration into power systems presents challenges, including load profile alterations, power quality issues like harmonics and voltage imbalances, and stress on grid assets. These topics are discussed in detail, with a focus on how they affect grid stability and reliability.

**Adoption of EV:** This section examines the factors that influence the widespread adoption of EVs, focusing on both the drivers and barriers that affect consumer decisions and market dynamics. It explores the role of governmental incentives, public awareness, infrastructure availability, and technological advancements in accelerating EV adoption.

**Optimization and Future Trends:** The final section of the diagram addresses the strategies for optimizing EV integration, including load management and grid

modernization efforts. It also explores future trends and innovations that could shape the future of EVs and their role in energy systems.

**Key Insights and Challenges:** The conclusion summarizes the key insights gained from this comprehensive review and highlights the challenges that remain for the successful and widespread adoption of EVs.

This diagram serves as a roadmap for the paper, making the structure and flow of the content more accessible and allowing readers to grasp the novelty and scope of the study at a glance.



FIGURE 3. Structural representation of the review paper.

## II. EV TECHNOLOGIES AND OPERATIONS

This section presents a comprehensive analysis of the existing literature that specifically examines EV technology and operations. The main focus is on various factors connected to charging, which will be discussed in detail in the following sections.

### A. EV CLASSIFICATION

Electric vehicles encompass all forms of vehicles that utilize electricity, either entirely or partially, for their propulsion. All-electric cars (AEVs) and hybrid electric vehicles (HEVs) are commonly categorized based on their energy source and energy management system [13], [14], [15]. AEVs encompass both battery electric cars (BEVs) and fuel cell electric vehicles (FCEVs). Plug-in hybrid electric vehicles (PEHVs) are a type of HEV that utilize both an electric motor and an internal combustion engine to generate power for the wheels. Additionally, PEHVs have the capability to be connected to the power

grid for recharging. This study restricts the definition of electric cars to just include BEVs and PEHVs, which will be referred to as EVs for the sake of conciseness. To learn about EV hardware technologies, we recommend consulting the detailed reviews offered in [16] and [17] as this topic is not within the focus of our work.

*B. CHARGING MODES AND STANDARDS*

EV charging modes are classified according to the type of power source (AC or DC), the power level, and the charging characteristics. Two primary standards govern these classifications: the Society of Automotive Engineers (SAE) J1772 standard, predominantly used in North America, and the International Electrotechnical Commission (IEC) 61851 standard, which is widely adopted in Europe and other parts of the world. A detailed comparison between these standards is essential for understanding their application and the differences in EV infrastructure requirements.

The SAE J1772 standard classifies charging into three levels [18]:

Level 1: This is typically used for residential charging and involves a 120 V single-phase AC supply with a power rating of up to 1.9 kW. Charging times are longer, often taking up to 11 hours to fully charge a vehicle, making it suitable for overnight charging at home [19], [20], [21].

Level 2: Commonly found in both residential and public settings, this level uses a 208-240 V AC supply and offers power levels between 2.5 kW and 19.2 kW. Level 2 charging is faster, with a typical charging time of 4-8 hours, and is well-suited for commercial establishments, workplaces, and public parking spaces [22], [23], [24], [25].

Level 3 (DC Fast Charging): This level bypasses the onboard charger and provides direct DC power to the battery, significantly reducing charging times to

under an hour. The power output can reach up to 240 kW, making it ideal for highway charging stations and scenarios where rapid charging is essential [26]. The summary of charging levels in SAEJ1772 is summarized in Table 1. On the other hand, IEC 61851 standard categorizes charging into four modes [27], [28] and it is given in Table 2:

Mode 1: This mode uses a standard household outlet (230 V single-phase or 480 V three-phase AC) with a maximum current of 16 A and a power output up to 3.7 kW. It is primarily used for slow, overnight charging without any communication between the vehicle and the charging station, making it the most basic charging method.

Mode 2: Similar to Mode 1, but with additional safety features such as in-cable control and protective devices. The power output ranges from 3.7 kW to 7.4 kW, and it is used in residential and light commercial applications.

Mode 3: This mode involves dedicated EV supply equipment (EVSE) with enhanced communication between the EV and the charger. The power output can range from 3.7 kW to 43 kW, making it suitable for semi-fast charging in public spaces and commercial establishments. Mode 3 is analogous to SAE Level 2 but offers a broader range of power levels and typically involves three-phase power.

Mode 4: This mode is equivalent to SAE Level 3 (DC Fast Charging) and provides direct DC power to the EV battery, with power levels exceeding 150 kW. Mode 4 charging is designed for fast charging stations and supports the rapid replenishment of EV batteries in under an hour.

1) KEY DIFFERENCES AND COMPARISONS

*a: POWER SUPPLY AND INFRASTRUCTURE*

SAE levels primarily focus on North American power supply standards, with Level 1 using 120 V AC, while IEC modes

TABLE 1. Charging Levels-SAE J1772.

	Supply Configuration	Charger	Supply Type	Rated Current	Rated Power
Level 1	Household outlet	On-board	120 V, Single Phase, AC	12-16 A	1.9 kW
Level 2	Household outlet or EVSE	On-board	208-240 V, Single Phase, AC 12-80 A 2.5-19.2 kW Three phase, AC	12-80 A (Typ. 30 A)	2.5-19.2 kW (Typ. 7 kW)
Level 3	DC connector DC fast charging	Off-board By-passed	208-600 V, Three phase, AC	400 A (Typ. 60 A)	Up to 240 kW (Typ. 50 kW)

TABLE 2. Charging MODES-IEC61851-1.

	Supply Configuration	Charger	Supply Type	Rated Current	Rated Power
Mode 1	Household outlet	On-board	230 V, Single Phase, AC 480 V, Three Phase, AC	Less than 16A	3.7 kW
Mode 2	Household outlet/Industrial Outlet	On-board	230 V, Single Phase, AC 480 V, Three Phase, AC	16-32 A	3.7-7.4 kW
Mode 3	Dedicated EVSE "Semi-Fast" Charging	On-board	230 V, Single Phase, AC 480 V, Three Phase, AC	32 A, 63 A upto 70 A	3.7-43 kW
Mode 4	Dedicated EVSE through DC connector	Off-board	DC Charging 200-1000 V	Up to 200 A	Over 150 kW

accommodate both single-phase and three-phase AC supplies commonly found in Europe and other regions. Mode 3 and Mode 4 in IEC offer a more flexible range of power outputs, catering to different charging needs from residential to high-speed commercial applications.

*b: SAFETY AND COMMUNICATION*

IEC standards place a stronger emphasis on communication and safety features, particularly in Modes 2 and 3, where in-cable protection and EVSE communication are required. These features are designed to enhance user safety and optimize charging efficiency.

*c: ADOPTION AND USE CASES*

SAE standards are predominantly used in North America, where the power infrastructure and consumer behavior favor the classifications outlined in J1772. In contrast, IEC standards are more widely adopted internationally, offering a more diverse range of charging options to meet varying infrastructure capabilities and regulatory requirements.

On-board and off-board charging are types of conductive charging commonly utilized in EV charging. They are known for their robustness and reliability, as they require a physical contact between the EV and the power supply. Inductive charging, on the other hand, eliminates the need for physical contact and instead relies on wireless power transfer (WPT). This method allows for charging at various levels and can deliver power up to 20 kW, with an efficiency of up to 90% as reported in studies [19], [29], [30]. Inductive charging utilizes the principle of mutual induction to transfer power between the supply network and the EV. The setup is more compact compared to conductive charging, as

isolation transformers are not always necessary [31]. The literature discusses various techniques of wireless power

transfer, including resonant inductive, inductive, capacitive, and low-frequency permanent coupling power transfer. These techniques are analyzed in terms of their efficiency, operating distance, and frequency [32], [33], [34].

*C. CHARGING COORDINATION AND CONTROL*

The advancements in smart grid communications and control have played a crucial role in the development of various grid-connected EV technologies. These technologies aim to enhance power system operations by effectively managing and controlling EV charging. As a result, they offer promising opportunities for integrating EVs into power grids, benefiting all stakeholders involved. The integration between EVs and the grid can be categorized, in terms of charging coordination and control, into uncoordinated (dumb) charging and coordinated (smart) charging. The haphazard charging occurs regardless of the grid's condition, which can have a detrimental impact on the stability and reliability of the grid, especially when there is a high number of EVs. EV users would plug into the grid as they see fit, without any involvement from aggregators who would manage and oversee the charging demand placed on the grid. Uncoordinated charging can lead to an increased risk of overloading distribution transformers and cables, which in turn can worsen power losses [11], [13]. Through coordinated or smart charging, EV charging can be scheduled to maximize both technical and economic benefits. These charging strategies involve adjusting EV charging patterns, cycles, and operations to align with the constraints and requirements of the power grid, the preferences of EV users, and the availability of renewable energy resources. It promotes the idea of

adjusting the charging schedule to align with periods of abundant renewable energy generation, allowing for a greater incorporation of renewable sources in the overall power supply. Smart charging offers a range

of control options for EV charging, allowing for flexibility in pricing and advanced technical charging alternatives. Therefore, by utilizing smart charging, EVs can help to even out peak demand, fill in gaps in power usage, and contribute to the stability of power grids. Various mechanisms are used in smart charging, such as static, uncontrolled Time-of-use (TOU) tariffs that encourage charging during off-peak periods, basic on/off switching of charging, dynamic unidirectional controlled charging (V1G), more advanced bidirectional controlled charging (V2G), and dynamic pricing with automated control. Refer to Fig. 4 for a summary of these mechanisms.

These options are designed to minimize the impact of EV charging load on peak system demand, which helps avoid the need for infrastructure upgrades in generation, transmission, and distribution [35], [36]. Off-peak charging is a straightforward method of adjusting charging times to coincide with periods of low demand. This approach encourages the use of off-peak charging to alleviate the strain on the power grid and decrease the demand for EVs during peak times [37]. This can be achieved through the use of static off-peak tariffs or by implementing simple end-user programming [3]. Off-peak tariffs can be customized and regularly adjusted to align with the unique market characteristics of a nation or region, taking into account fluctuations in consumption and load profile. Utilizing cost advantages and advanced technology can boost and stimulate increased off-peak EV charging.

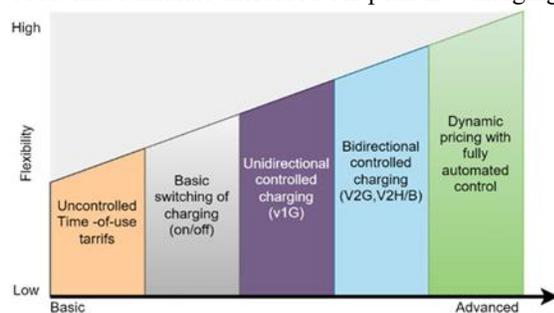


FIGURE 4. Flexibility levels provided by EV smart charging to grid.

EV charging in the unidirectional controlled charging

(V1G) method is optimized to align with the grid's constraints and requirements. This is achieved by carefully controlling the timing, rate, and duration of the charging process. This can be achieved by sending signals from utilities or aggregators to EVs/EVSEs in order to control the charging demand and optimize the use of electricity during off-peak periods, thereby reducing peak demand. During unidirectional charging, EVs function as a load for the grid, drawing power from it to charge their batteries. Implementing unidirectional V1G is relatively straightforward and can offer ancillary services such as regulation and spinning reserve [38]. Nevertheless, it is crucial to establish a regulatory framework and energy trading policy that can benefit both the grid operator and EV owner [39]. By utilizing active control, V1G can enhance the

proportion of renewable energy generation by aligning charging with optimal periods of solar irradiance and wind-based electricity production. This maximizes the utilization of both solar and wind power. In V1G, aggregators serve as crucial intermediaries, overseeing communications and control functions between all stakeholders involved. They also help alleviate the need for network infrastructure upgrades in terms of control and communication capabilities [3].

Vehicle to grid (V2G) technology, on the other hand, has the potential to revolutionize the energy landscape. It enables a two-way flow of energy between EVs and the grid, transforming EVs into storage systems and power providers rather than just consumers. This active participation allows EVs to actively contribute to peak shaving. Through the utilization of necessary infrastructure for V2G deployment, the grid operator effectively manages the power flow to maximize the benefits of V2G, including improved power quality, reduced emissions, and increased economic profit [11], [40], [41]. With bidirectional EV charging, there is a broader array of ancillary services available and greater flexibility compared to the unidirectional mode. This involves: providing active and reactive power support by managing peak load and ensuring a balanced power supply; optimizing the size of the charger DC link capacitor and implementing efficient switching control; regulating power factor to minimize grid losses; and facilitating the integration of renewable energy by acting as a storage source to address the

intermittent nature of renewable energy resources [42], [43], [44]. However, there are other technical challenges that can impact the potential of V2G. One such challenge is the premature battery degradation caused by frequent charging and discharging cycles [45].

#### D. HARDWARE ADVANCEMENT IN EVs

Electric vehicle hardware technology has seen significant advancements in recent years, particularly in areas that directly influence charging efficiency and grid integration. These hardware developments play a critical role in enhancing the performance, reliability, and compatibility of EVs with existing and future power infrastructure.

1). **Battery Technology: Lithium-ion Batteries:** The widespread adoption of lithium-ion batteries has been a key driver of EV growth due to their high energy density, long cycle life, and decreasing costs. Recent advancements include improvements in energy density, which allows for longer driving ranges, and the development of fast-charging capabilities, which reduce charging times significantly [46], [47]. **Solid-state Batteries:** Emerging as a promising alternative, solid-state batteries offer higher energy densities, faster charging, and improved safety compared to conventional lithium-ion batteries. While still in the research and development stage, they have the potential to revolutionize the EV market by addressing key limitations of current battery technologies [48].

2). **Charging Infrastructure: DC Fast Chargers:** Hardware advancements in direct current (DC) fast chargers have significantly reduced charging times, making EVs more convenient for long-distance travel. These chargers can deliver high power levels (up to 350 kW) and are increasingly being integrated into public charging networks [49], [50]. **Bidirectional Chargers:** These chargers, essential for V2G applications, allow energy to flow both from the grid to the vehicle and from the vehicle back to the grid. This capability is crucial for smart charging strategies, enabling EVs to act as mobile energy storage units that can support grid stability and renewable energy integration [51].

3). **Power Electronics: Onboard Chargers:** Modern onboard chargers have become more efficient and compact, allowing for faster AC charging and reducing energy losses during the charging process. Innovations

in power electronics, such as silicon carbide (SiC) and gallium nitride (GaN) semiconductors, have further improved the efficiency and thermal performance of these chargers [52], [53]. **Inverters:** Inverters, which convert DC from the battery to AC for the motor, have also seen significant advancements. The use of SiC and GaN technologies in inverters has resulted in higher efficiency, reduced size and weight, and improved thermal management, contributing to better overall vehicle performance and extended range [54].

4). **Thermal Management Systems:** As power density in batteries and power electronics increases, effective thermal management has become crucial. Advanced cooling systems, including liquid cooling and phase-change materials, are now being integrated into EVs to maintain optimal operating temperatures, thereby enhancing safety, performance, and longevity of components [55].

5). **Wireless Charging:** Wireless or inductive charging is an emerging technology that allows for convenient, cable-free charging. While currently less efficient than wired methods, advancements are being made to improve the power transfer efficiency and range of these systems.

Wireless charging has the potential to simplify the charging process, particularly in urban environments and for autonomous vehicles [56].

Understanding the operations of EVs, including their classification and the charging modes they employ, is crucial not only for improving their efficiency and user experience but also for comprehending their broader impact on the energy systems they interact with. As EV adoption increases, these operational factors play a significant role in shaping how these vehicles interface with power grids, ultimately influencing the stability, reliability, and efficiency of electricity distribution networks.

Given the operational intricacies of EVs, their integration into existing power grids presents both opportunities and challenges. As EVs become more prevalent, their impact on power grid dynamics grows increasingly significant. The manner in which EVs charge, discharge, and interact with the grid can lead to substantial implications for grid stability, power quality, and infrastructure resilience. Therefore, it is essential to explore these impacts in greater detail to understand the potential benefits and

challenges of widespread EV adoption on power systems.

### III. IMPACT ON POWER GRID

The impact of EVs on power grids has become a critical area of study as the number of EVs continues to rise. The load profiles of EVs, their charging behavior, and the associated power quality issues such as harmonics, voltage imbalances, and grid asset stress are central concerns that need to be addressed to ensure a smooth integration of EVs into power systems. The power consumption of EVs can be influenced by factors such as the battery capacity, driving characteristics, and the specific car model. However, the charging demand is influenced by various factors and can vary based on the battery’s chemistry, state of charge, supply voltage, number of phases, drawn current, charging mechanism, and its connection to the grid for energy tapping and/or providing additional services [57]. Furthermore, the integration of EVs into power systems poses several challenges, particularly concerning power quality issues such as harmonics, which can affect the stability and reliability of the grid. Harmonics are distortions in the voltage and current waveforms caused by non-linear loads, such as EV chargers. These distortions are typically quantified using Total Harmonic Distortion (THD), which is a measure of the cumulative effect of all harmonic components relative to the fundamental frequency.

The THD for voltage (THD<sub>v</sub>) and current (THD<sub>i</sub>) are given by the following formulas:

$$THD_v = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2}}{V_1} \times 100\% \quad (1)$$

$$THD_i = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2}}{I_1} \times 100\% \quad (2)$$

where  $V_1$  and  $I_1$  represent the RMS values of the fundamental

frequency components of voltage and current, respectively, and  $V_2, I_2, \dots, V_n, I_n$  are the RMS values of their harmonic components. High THD values indicate significant distortion, which can lead to inefficiencies, overheating, and potential damage to grid infrastructure. Managing and mitigating THD is therefore critical in ensuring the smooth integration of EVs into power systems [58].

In this section, we present a summary of studies that have examined the effects of EVs on the electric grid. Initially, we examine scholarly articles that have examined the influence of EVs on the electric grid in relation to their load profile. Next, we redirect our attention towards identifying research that have examined the capacity of EVs to facilitate the integration of renewable energy sources into the power grid. Next, we provide a concise overview of initiatives that

addressed several technical concerns linked to EVs, such as their impact on the stability of the electrical grid, power loss, the injection of harmonics, voltage and phase imbalances, and the impact on grid assets.

#### A. LOAD PROFILE

The widespread adoption of EVs poses issues to electricity systems. The introduction of additional loads at peak periods, caused by the charging and discharging behavior, is a significant concern. This further complicates the ongoing efforts to balance supply and demand, especially in cases when charging is not coordinated [57], [59], [60]. Multiple studies have examined the effect of integrating EVs into various national power networks on the demand profile [61]. Studies conducted in countries such as Germany and Korea have indicated that the load profile may be artificially increased, leading to a detrimental effect on the grid’s reliability. Therefore, this necessitates further investment in both the transmission and generation sectors [62], [63]. An analysis was conducted to hypothetically assess the impact of EV charging on peak load. The objective was to compare the maximum potential peak load resulting from the integration of EV loads [64]. The study examined the possible effect on the baseline peak load in each country for different levels of EV adoption, expressed as a percentage of households who own EVs. The analysis explored several charging capacity levels, including 2 kW, 4 kW, 20 kW, and 40 kW. It was presumed that all EV loads are linked to the grid during the period when the grid reaches its highest demand of the year. Table 3 [64] demonstrates a significant disparity in the preparedness of power networks to handle the increasing demand for EV charging. The power grids in the United States and Europe are better equipped to meet this demand compared to China.

Existing literature frequently highlights how EV

charging increases peak demand, potentially destabilizing the power grid without smart management solutions. Studies often emphasize the technical challenges but less so on practical, scalable solutions. Moreover, the reliance on assumptions about charging behavior and the availability of renewable energy integration leaves a gap in addressing real-world variabilities and consumer behavior unpredictability. We propose that future research should focus more on developing adaptive smart grid technologies that can dynamically respond to changes in EV charging demand. There is a need for more robust data analytics that can predict charging behaviors based on real-time data rather than static models. Also, integrating AI and machine learning could refine load forecasting methods, enhancing grid stability. Furthermore, to ensure a comprehensive understanding of load profile, it is essential to consider future technological advancements in both EVs and grid infrastructure that could alter these impacts.

#### 1). INCREASED ENERGY DENSITY

Future advancements in battery technology, such as solid-state batteries, are expected to offer higher energy densities, leading to longer driving ranges. This could result in less frequent charging, thereby smoothing out demand spikes and reducing the impact on the load profile.

#### 2). FASTER CHARGING CAPABILITIES

As batteries become capable of faster charging, the demand for high-power, short-duration charging will increase. While this could create new peak demands, it also presents an opportunity to align charging with periods of renewable energy surplus, thereby mitigating potential negative impacts on the grid.

#### 3). EFFICIENT INVERTERS AND CHARGERS

The adoption of silicon carbide (SiC) and gallium nitride (GaN) technologies in power electronics will improve the efficiency of inverters and onboard chargers. These advancements reduce energy losses during conversion and charging, which can help stabilize the grid by minimizing unnecessary demand spikes.

#### 4). BIDIRECTIONAL CHARGING

V2G technology allows EVs to return electricity to the grid, providing a form of distributed energy storage. This capability can help balance load profiles by absorbing excess generation during low-demand periods and discharging during peak demand, thus reducing strain on grid infrastructure.

#### 5). DYNAMIC LOAD MANAGEMENT

Future smart grid technologies will likely incorporate more sophisticated load management systems that can dynamically adjust to real-time demand and supply conditions. This includes more effective demand response programs and the integration of AI-driven predictive analytics to forecast and manage EV charging patterns more accurately.

#### 6). GRID MODERNIZATION

Investments in grid modernization, including the deployment of advanced metering infrastructure (AMI) and enhanced communication networks, will enable better monitoring and control of EV loads. This will help mitigate the potential negative impacts of EV charging on the load profile, particularly in regions with high penetration rates.

#### 7). RENEWABLE ENERGY ALIGNMENT

The increasing share of renewable energy in the grid, coupled with advancements in energy storage, will influence the load profile by providing more opportunities for off-peak EV charging. For example, smart charging strategies can align EV charging times with periods of high renewable generation, such as midday solar peaks, to reduce reliance on non-renewable generation and smooth out the load profile.

#### 8). DISTRIBUTED ENERGY RESOURCES (DERs)

The growth of distributed energy resources, including residential solar panels and local energy storage, will provide additional flexibility to the grid. This can help absorb local EV charging loads and reduce the burden on central generation and transmission systems, thereby stabilizing the overall load profile. As these technological advancements and infrastructure developments continue to evolve, the influence of EVs on the load profile is likely to become more manageable. While high penetration rates of EVs could initially exacerbate peak demands

and stress the grid, the strategic deployment of V2G technology, smart charging, and grid modernization efforts will play a crucial role in mitigating these effects. Therefore, any assessment of the impact of EV integration on the load profile must consider these future developments to provide a more accurate and forward-looking analysis.

TABLE 3. EV charging impact on peak load at different penetration levels.

Charging Capacity Levels		Germany	Denmark	France	California	China
1% Penetration	2kW	1.00%	0.80%	0.60%	0.50%	1.30%
	4kW	1.90%	1.60%	1.10%	1.10%	2.60%
	20kW	9.70%	8.10%	5.50%	5.40%	13.20%
	40kW	19.50%	16.30%	11.10%	10.70%	26.30%
3% Penetration	2kW	2.90%	2.40%	1.70%	1.60%	4.00%
	4kW	5.80%	4.90%	3.30%	3.20%	7.90%
	20kW	29.20%	24.40%	16.60%	16.10%	39.50%
	40kW	58.40%	48.90%	33.20%	32.20%	79.00%
5% Penetration	2kW	4.90%	4.10%	2.80%	2.70%	6.60%
	4kW	9.70%	8.10%	5.50%	5.40%	13.20%
	20kW	48.70%	40.70%	27.70%	26.80%	65.80%
	40kW	97.30%	81.50%	55.40%	53.60%	131.70%
7% Penetration	2kW	6.80%	5.70%	3.90%	3.80%	9.20%
	4kW	13.60%	11.40%	7.70%	7.50%	18.40%
	20kW	68.10%	57.00%	38.70%	37.60%	92.20%
	40kW	136.30%	114.10%	77.50%	75.10%	184.40%

**B. RENEWABLE ENERGY**

Multiple studies indicate that EVs can effectively assist in integrating renewable resources into the grid and mitigating their intermittent nature over time. This addresses a persistent difficulty encountered by utility firms. Research indicates that EVs, with their efficient power electronics converters and storage technology, can support the integration of renewable energy sources into the power grid. This integration of renewables can help mitigate any negative effects that EVs may have on the grid [65]. The integration of smart scheduling of EV charging with renewable energy, using a rolling horizon approach, indicates that it is possible to lower the annual demand on the grid without making major changes to the peak demand requirements [66].

The scheduling of EV charging can help in effectively regulating and reducing the duck curve, which is created by the mismatch between high power demand and renewable energy generation [67]. With the growing reliance on renewable energy

sources such as solar power to meet the rising power demand, the conventional load curve, as shown in Fig. 5, undergoes a distinct transformation.

Grid operators are confronted with the need to swiftly take power plants offline and bring them back online, which imposes additional ramping requirements. This has a detrimental impact on the flexibility, dependability, and maintenance cost of the grid. A digital model was suggested for intelligent scheduling of EV chargers, which reduces the need for rapid power adjustments and minimizes the chances of excessive power generation [68].

While the benefits of integrating EVs with renewable energy sources are well documented, the practical aspects of such integration at scale remain underexplored. Most studies provide a theoretical framework without addressing the economic and regulatory hurdles that hinder widespread adoption. Our analysis suggests a multi-stakeholder approach is crucial, involving policymakers, energy providers, and technology developers. Incentives should be aligned to promote not just EV adoption but also the establishment of renewable-powered charging stations. Additionally, innovations in battery technology that allow for faster charging during renewable peak production times could align EV charging demands with renewable energy availability.

**C. GRID STABILITY**

Refers to the ability of an electrical grid to provide a steady and reliable supply of electricity without experiencing disruptions or fluctuations. The integration of a large number of EVs into the power grid primarily results in a temporary deviation from its normal functioning and impacts its vulnerability to disruptions and the duration required to return to stable conditions [69]. Unregulated EV charging can cause instability in distribution networks by overloading them, leading to congestion [70]. An analysis of voltage stability was conducted to assess the influence of EVs on the steady-state voltage stability of the power grid. This was achieved by creating models of rapid charging stations and considering the unique characteristics of EV load. The study determined that the specifications of EV chargers have an impact on the system loading margin in various scenarios [71]. However, the effect on stability is still uncertain and requires additional

exploration. For instance, when EVs are connected to the power grid, their integration improves the stability of the grid [72]. A simulation research performed on the IEEE RTS-96 24 bus system discovered that the integration of EVs had a positive impact on the Short-Term Voltage Stability Index

(SVSI). The improvement was dependent on the aggregated connected load and the specific location (load bus) where the EVs were connected [73]. On the other hand, the effect on the stability of the power grid was examined using

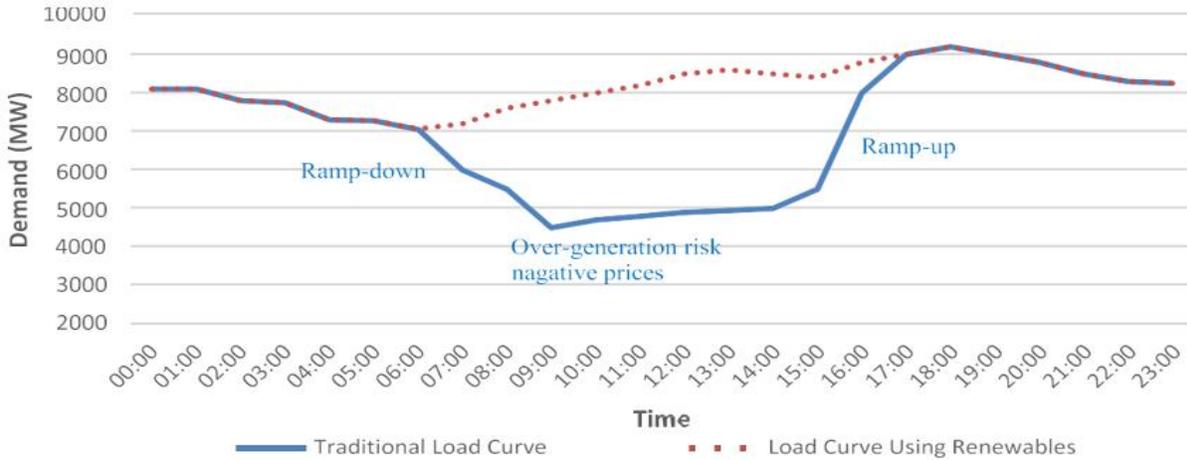


FIGURE 5. A typical duck curve.

the IEEE 33 bus network. The installation of rapid chargers at vulnerable buses resulted in a drop in voltage stability [74]. The integration of EVs into the power grid introduces challenges such as phase unbalance and overload, particularly as EV adoption increases. These issues can lead to inefficiencies, increased power losses, and potential damage to grid infrastructure. To address these challenges, several strategies have been developed and are being implemented to ensure stable grid operations.

### 1). SMART CHARGING AND LOAD MANAGEMENT

Smart charging involves controlling the time and rate of EV charging to align with grid conditions and avoid peak demand periods. This strategy can reduce the risk of overload and help balance the load across the three phases of the grid. At low levels of EV penetration, smart charging can effectively distribute the charging load, minimizing the risk of phase unbalance. The impact on the grid is generally manageable, and existing infrastructure can accommodate the additional load with minimal modifications. As EV adoption increases, the effectiveness of smart charging becomes more critical. Advanced algorithms that optimize charging schedules based on real-time

grid conditions and forecasts are required to prevent overload and maintain phase balance. However, in grids with limited flexibility or outdated infrastructure, the benefits of smart charging may be reduced, necessitating further grid upgrades [75].

### 2). PHASE BALANCING ALGORITHMS

Phase balancing algorithms are used to dynamically adjust the load on each phase by switching the charging phases of EVs. These algorithms can be implemented in charging stations to ensure that the load is evenly distributed across all three phases. In grids with well-maintained infrastructure and moderate EV penetration, phase balancing algorithms can maintain a stable and balanced load, preventing phase unbalance from becoming a significant issue [76].

### 3). VEHICLE-TO-GRID (V2G) TECHNOLOGY

V2G technology allows EVs to discharge electricity back to the grid, providing a means to balance supply and demand dynamically. V2G can be used to support phase balancing by directing energy to underutilized phases or alleviating overloads by discharging during peak periods. In grids with low to moderate EV adoption, V2G can effectively mitigate both phase unbalance and overload by acting as

a distributed energy resource. The grid benefits from enhanced flexibility and reduced peak loads. At high levels of EV adoption, the effectiveness of V2G depends on widespread participation and sophisticated coordination between EVs and the grid. While V2G can provide significant benefits, its implementation is complex, requiring robust communication infrastructure and incentives for EV owners to participate [77].

#### 4). DISTRIBUTED ENERGY RESOURCES (DERs)

Integrating distributed energy resources, such as rooftop solar panels and local energy storage systems, can help alleviate phase unbalance and overload by providing additional local generation and load balancing capabilities. In localized grids or microgrids, DERs can significantly enhance phase balance and reduce the risk of overload by providing supplementary power during peak demand periods. This is especially effective when coupled with smart inverters that can control the flow of energy across phases. In larger, wide-area grids, the impact of DERs on phase balance and overload is more dispersed but still beneficial. The key to maximizing their effectiveness lies in the integration of DERs with advanced grid management systems that can coordinate their output in real time [78], [79].

#### *D. POWER LOSS*

The integration of EVs into the power grid has a significant impact on power losses, particularly as the penetration levels of EVs increase. The magnitude of these losses is influenced

by several factors, including the level of EV penetration, the charging power level, and the charging strategies employed. As EV penetration increases, the total power demand on the grid rises correspondingly, leading to higher distribution losses. Studies have shown that at low penetration levels (e.g., 1-5% of the total vehicle fleet), the impact on power losses is relatively moderate. However, as penetration levels reach 20% or more, the losses can increase significantly. For instance, at a 20% penetration level with uncoordinated charging, power losses can rise by approximately 40%, depending on the charging power and the grids capacity to handle the additional load [74], [80], [81]. Different charging

scenarios further exacerbate or mitigate these losses:

#### 1). UNCOORDINATED CHARGING

This scenario, where EVs are charged as soon as they are plugged in without any consideration for the grid's load conditions, typically leads to the highest power losses. The simultaneous charging of multiple EVs during peak hours can create severe stress on the grid, leading to congestion and increased losses in distribution lines.

#### 2). OFF-PEAK CHARGING

Encouraging EV charging during off-peak hours can help reduce peak demand and associated losses. However, if a large number of EVs charge simultaneously during off-peak periods, significant power losses can still occur, especially in areas with limited grid infrastructure.

#### 3). SMART CHARGING (V1G)

This scenario involves controlled charging where the timing, rate, and duration of EV charging are optimized to align with grid conditions and renewable energy availability. Smart charging can significantly reduce power losses by distributing the load more evenly and avoiding peak demand periods. Studies have shown that implementing smart charging can reduce power losses by up to 10% compared to uncoordinated charging.

#### 4). VEHICLE-TO-GRID (V2G) CHARGING

V2G technology allows for bidirectional energy flow, where EVs can discharge power back to the grid. This scenario can help balance supply and demand, particularly during peak periods, and reduce the need for additional generation capacity. However, the complexity of managing V2G operations and the potential wear and tear on EV batteries must be considered.

The increase in power losses due to high EV penetration levels and varying charging scenarios necessitates upgrades in grid infrastructure. Without appropriate investments in transmission and distribution networks, the rising power losses could lead to reduced grid reliability, increased operational costs, and potential service disruptions.

In conclusion, a comprehensive assessment of power losses must consider not only the level of EV penetration but also

the specific charging scenarios in place. By adopting smart charging strategies and making necessary grid upgrades, it is possible to mitigate the negative impacts of EV integration on power losses and ensure a more stable and efficient power system [82].

#### *E. HARMONICS INJECTION*

The power electronics in EV chargers play a crucial role in determining the harmonics that are introduced into the power grid during the process of power conversion. This can result in harmonic distortion and other power quality problems for the grid, as well as potentially overloading distribution assets and reducing their lifespan [22]. Prior research indicated that the rise in total harmonic distortion (THD) resulting from residential single-phase loads and EV charging was not excessive and should not be worrisome [83]. This claim was further supported by a subsequent study that took into account the dynamic aspects of EV charging, such as the variability in charging time, duration, and locations [84]. However, a different study indicated that Level 1 chargers can elevate the neutral to earth voltage, increasing the probability of stray voltage incidents. EV rapid chargers can have a substantial effect on the power system by introducing high harmonic currents that can cause voltage distortion above acceptable limits [85]. A simulation was conducted to evaluate the effectiveness of using PV inverter control to reduce harmonic injections resulting from fast charging. The simulation findings demonstrated a decrease in total harmonic distortion (THD) for both current and voltage [85].

#### *F. VOLTAGE AND PHASE IMBALANCE*

The power delivered to customers can be impacted by voltage drop and voltage deviation at the point where the EV grid connects [86]. When there are many EVs linked to the grid, there is a possibility that the voltage needs may not be met, resulting in a voltage drop that exceeds the permitted limit. An examination was conducted to investigate the impact of charging load on the grid [87]. The analysis considered various charging strategies and found that uncoordinated charging at high penetration levels exceeded the acceptable voltage limits, unlike in the case of V2G charging where the voltage remained within acceptable limits up to a penetration level of 50%. Furthermore, EV chargers can contribute to the

issue of phase unbalance, particularly in the context of single phase slow residential charging. This occurs when the loads are not equally spread throughout the phases, which might impede the expansion of EV charger installations [80].

#### *G. GRID ASSETS*

The constraints on the physical components of distribution grids are examined in relation to the integration of EVs and their influence on the overall performance. The surge in energy usage resulting from the demand for EV charging often exceeds the capacity of the network components, leading to overload. The increased prevalence of EVs is

commonly linked to thermal overloading, reduced lifespan of assets, and aging. A study examining the impact of AC level 1 and level 2 chargers on the aging of distribution transformers discovered that the aging factor of the transformers was more than double for level 2 chargers compared to level 1 chargers [88]. A separate study examined the effects of disorganized EV charging on the cables' ability to carry electricity. The study discovered that under typical charging conditions, a cable can handle up to 25% of EVs being connected. However, in fast charging situations, the cable's capacity is limited to only 15%, which restricts the ability to accommodate higher levels of EV usage [89].

While the integration of EVs into the power grid presents both opportunities and challenges, the success of this integration hinges on widespread adoption. The following section will examine the factors influencing EV adoption, exploring the drivers, barriers, and strategies that can accelerate the shift towards electric mobility.

## IV. KEY INSIGHTS AND CHALLENGES

The successful integration of EVs into the power grid requires a comprehensive analysis of both technical and social variables. This analysis is necessary to evaluate the possible benefits and drawbacks, as well as to identify the obstacles, possibilities, and gaps associated with EV integration.

Regarding charging technology, it is crucial to establish a uniform standard for charging infrastructure and components. This would ensure widespread acceptance across countries and reduce manufacturing

costs through standardization. The compatibility issues between EV models and charging stations continue to challenge convenience, as not all charging stations can deliver the required charging levels for all EV models.

At a strategic level, research is ongoing to design an appropriate framework for integrating EVs into the power grid. In this framework, EVs are seen as both a regular load, a storage source, and a communication node within an integrated network. Therefore, progress in smart grid technology will mainly propel the growth of EVs that can be connected to the grid. The importance of the aggregator agent cannot be overstated in anticipation of the increased use of EVs and their integration into the power grid.

The literature clearly demonstrates that many research have examined both the adverse effects of integrating EVs into the grid and their ability to provide auxiliary services. However, it is clear that varying concentrations of EV loads introduce considerable uncertainty in both time and space, which is further complicated by the inherent complexity of load forecasting.

Another aim of the literature study was to gain a deeper understanding and conceptualization of the many obstacles and motivators for EV adoption. This information can then be used to develop strategies and policy tools to encourage a greater uptake of EVs. In order for EV to have a significant presence in the market at a national level, stakeholders must collaborate to improve visibility, awareness, and market acceptance. Crucially, offering solutions that are attractive to the many demographic groupings. The literature indicates that the hurdles and drivers of EV adoption are intricate and multifaceted, and cannot be effectively addressed in isolation

due to their interconnected nature. Instead, a whole ecological approach is necessary

To enhance customers' impression of EVs and boost their inclination to acquire them, it is necessary to initiate awareness efforts highlighting the financial incentives and advantages of EVs. These campaigns should aim to rectify any misconceptions regarding the perceived inferiority of EVs. Increasing awareness will ultimately inform customers' purchasing decisions as knowledge of incentives, once established, can stimulate consumer interest. Therefore, marketing strategies should be formulated to prioritize the ways in which EVs can enhance consumer

convenience and provide environmental advantages. Due to the unique challenges faced by the EV market, it is crucial to develop government-led strategies that stimulate consumer demand. These strategies should include subsidies for EV registration, incentives for vehicle purchases, and subsidies for home chargers. Additionally, implementing convenient measures like free parking policies, which have proven effective in boosting EV sales in other countries [106], would be beneficial. It is crucial to highlight that the government must ensure the flexibility and adaptability of policy instruments to effectively cater to the unique characteristics of its community, including both residents and citizens. An impending challenge is the restricted range of EV models available. Existing research indicates

EV technologies have a high buying price. Many potential users/owners are unwilling to invest in a car with significant fixed costs unless there are other economic incentives. One commonly used method to encourage such actions among consumers is to decrease taxation. While it may not be immediately feasible in nations that have tax exemptions for non-business transactions, it is worth exploring as a potential avenue to promote the adoption of EVs at the individual level. Successful implementation of electric mass transit buses, coupled with a rise in ridership, has the potential to enhance the appeal of EVs as a mobility choice for individuals. Increased adoption of public electric buses can lead to a significant reduction in the average distance traveled each trip by personal vehicles, as individuals may be limited to utilizing their cars for shorter first- and last-mile journeys. Consequently, this leads to decreased CO<sub>2</sub> emissions and may also incentivize more people to switch from combustion-based vehicles to EVs due to their convenience for short trips and lower operating costs. Evaluating this situation inside a simulated setting could additionally aid in formulating more effective incentives to increase ridership. Another crucial aspect to take into account when formulating transitioning strategies for EV adoption is implementing a viable and environmentally-friendly business model that encourages the widespread use of EVs. A comprehensive business model should consider both primary stakeholders, such as end-users and

operators, as well as secondary stakeholders, such as suppliers and other environmentally conscious businesses that could benefit from EV adoption. The literature analysis found that allowing private investment in charging infrastructure through public-private partnerships (PPP) could increase the acceptance and adoption of EVs. According to a case study focused on Shenzhen, the city's present business model, which combines company innovation with government regulations and regulation, might be improved by encouraging private investment in charging infrastructure under a Public-Private Partnership (PPP) framework [116]. It is important to note that the literature does not provide clear recommendations on how to construct partnership and business models [90]. However, a few studies have examined methods for evaluating these models in various markets (see, for example, [146]). This paper further examines and evaluates the current body of literature on optimization endeavors in the context of incorporating EVs into smart grids. Although extensive research has been carried out in several fields of study with the goal of optimizing distinct objectives in recent years, there is a noticeable lack of systematic examination in certain areas. Furthermore, the areas that have been studied already show potential for further exploration and improvement. One shortcoming that has been identified is the failure to take into account the stochastic nature of EV demand and availability for charging and discharging. While only a limited number of research endeavors have taken this element into account within their problem settings, it nevertheless merits additional inquiry. Another intriguing topic that arises from the field of operations research is the location and allocation problem, also known as facility planning. This problem aims to optimize the placement and assignment of charging stations in a well-informed infrastructure development. Another notable area for potential optimization is in enhancing public policy to encourage the widespread adoption of EVs and creating favorable market circumstances through the implementation of incentives and levies. Within the framework of demand side management, it is important to conduct additional study on the social behavior, attitude towards pricing, and trust in EVs as they are significant factors to consider. Insufficient research has been conducted on the optimization of

electric car battery degradation. It is worth noting that most of the surveyed work focused on optimizing a single objective, rather than addressing the complex problem of vehicle integration. This problem involves multiple conflicting aspects and stakeholders, and any solution in this context requires making trade-offs. Therefore, further investigation into multi-objective optimization is necessary. The expected decrease in CO<sub>2</sub> emissions resulting from the incorporation of EVs into the power grid was seldom a goal in the analyzed issues. There is still much work to be done to improve the environmental benefits of V2G and EV technology.

Having explored the insights and challenges associated with EV adoption and integration, we now turn to the conclusion. This final section encapsulates the findings of this study, offering a comprehensive view of the current state and future prospects of electric mobility.

## V. CONCLUSION

This paper provided a comprehensive examination of the current EV charging processes, charging modes, and standards from a technical standpoint. Continued progress in smart grids and EV technologies is crucial to ensure the successful integration of EVs with the power system. It is necessary to evaluate the benefits and advantages. Furthermore, it is crucial to evaluate and measure the adverse effects in a setting that facilitates intelligent charging, dependable communication, and a well-organized framework that takes into account the interests of both EV owners and power grids. This study also examined variables, from a sociological standpoint, that could contribute to the expansion of EV adoption. This includes identifying hurdles and drivers that could either impede or stimulate the widespread adoption of EVs. Four primary domains were identified to facilitate the transition to a broader EV adoption. The four key factors are rules and governance, charging infrastructure, economic feasibility, and business models. The literature uncovered many methods and regulations that have the potential to stimulate the growth of EVs in different cities and regions. The common thread throughout all is the significance of context. Ultimately, we explored many strategies to optimize the planning of EV operations and its integration into

the electric grid. Several potential avenues were found that would enhance the current body of material.

## VI. ACKNOWLEDGMENT

The statements made herein are solely the responsibility of the authors.

## REFERENCES

- [1] P. Chen, T. Grünewald, T. J. Noffsinger, and E. Samseth. (Feb. 2024). Global Energy Perspective 2023\_Power Outlook\_McKinsey. Accessed: May 1, 2024. [Online]. Available: <https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-power-outlook>
- [2] (2023). CO2 Emissions in 2023. [Online]. Available: <http://www.iea.org>
- [3] Energy Agency. (2024). Global EV Outlook 2024 Moving Towards Increased Affordability. [Online]. Available: <https://www.iea.org>
- [4] International Energy Agency. (2023). Global EV Outlook 2023: Catching Up With Climate Ambitions. [Online]. Available: <https://www.iea.org>
- [5] Virta Global. The Global Electric Vehicle Market Overview in 2024-Virta. Accessed: May 2, 2024. [Online]. Available: <https://www.virta.global/en/global-electric-vehicle-market>
- [6] D. Brdar. EV Trends for 2024: What to Expect from the Electric Vehicle Market. Nasdaq. Accessed: May 2, 2024. [Online]. Available: <https://www.nasdaq.com/articles/ev-trends-for-2024-what-to-expect-from-the-electric-vehicle-market>
- [7] H. Ritchie. Tracking Global Data on Electric Vehicles. Our World Data. Accessed: May 2, 2024. [Online]. Available: <https://ourworldindata.org/electric-car-sales>
- [8] ACEA. (18, 2024). New Car Registrations, European Union. Accessed: May 2, 2024. [Online]. Available: <https://www.acea.auto/>
- [9] D. Cui, Z. Wang, P. Liu, S. Wang, D. G. Dorrell, X. Li, and W. Zhan, "Operation optimization approaches of electric vehicle battery swapping and charging station: A literature review," *Energy*, vol. 263, Jan. 2023, Art. no. 126095, doi: 10.1016/j.energy.2022.126095.
- [10] R. Das, Y. Wang, G. Putrus, R. Kotter, M. Marzband, B. Herteleer, and J. Warmerdam, "Multi-objective techno-economic-environmental optimisation of electric vehicle for energy services," *Appl. Energy*, vol. 257, Jan. 2020, Art. no. 113965, doi: 10.1016/j.apenergy.2019.113965.
- [11] M. Inci, Ö. Çelik, A. Lashab, K. Ç. Bayındır, J. C. Vasquez, and J. M. Guerrero, "Power system integration of electric vehicles: A review on impacts and contributions to the smart grid," *Appl. Sci.*, vol. 14, no. 6, p. 2246, Mar. 2024, doi: 10.3390/app14062246.
- [12] R. R. Kumar and K. Alok, "Adoption of electric vehicle: A literature review and prospects for sustainability," *J. Cleaner Prod.*, vol. 253, Apr. 2020, Art. no. 119911, doi: 10.1016/j.jclepro.2019.119911.
- [13] H. S. Das, M. M. Rahman, S. Li, and C. W. Tan, "Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review," *Renew. Sustain. Energy Rev.*, vol. 120, Mar. 2020, Art. no. 109618, doi: 10.1016/j.rser.2019.109618.
- [14] A. K. Karmaker, Md. A. Hossain, H. R. Pota, A. Onen, and J. Jung, "Energy management system for hybrid renewable energy-based electric vehicle charging station," *IEEE Access*, vol. 11, pp. 27793–27805, 2023, doi: 10.1109/ACCESS.2023.3259232.
- [15] M. Nazari, A. Hussain, and P. Musilek, "Applications of clustering methods for different aspects of electric vehicles," *Electronics*, vol. 12, no. 4, p. 790, Feb. 2023, doi: 10.3390/electronics12040790.
- [16] O. M. Govardhan, "Fundamentals and classification of hybrid electric vehicles," *Int. J. Eng. Techn.*, vol. 3, no. 5, pp. 194–198, 2017.
- [17] S. A. Khan and M. Kushler, "Plug-in electric vehicles: Challenges and opportunities," *Amer. Council Energy-Efficient Economy*, Washington, DC, USA, Tech. Rep. T133, Jun. 2013.
- [18] SAE Int. (2020). SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler. Accessed: May 14, 2020. [Online]. Available: [https://www.sae.org/standards/content/j1772\\_20](https://www.sae.org/standards/content/j1772_20)

1710/

- [19] F. N. Esfahani, A. Darwish, X. Ma, and P. Twigg, "Non-integrated and integrated on-board battery chargers (iOBCs) for electric vehicles (EVs): A critical review," *Energies*, vol. 17, no. 10, p. 2285, May 2024, doi: 10.3390/en17102285.
- [20] Y. Zheng, S. Niu, Y. Shang, Z. Shao, and L. Jian, "Integrating plug-in electric vehicles into power grids: A comprehensive review on power interaction mode, scheduling methodology and mathematical foundation," *Renew. Sustain. Energy Rev.*, vol. 112, pp. 424–439, Sep. 2019, doi: 10.1016/j.rser.2019.05.059.
- [21] D. Aggeler, F. Canales, H. Z.-D. L. Parra, A. Coccia, N. Butcher, and O. Apeldoorn, "Ultra-fast DC-charge infrastructures for EV-mobility and future smart grids," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT Europe)*, Oct. 2010, pp. 1–8, doi: 10.1109/ISGTEU-ROPE.2010.5638899.
- [22] M. R. Khalid, M. S. Alam, A. Sarwar, and M. S. J. Asghar, "A comprehensive review on electric vehicles charging infrastructures and their impacts on power-quality of the utility grid," *eTransportation*, vol. 1, Aug. 2019, Art. no. 100006, doi: 10.1016/j.etrans.2019.100006.