Comprehensive Analysis of Factors Affecting the Electric Vehicle Charging Ecosystem

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Abstract. The transition to electric vehicles (EVs) represents a pivotal strategy in achieving sustainable transportation and reducing greenhouse gas emissions. It examines the trends in EV imports to Uzbekistan between 2018 and 2024, highlighting the nation's increasing integration into the global shift toward sustainable mobility. The review covers the availability of charging infrastructure, its critical role in supporting EV adoption, and the implications of power supply and grid stability amid growing energy demands. Economic considerations, including the cost of EVs and infrastructure investment, are assessed alongside broader environmental and policy frameworks. The findings underscore the importance of integrated strategies that balance technological innovation, economic viability, and regulatory support to ensure the sustainable growth of the EV sector.

INTRODUCTION

Recent technological advancements have significantly contributed to global decarbonization by driving the development of electric vehicles (EVs). EVs reduce transportation's reliance on fossil fuels for energy. It is estimated that over 50% of global petroleum products are consumed by the transportation sector, which accounts for more than 90% of all transportation energy source[1]. With the tightening of environmental regulations on greenhouse gas (GHG) emissions worldwide, the shift from traditional fuel vehicles to battery electric vehicles (BEVs) has become an inevitable trend in the automotive industry[2]. To enhance consumer interest, many countries are implementing tax exemptions on EV imports and providing financial incentives to businesses for the adoption of EVs in urban areas. These measures aim to accelerate the transition to sustainable transportation by reducing the cost burden on consumers and promoting the integration of EVs into commercial and public fleets. It is essential to analyze the factors influencing the EV charging process. A comprehensive examination of these factors, including charging infrastructure availability, grid capacity, charging speed, battery technology, and environmental conditions, can contribute to optimizing charging efficiency and enhancing the overall adoption of EVs. Understanding these elements is crucial for the development of sustainable and effective EV charging networks.

Ruseruka et al. [1] investigated the evolving needs of EV users and identified key factors influencing charging demand using an extreme gradient boosting model. The findings of this research identify key factors influencing EV charging needs, providing a valuable foundation for decision-makers and stakeholders in determining optimal locations for EV charging stations. This ensures improved usability, efficiency, sustainability, and overall social welfare. Yang et al. [3] analyzed fast charging behavior using connected data from 130 private BEVs in Beijing. Key determinants of fast charging included the battery state of charge at the start time, and developed a predictive model to estimate fast charging occurrences within daily trajectories. Raoofi et al. [4] developed a system dynamics model to examine the long-term adoption of electric trucks and charging infrastructure, considering technology maturity, awareness, and cost. Their findings indicate that subsidies for charging stations significantly boost adoption, while investing in vehicle technology maturity is the most cost-effective under financial constraints. Das et al. [5] reviewed the EV market, charging infrastructure, and grid integration, highlighting key standards, control architectures, and optimization strategies. They examined the role of EV aggregators, emerging technologies, and future energy Internet development, identifying challenges and recommendations for EV-grid integration. Al-Hanahi et al. [6] proposed a smart charging system to optimize electric truck charging under a return-to-base strategy, reducing facility peak demand and lowering demand charges by up to 54%.

Despite extensive research, there remains a gap in understanding the factors influencing the charging process of electric trucks, as they have received limited attention. This study aims to address this gap by identifying and analyzing the key factors affecting electric truck charging efficiency and integration.

Trends in electric vehicle imports to Uzbekistan (2018–2024). The importation of electric vehicles (EVs) in Uzbekistan has demonstrated a significant upward trend over the past few years (given in Figure 1). In 2018, only 13 EVs were imported into the country, marking the initial stage of EV adoption. This number saw a gradual increase in subsequent years, reaching 39 units in 2019, 131 in 2020, 809 in 2021, and 2,180 in 2022. A substantial surge occurred in 2023, with 16,084 EVs imported, reflecting a growing emphasis on sustainable transportation. This rapid growth continued into 2024, with imports peaking at 24,095 units ([1]). These figures highlight Uzbekistan's increasing commitment to electric mobility, likely driven by policy incentives, infrastructure development, and rising consumer demand for environmentally friendly transportation.

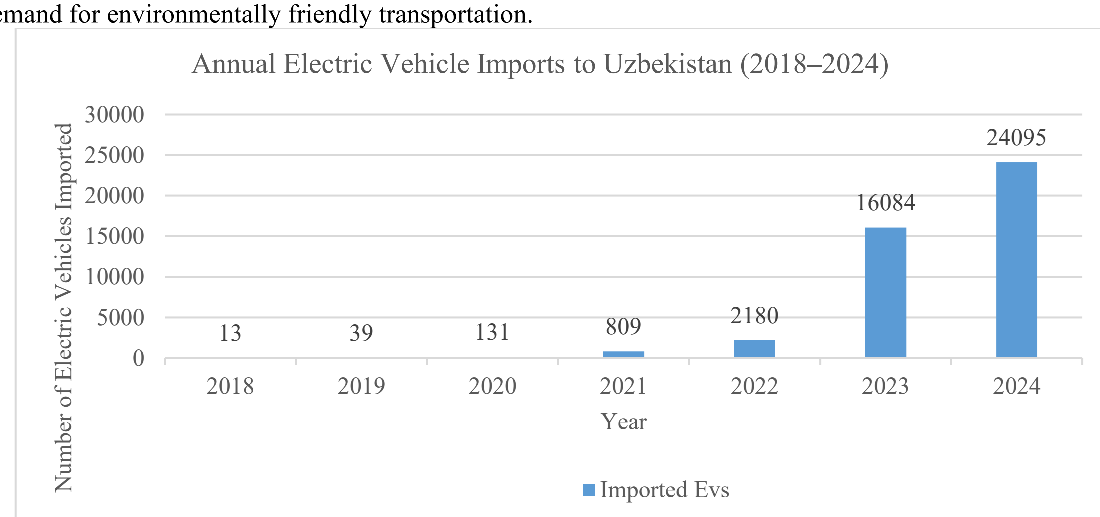

FIGURE 1. Annual Electric Vehicle Imports to Uzbekistan (2018–2024)

EXPERIMENTAL RESEARCH

Charging infrastructure availability. The number of EVs increases, the demand for charging infrastructure also rises to support their widespread use and ensure efficient operation. EVs on the road require a greater number of charging stations, faster charging solutions, and improved grid integration to meet energy demands. This section models the delay in charging station construction through two interconnected stock variables, representing the transition from under-construction charging stations (UCC) to installed charging stations (IC), as expressed in Eq. (1) and inspired by[7].

$$UCC(t) = \int \big(BC(t) - FC(t)\big)dt$$

$$IC(t) = \int \big(FC(t) - SC(t)\big)dt \tag{1}$$

For a given time t, $BC(t)$ represents the number of charging stations under construction, as described in Equation (2). Meanwhile, $FC(t)$ denotes the number of charging stations that have been completed, and $SC(t)$ signifies the number of charging stations that have been decommissioned.

[1] https://stat.uz/en/

$$BC = \frac{GIC_{actual} - PIC_{actual}}{capex_c} \tag{2}$$

Where GIC_{actual} represents the actual annual government investment in charging stations, PIC_{actual} denotes the actual annual private investment in charging stations, and $capex_c$ refers to the construction cost or capital expenditure ($capex$) per charging station[4]. Charging infrastructure availability is a crucial factor in the charging process because it directly impacts the efficiency, convenience, and feasibility of EV adoption. The study by [8] authors employs a binary atom search optimization algorithm to optimize station location and capacity planning. The simulation results confirm the model's effectiveness in balancing station utilization and waiting time.

Charging infrastructure availability is essential for supporting the growing number of electric vehicles. Modeling construction delays through investment-based equations highlights the impact of government and private funding on deployment speed. Optimizing station location and capacity using advanced algorithms improves efficiency and reduces waiting times, reinforcing the need for strategic infrastructure planning to enable effective and scalable EV adoption.

Power supply and grid stability. Power system stability refers to the capability of an electrical power system to restore its steady-state operating condition following a disturbance[9]. EVs have both beneficial and adverse effects on the power system. While they contribute to frequency regulation, voltage regulation and reactive power compensation, congestion management and improving power quality, their integration can also introduce challenges such as harmonic distortion, increase in power losses, overloading of distribution network components, voltage instability and phase unbalance and impacts due to increase in peak demand[10]. The author's analysis of charger data shows that most EV users overstay after charging. Nearly 90% of 330 users could fully recharge in less time, even with a 3.6 kW AC charger[11]. The fact that many EVs are parked during the day[12] offers a unique opportunity to support grid stability, especially as renewable energy integration increases. Numerous studies have demonstrated that the controlled charging of electric vehicles can enhance power system efficiency, lower operational costs, and reduce the curtailment of renewable energy sources (RESs). Furthermore, the controlled discharging of EVs can offer additional advantages and contribute to providing essential electrical services[13]. Advanced EV-grid interaction models will investigate emerging vehicle-to-everything (V2X) paradigms, extending beyond conventional vehicle-to-grid (V2G) applications to encompass vehicle-to-vehicle (V2V), vehicle-to-home (V2H), and vehicle-to-building (V2B) frameworks. These models will enable EVs to serve as distributed energy resources, facilitating peak load management, enhancing demand response strategies, and improving overall grid stability[14]. If the EV charger operates with a sinusoidal current waveform and a unitary power factor, the total harmonic distortion (THD) of the overall current in the electrical grid is significantly reduced, while voltage levels remain unaffected[15]. The modernization of power systems is driving the increased adoption of electric vehicles through V2G technology. Within a smart grid environment, EVs serve as a potential solution for mitigating power fluctuations caused by the intermittent nature of RESs [16].

Although electric vehicles offer significant advantages for transportation, their impact on power systems cannot be overlooked [17]. The large-scale integration of EV charging in an uncontrolled manner can significantly increase peak demand, leading to higher operational costs and necessitating infrastructure upgrades if demand exceeds generation, transmission, or distribution capacity[10]. EV penetration has minimal impact on voltage levels, even with uncontrolled charging. However, high EV penetration can cause significant voltage drops, exceeding acceptable limits, particularly in rural networks, necessitating voltage regulation devices. Additionally, phase unbalance poses a challenge, as most EVs rely on single-phase chargers. While low EV penetration causes minor unbalance, high penetration and uneven charger distribution can lead to voltage unbalance factors (VUF) exceeding permissible limits. Traditional EV chargers generate excessive harmonics, which can shorten the lifespan of distribution network components such as transformers and cables. However, optimizing charger circuit design, control strategies, and integrating filters can significantly mitigate harmonic distortion[5, 10, 16]. A significant drawback of EV penetration is the potential overloading of distribution networks and increased power losses. Implementing appropriate charging and discharging strategies, such as delayed charging, controlled charging, V2G, V2B, and V2H, enables distribution networks to accommodate higher EV penetration levels without exceeding capacity limits while also reducing power losses. A high penetration of photovoltaic (PV) systems and EVs can individually pose challenges to grid stability and power quality due to the intermittent nature of PV energy generation and the unpredictable load characteristics of EVs. However, the implementation of coordinated or integrated operational strategies for PV systems and EVs can effectively mitigate these adverse impacts, enhancing overall power quality and grid stability[18].

Electric vehicles offer both benefits and challenges to power grid stability. Controlled charging and discharging strategies, including V2G, V2H, and V2B, can enhance grid performance, reduce losses, and support renewable integration. However, uncontrolled EV adoption may lead to overloading, voltage instability, and increased harmonics. Coordinated management and smart grid technologies are essential to mitigate these impacts and ensure a stable, efficient, and sustainable energy system.

Charging speed and technology. In various types of EVs, including plug-in hybrid electric vehicles (PHEVs), the battery pack charging process is conducted externally via a power network using a dedicated device known as a battery charger. The fundamental configuration of battery chargers is illustrated in Figure 2.[16]. A three-phase Alternating Current (AC) supply is converted to Direct Current (DC) via an AC-DC rectifier, then regulated by a DC-DC converter before reaching the battery, ensuring efficient and stable charging.

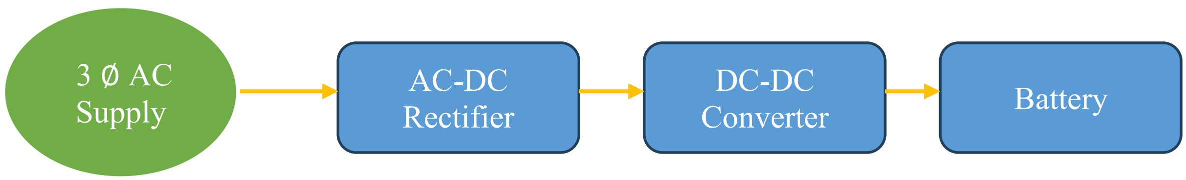

FIGURE 2. Basic Configuration of Battery Charger

RESEARCH RESULTS

Method of energy transfer. EV charging systems can be categorized based on the method of energy transfer, including: conductive charging, wireless (i.e., contactless) charging (WC), and battery swapping[10, 16, 19]. In conductive charging, a direct physical connection exists between the battery and the power supply, enabling energy transfer through cables and connectors. In contrast, wireless charging operates without any physical contact, using electromagnetic fields to transfer energy between the charger and the vehicle's battery. Moreover, [20] presented multiple solutions for EV wireless power transfer (WPT) systems to minimize costs while ensuring high transmission efficiency despite receiver misalignment. Battery swapping technology involves replacing a depleted or fully discharged battery with a fully charged one, eliminating the need for conventional charging time[21, 22]. **Error! Reference source not found.** illustrates integrated onboard, offboard, and wireless power conversion system for a light-duty electric truck. The system is designed to efficiently manage and convert electrical energy from an AC supply to a form suitable for vehicle operation.

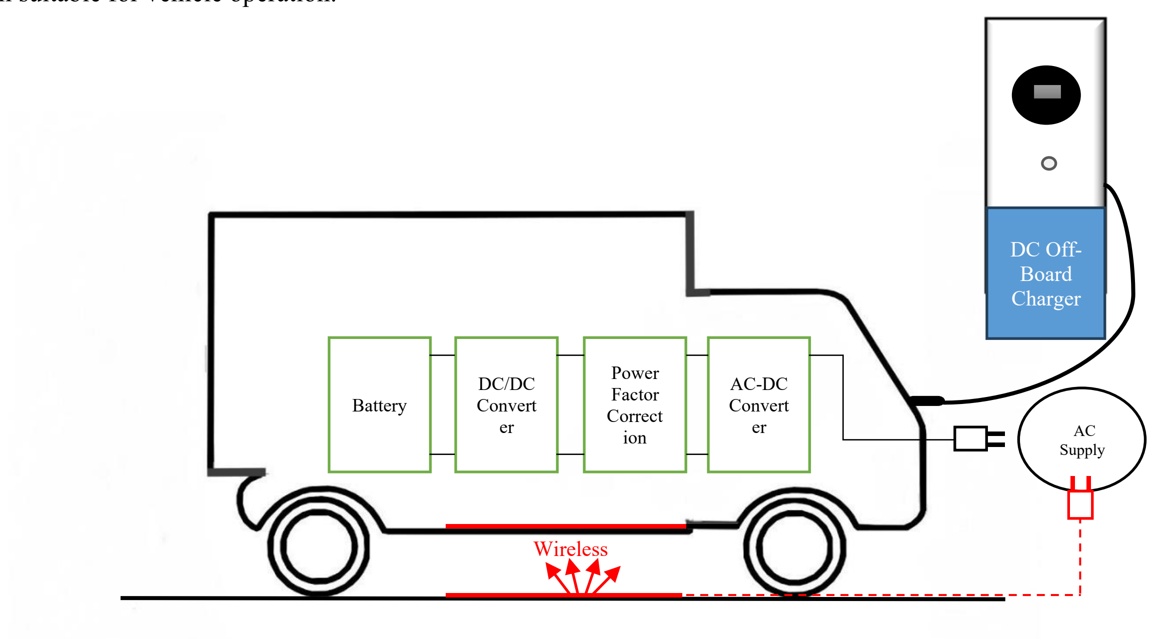

FIGURE 3. Integrated Onboard, Offboard, and Wireless Power Conversion System for a Light-Duty Electric Truck

In ***Error! Reference source not found.*** classification of EV charging systems is given. EV charging systems can be systematically categorized based on various parameters, including the type of power used, the method of energy transfer, charging circuit configuration, physical contact, and power flow direction.

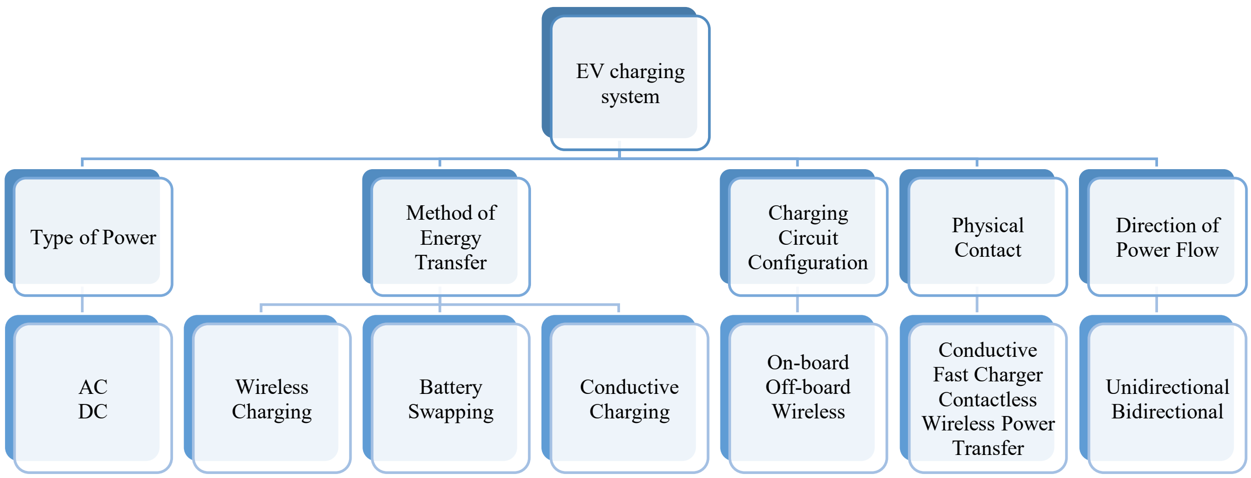

FIGURE 4. Classification of Electric Vehicle Charging Systems

Type of Power. EV charging can be classified into Alternating Current (AC) and Direct Current (DC) charging, where AC charging is commonly used in home and workplace charging, while DC charging is employed for fast-charging applications.

Charging Circuit Configuration. Based on the placement of the charging circuit, EV charging can be classified into on-board charging, where the charger is integrated within the vehicle, and off board charging, where the power conversion occurs externally. Wireless charging falls under this category as well, offering a contactless charging solution.

Physical Contact. Charging systems can be further divided into conductive fast chargers, which establish a direct electrical connection between the vehicle and the charging station, and contactless wireless power transfer, which relies on inductive or capacitive coupling for energy transmission.[23]

Direction of Power Flow. EV charging systems can operate in a unidirectional mode, where power flows only from the grid to the vehicle, or a bidirectional mode, where power can flow in both directions, enabling V2G or V2H applications, contributing to grid stability and energy management.

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Table 1 presents a comparison of AC and DC charging levels for electric vehicles, highlighting key parameters such as voltage, current, power, and estimated charging times based on SEA standards[18, 24]. References [6, 25-27] provide a review of various strategies, algorithms, and methods for implementing a smart charging control system. Additionally, [3, 28, 29] discuss the state-of-the-art EV charging infrastructure, its impact as a significant load on the grid, and the characteristics of fast charging. Furthermore, influential factors affecting the planning and optimization of fast charging stations are examined in [8, 30]

Charging speed and technology significantly impact the efficiency, cost, and feasibility of EV adoption. While slow charging is reliable but time-consuming, fast charging enhances convenience but poses grid stability challenges and requires advanced power management. Wireless charging offers safety and ease of use but remains limited by efficiency and infrastructure costs. Battery swapping, though promising, faces hurdles such as high initial investment and battery standardization. Future advancements should focus on optimizing efficiency, reducing costs, and integrating bidirectional power flow to enhance grid interaction and overall charging effectiveness.

TABLE 1. EV Charging Levels and Specifications for AC and DC Electric Vehicle Charging Systems Based on SAE Standards

Charging Type	Location	Level	Voltage (V)	Max Current (A)	Max Power (kW)	Estimated Charging Time
AC	On-board	Level 1	120 V	12 A	1.92kW	17 h
	On-board	Level 2	240 V	16 A	20 kW	1.2 h
	—	Level 3	—	—	>20 kW	—
DC	Off-board	Level 1	200-500 V	80 A	Up to 20 kW	1.2 h
	Off-board	Level 2	200-500 V	200 A	Up to 80 kW	20 min
	Off-board	Level 3	200-600 V	400 A	>30 kW	Less 10 min

Cost and economic factors. Investment in charging infrastructure is a significant cost consideration for fleet operators, as the establishment of fast-charging stations requires substantial capital. The total investment includes installation expenses, operational costs, and maintenance expenditures [21]. Among these, the cost of extreme fast charging (XFC) installation and equipment plays a crucial role in shaping the business feasibility of this technology [31]. However, financial sustainability is highly sensitive to revenue fluctuations, which have the greatest impact on the feasibility and effectiveness of charging station operations[32]. In [33-35], the economic factors influencing the deployment and operation of EV charging stations are also reviewed.

To mitigate these financial challenges, many regions provide financial support for battery-electric truck charging infrastructure. This support is typically categorized into three primary areas: research and innovation, procurement and installation, and grid connectivity[33]. Despite these efforts, high land leasing costs and uncertainties regarding subsidy availability pose significant obstacles to large-scale charging station deployment. Notably, research suggests that subsidy strategies focused on operational support, rather than upfront capital investment, are more effective in enhancing the financial feasibility of charging facilities [34].

Beyond financial factors, the spatial distribution of charging stations plays a crucial role in determining their overall impact and accessibility. The allocation of charging stations depends on several key variables, including the total number of stations, charging demand at critical intersections, and the probabilistic occurrence of daily charging events[35]. A well-optimized distribution strategy is essential for ensuring efficient infrastructure utilization, minimizing congestion, and supporting the broader adoption of battery-electric trucks.

The successful deployment of charging infrastructure for battery-electric trucks requires a careful balance between financial investment, revenue sustainability, and strategic station allocation. While the high costs of installation, operation, and maintenance pose significant challenges, financial support mechanisms—particularly those focused on operational subsidies—can enhance the economic feasibility of charging facilities. Additionally, revenue fluctuations remain a critical factor influencing long-term viability. Beyond financial considerations, the spatial distribution of charging stations plays a key role in optimizing accessibility and efficiency. Therefore, an integrated approach that combines financial planning, policy support, and data-driven station placement strategies is essential for the sustainable expansion of charging infrastructure.

Environmental and Policy Considerations. Reducing air pollution is a major driver for EV adoption[36]. The environmental impact of EVs largely depends on the energy source used for charging[37]. Charging with electricity generated from renewable sources significantly reduces greenhouse gas emissions and air pollutants. However, if the grid relies on fossil fuels, the environmental benefits of EVs are diminished. Additionally, the charging process itself can strain the grid during peak hours, potentially increasing emissions if fossil fuel backup is used. Therefore, integrating renewable energy, smart charging systems, and energy storage is essential for making the EV charging process truly sustainable. Sustainable EV charging infrastructure requires ecological footprint analysis and economic evaluation[38]. In the study [39]regression analysis of 58 California counties shows that expanding charging infrastructure boosts PEV adoption, reduces emissions, and offers strong benefit-cost outcomes in key areas.

The adoption of electric vehicles (EVs) is rapidly advancing, driven by a combination of policy measures, energy system reforms, and the continuous expansion of charging infrastructure. These efforts are further reinforced by tax incentives, direct subsidies, and the establishment of ambitious national targets aimed at reducing carbon emissions and promoting sustainable mobility. China, in particular, has emerged as a global leader, possessing the highest number of publicly available charging stations[40]. In addition to government interventions, several key factors significantly influence the growing adoption of EVs. These include the purchase cost of electric vehicles, their relatively low maintenance requirements, the availability and accessibility of charging stations, and the duration of the charging process. Together, these elements form a comprehensive framework that shapes consumer behavior and market dynamics, highlighting the critical role of integrated policy and infrastructure development in accelerating the transition to electric mobility.

An effective policy framework should not only promote the initial adoption of EVs and the expansion of charging infrastructure but also aim to establish the long-term sustainability of the EV market beyond the period of government incentives. While subsidies remain the most widely recognized form of support among the public[41]. a more comprehensive approach—including the standardization of high-speed charging systems and targeted subsidies for both charging costs and infrastructure deployment—is essential for sustained EV growth[42]. Government-led incentive strategies play a pivotal role in accelerating EV adoption. These policies contribute significantly to the broader development of smart cities by fostering industrial advancement and creating an enabling environment for widespread EV integration[43].

The adoption of EVs is closely linked to environmental goals and policy support. While EVs offer significant potential to reduce emissions, their true environmental benefits depend on charging with renewable energy. Sustainable charging infrastructure requires smart grid integration, energy storage, and ecological and economic evaluations.

Effective policy frameworks—combining subsidies, tax incentives, and infrastructure development—are essential to accelerate adoption and ensure long-term market sustainability. Standardizing high-speed charging and promoting equitable access are also key. Global examples, such as China and California, demonstrate the importance of coordinated strategies in advancing EV integration and supporting the broader goals of smart, low-carbon urban development.

CONCLUSIONS

The adoption of EVs is a key step toward achieving sustainable and low-emission transportation systems. However, this shift requires coordinated advancements in charging infrastructure, grid integration, and charging technologies. Delays in station construction, grid instability due to uncontrolled charging, and economic constraints remain critical challenges. Controlled charging strategies and bidirectional power flows (V2G, V2H, V2B) offer promising solutions to manage energy demand and improve grid performance. Financial sustainability, supported by operational subsidies and optimized station distribution, is essential for long-term infrastructure success. Ultimately, comprehensive policy frameworks and smart planning are vital to ensure the effective, efficient, and equitable integration of EVs into modern energy and transportation networks.

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