

Review

Electric Vehicle Charging Infrastructure: Impacts and Future Challenges of Photovoltaic Integration with Examples from a Tunisian Case

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Abstract

The challenges of global warming and other environmental concerns have prompted governments worldwide to transition from fossil-fuel vehicles to low-emission electric vehicles (EVs). The energy crisis, coupled with environmental issues like air pollution and climate change, has been a driving force behind the development of EVs. In recent years, EVs have emerged as one of the most innovative and vital advancements in clean transportation. According to recent reports, EVs are gradually replacing traditional automobiles, offering benefits such as pollution reduction and the conservation of natural resources. This research focuses on analyzing and reviewing the impact of EV integration on electrical networks, with particular attention to photovoltaic (PV) energy as a sustainable charging solution. It examines both current and anticipated challenges, especially those related to power quality, harmonics, and voltage imbalance. A special emphasis is placed on Tunisia, a country with high solar energy potential and increasing interest in EV deployment. By exploring the technical and infrastructural readiness of Tunisia for PV-based EV charging systems, this paper aims to inform regional strategies and contribute to the broader goal of sustainable energy integration in developing countries as part of future work.

Keywords: electric vehicles (EVs); climate change; economic; renewable energy; impact; challenges; power quality; voltage imbalance; harmonics



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1. Introduction

The sectors of transportation and electricity production are fundamentally connected to some of the most pressing challenges of the 21st century: peak oil, climate change, and energy independence. Together, these sectors account for over 60% of the world's primary energy demand, with most of the global coal consumption dedicated to electricity generation and most of the global oil consumption driven by transportation needs [1].

To address these challenges, alternative vehicle technologies, including EVs, are in progress to minimize global reliance on oil for mobility and to control the CO₂ emissions

linked to this sector. Similarly, the advancement and deployment of renewable energy sources (RESs) aim to replace fossil fuel-based power generation, thereby decreasing greenhouse gas emissions (GHGs) and reducing other pollutants, such as nitrogen oxide and sulfur dioxide. The emergence of the mobility and electricity sectors, driven by the adoption of EVs and RESs, offers substantial potential to lower global dependence on fossil fuels and mitigate GHGs [2].

Recent advancements in energy system integration have explored various strategies to enhance sustainability, grid stability, and urban decarbonization. In [3], the authors proposed a novel Community-to-Vehicle-to-Community service, where EVs act as mobile energy carriers between different communities. They introduced an advanced smart charging/discharging control that optimizes energy delivery based on inter-community power balances, demonstrating that larger EV fleets and batteries improve performance, especially in RES-rich workplaces. Complementarily, in [4], a global optimal control strategy was developed for chilled water plants incorporating small-scale stratified thermal energy storage tanks. The control scheme, which adjusts chiller operations and storage tank flows, achieved up to 7.67% energy savings under varying climate conditions. In the domain of urban transportation, Reference [5] suggested a cost-efficient deployment of rooftop solar PV and batteries to power electric buses in high-density cities. Using a hybrid GA-ILP approach combined with 3D-GIS and deep learning models, the strategy achieved an optimal system payback period of 3.98 years while effectively minimizing grid stress. Further addressing urban PV deployment challenges, Reference [6] proposed an integer learning programming strategy for municipal-scale PV planning. The method, tested on 582 rooftops, outperformed heuristic approaches by up to 23.3%, optimizing energy generation under budget and export constraints. Lastly, in [7], a comparative study of EV fleet charging control mechanisms highlighted that top-down coordination offers superior peak shaving and solar utilization benefits, though at the cost of higher computational complexity. Together, these studies provide a multidimensional perspective on integrating EVs, renewables, and storage systems into future smart energy infrastructures.

Using EV is steadily rising. The integration of EV chargers and RES is fundamental in diminishing the reliance on fossil fuels and represents a natural evolution in energy infrastructure [8]. However, the nonlinear nature of EV charging loads increases transformer temperatures and associated losses, ultimately reducing transformer lifespan. During EV battery charging, the nonlinearity of certain loads generates total harmonic distortion (THD) in the charging current, which affects the power quality of the distribution network [9]. To address these issues, active power filters and FACTS devices—such as shunt and series active power filters, dynamic voltage regulations, and unified power quality conditioners—are commonly employed. Power quality challenges, including increased neutral currents, reactive power demands, and THD, are exacerbated by high frequency switching in AC/DC systems. Numerous studies have explored power quality concerns and their impact on the grid [10–12].

An EV battery charger, equipped with one-owner electronic circuits and appropriate converters, is applied to transform AC power into DC for battery charging at designated voltages. This process introduces nonlinearity in the network, resulting in THD in both grid voltage and current [13]. The presence of THD causes several negative effects, including higher insulation temperatures, reduced insulation lifespan, lower power factors, decreased performance and greater heat generation [14–23].

Uncontrolled connection and disconnection of EVs to the network can cause voltage imbalances, which may increase the charge of voltage correction materials. Additionally, switching losses in the AC-DC converters of EV charging stations contribute to overall power losses [24]. Among all grid components, distribution transformers are especially

susceptible to failures when EVs are integrated into the system. Harmonic levels in EVs can range from 3% at the start of charging to approximately 28% at the end [25,26]. Beyond charging, enhanced grid integration of EVs involves addressing various electricity quality challenges. Research on EV charging and its impact on power grids provides valuable insights for stakeholders to develop mitigation strategies and implement technologies to minimize negative effects on power distribution systems. This work reviews multiple studies to highlight the effect of EV charging in the network and recommend measures for improvement.

This paper provides a comprehensive review of the integration of EVs into the power grid, with a particular emphasis on the impacts and challenges associated with PV integration. The main contribution of this work lies in analyzing the technical barriers related to power quality, voltage imbalance, and harmonics, and presenting the most relevant mitigation strategies drawn from the recent literature. Furthermore, it contributes a regional perspective by focusing on the context of Tunisia as a country with significant solar energy potential and growing interest in clean transportation. By addressing the specific opportunities and limitations of PV-based EV charging infrastructure in Tunisia, this work aims to support national efforts toward sustainable energy transition and provide insights applicable to other developing countries with similar profiles.

Several review articles have previously examined the integration of EVs with photovoltaic systems, addressing topics such as system architecture, environmental impact, and smart charging technologies [27–30]. However, these studies are largely centered on developed countries with robust grid infrastructure and established policy frameworks. In contrast, the originality of this manuscript lies in its dual-layered perspective: it not only explores the global technical challenges of PV-EV integration, such as power quality disturbances, harmonics, and supraharmonics, but also contextualizes these issues within the emerging energy landscape of Tunisia. The paper uniquely integrates advanced energy management strategies (EMSs), regulatory gaps, and socio-economic factors specific to North African regions. By focusing on Tunisia as a case study, this work aims to fill a significant gap in the literature and provide practical guidance for implementing scalable, sustainable, and technically resilient EV charging infrastructure in solar-rich developing nations.

Specifically, we recognize that the limited availability of comprehensive real-world data from Tunisia constrains the ability to fully validate modeling assumptions and forecast precise impacts of PV-based EV charging infrastructure in this context. This scarcity reflects the nascent stage of EV adoption and RES integration in the region, which also affects the granularity and reliability of grid performance data.

Furthermore, we discuss the challenges inherent to scaling PV-based charging infrastructure in developing regions, including financial constraints, regulatory and policy barriers, and infrastructural deficits. These factors collectively pose significant hurdles to widespread deployment and long-term sustainability. We emphasize that these limitations highlight the critical need for targeted pilot projects, enhanced data collection, and policy frameworks to support scalable and resilient infrastructure development.

This study's methodology uniquely advances the current literature by focusing on the integration of photovoltaic-based EV charging within the specific context of Tunisia's developing grid infrastructure, which faces distinctive challenges in harmonics and voltage imbalance due to limited deployment of advanced storage and smart grid technologies. Unlike prior works that primarily address these issues in mature grid systems, our approach jointly considers the nonlinear impact of EV charging loads and the variability of PV generation, including the often-overlooked supraharmonic distortions caused by high-frequency switching in converters. Furthermore, we evaluate advanced mitigation techniques such as

particle swarm optimization and genetic algorithms tailored for practical implementation in resource-constrained environments, complemented by an analysis of socioeconomic and regulatory factors that influence technical feasibility. This integrated and region-specific perspective provides novel insights into power quality management for PV-EV systems in emerging markets, setting this work apart from earlier studies.

Recent advances in PV technology, Vehicle-to-Grid (V2G) systems, and smart charging algorithms have significantly accelerated the potential for sustainable EV infrastructure. Improvements in PV panel efficiency and cost reduction have made solar energy integration increasingly viable. Concurrently, innovative V2G implementations enable bidirectional energy flows, enhancing grid stability and providing ancillary services. Moreover, adaptive smart charging algorithms, often leveraging artificial intelligence and real-time data analytics, optimize charging schedules to balance grid load and user convenience.

The remainder of this paper is organized as follows: Section 2 provides a comprehensive overview of EVs and their classification. Section 3 discusses the current challenges in PV integration within EV charging infrastructure, emphasizing technical, economic, and social aspects. Section 4 elaborates on the interaction between EVs and the power grid, identifying major impacts on power quality such as harmonics, voltage imbalance, and transformer aging. Section 5 focuses on the role of PV systems in EV charging, highlighting technical integration challenges, including variability in solar generation and bidirectional V2G technologies. Section 6 analyzes economic and environmental impacts of PV-based EV charging infrastructure, with a particular focus on emerging markets. Section 7 explores the impact of RES integration on grid stability and infrastructure modernization. Section 8 outlines future directions, policy recommendations, and regulatory considerations, with an in-depth emphasis on the Tunisian context, addressing the unique challenges and opportunities faced by developing countries in scaling PV-powered EV charging solutions. Finally, Section 9 concludes the paper by summarizing key findings and proposing avenues for future research, including advanced energy management strategies and integrated urban planning for sustainable mobility–energy ecosystems.

2. Present Challenges in Photovoltaic Integration for EV Charging Infrastructure

To ensure a comprehensive and focused review, we adopted a semi-systematic literature selection methodology. Relevant academic publications were identified using major databases such as IEEE Xplore, ScienceDirect, Scopus, and Web of Science. The search included studies published between 2015 and 2024, with a particular focus on peer-reviewed journal articles, high-impact conference proceedings, and authoritative reports. Key search terms included PV-EV charging, V2G, power quality, harmonics, EMS optimization, smart charging, and “grid stability in renewable energy systems.” Priority was given to sources addressing technical, economic, and regulatory challenges associated with PV-EV integration. Preference was also given to studies that included simulation models, quantitative metrics, or region-specific insights, particularly those relevant to developing countries with solar-rich environments such as Tunisia, Morocco, Egypt, and India. In total, more than 100 sources were initially screened, with approximately 60 selected for detailed analysis based on their relevance, citation impact, and contribution to the thematic structure of this review.

The integration of PV systems with EV charging infrastructure presents numerous present-day challenges that must be addressed to achieve efficient, reliable, and widespread deployment. From a technical perspective, the intermittent and variable nature of solar energy leads to fluctuations in power supply, causing voltage instability and power quality issues such as harmonic distortion and voltage imbalance in the distribution network.

These effects are exacerbated by the nonlinear loads introduced by EV chargers, which can accelerate transformer aging and reduce grid reliability. Additionally, managing bidirectional energy flows with V2G technology introduces complexities in grid coordination and real-time energy management.

Economically, the high upfront capital investment for PV arrays, energy storage systems, and advanced power electronics remains a significant barrier, especially in developing regions with limited financial resources. The lack of clear and supportive regulatory frameworks, including standardized interconnection protocols and permitting procedures, further complicates deployment efforts and delays project implementation. Social challenges such as public acceptance, site selection constraints due to urban planning or heritage preservation, and limited awareness about PV-powered EV charging benefits also hinder adoption.

Moreover, the rapid increase in EV adoption strains existing grid infrastructure, often designed without consideration for high penetration of distributed renewable energy sources. This calls for grid modernization efforts incorporating smart energy management systems, advanced forecasting, and adaptive control strategies. Finally, coordination among multiple stakeholder's utilities, policymakers, consumers, and manufacturers is essential to overcome these challenges and create economically viable, environmentally sustainable, and socially acceptable PV-based EV charging solutions.

Addressing these present challenges requires a multidisciplinary approach combining technological innovation, policy development, economic incentives, and community engagement to enable the transition toward a cleaner and smarter transportation–energy ecosystem.

One of the primary technical challenges in integrating PV systems with EV charging infrastructure is the inherent variability and intermittency of solar generation. Fluctuations in solar output due to weather conditions cause voltage instability and power quality issues on the distribution grid, necessitating advanced forecasting and adaptive energy management strategies to maintain reliability. Additionally, battery degradation poses a significant concern, as frequent fast charging and irregular charging cycles accelerate the aging of EV batteries, impacting their lifespan and performance. To mitigate these effects, smart charging algorithms that optimize charge rates and scheduling based on battery health and grid conditions are essential. Grid impact mitigation strategies further include deploying energy storage systems to buffer PV variability, employing advanced inverter technologies for harmonic compensation, and utilizing V2G systems to balance load and provide ancillary services, thereby enhancing overall grid stability and resilience.

Figure 1 illustrates a practical implementation framework designed to address the challenges discussed above. The system integrates PV panels, a battery bank, and a fast DC charger connected via a common DC bus to facilitate reliable and efficient EV charging. The DC-DC converters condition the variable outputs from the PV panels and battery storage before delivering energy through a centralized DC bus. This structure enhances system flexibility, supports bidirectional energy flow, and enables real-time energy management using V2G technology. An inverter interfaces the system with the main AC grid, ensuring stability and enabling surplus solar energy to be injected back into the grid when appropriate. By incorporating both renewable generation and energy storage, the configuration mitigates power quality issues, buffers solar intermittency, and supports smart charging operations directly responding to the technical and operational challenges previously outlined.

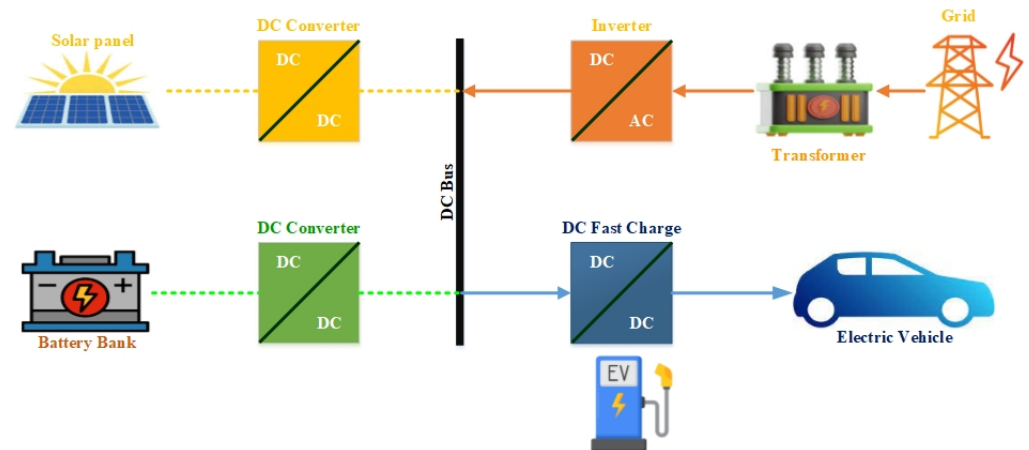


Figure 1. Architecture of a PV-Based EV charging system with grid and battery integration [27].

3. Economic Impacts

The economic implications of EV are generally examined from two main viewpoints: the individual vehicle owner and the broader electricity network. With ongoing improvements in battery technology and the expansion of large-scale manufacturing, the overall cost-effectiveness of EVs is expected to improve over their lifecycle. At present, battery electric vehicles (BEVs) are more expensive to purchase than plug-in hybrid electric vehicles (PHEVs), and both are costlier than traditional internal combustion engine vehicles (ICEVs) [31]. However, EVs benefit from significantly lower fuel and operating charge because of the remarkable performance of electric motors.

The economic feasibility of PV-based EV charging infrastructure hinges on balancing initial capital costs such as PV panels, energy storage, and charging stations with long-term savings from reduced energy consumption and lower operational expenses. While upfront investments remain substantial, declining PV and battery prices are shortening payback periods; studies indicate payback times dropping from over 20 years currently to under 5 years by 2035 in favorable markets [32]. Furthermore, implementing smart charging and integrating renewables enhances cost-effectiveness by optimizing energy use and minimizing grid stress. Policy incentives including subsidies, tax credits, and streamlined permitting are critical to lowering financial barriers and accelerating deployment, particularly in developing regions like Tunisia where supportive frameworks are still emerging. Innovative financing models and public–private partnerships also offer pathways to improve accessibility and investment appeal, fostering wider adoption of sustainable EV charging solutions.

Ref [33] predicts that the recovery period for a BEV, compared to a less expensive ICEV, is presently around 20 years; nevertheless, it is expected to dip to under 5 years by 2035. Similarly, ref. [34] supports this trend, while [35] predicts that the overall lifetime ownership investment for all vehicle types will align by 2035.

Usually, integrating EVs into the grid increases system charge because of elevated fuel consumption and transmission inefficiencies. Nevertheless, the choice of charging methods has a significant impact on overall system charge. Ref. [36] estimated a system charge of EUR 263 per vehicle per year in Denmark using a basic charging plan, whereas intelligent charging reduced this cost to EUR 36 per vehicle per year, resulting in savings of EUR 227 per vehicle annually. Similarly, ref. [37] found that intelligent charging could save USD 200,000 per week against the basic charging in a perspective Illinois power grid with a substantial wind energy contribution. In [38], authors calculated the financial system gains for the PJM and Midwest ISO (MISO) markets in the U.S., revealing that off-peak charging reduction cost versus on-peak charging depend heavily on the district energy

generation mix. In MISO, where there is excess coal generation capacity, smart charging provides smaller reduction charge. Conversely, in PJM, where reliance on costly natural gas peaking plants is high, smart charging yields much larger savings. Research of the network in Spain proved that the additional charge of electricity declines until a certain level of EV adoption is reached, after which it increases slightly [39].

An increasing number of studies have evaluated the economic viability of V2G participation across different market contexts [40–42]. Reported annual outcomes vary widely from losses of approximately USD 290 per vehicle to gains exceeding USD 4600. Nonetheless, most results fall within a profit range of USD 100 to USD 290 per year. Despite these potential gains, such margins may be insufficient to attract individual users or aggregator entities. As governmental efforts continue to encourage the adoption of EVs and V2G based energy services, key challenges persist in determining the most effective strategies for promoting engagement and ensuring optimal system integration.

4. Environmental Impacts

CO₂ emissions are widely adopted indicators to evaluate the environmental impact of transitioning to EVs generated by the grid. Ref. [43] estimated that integrating the electricity and transportation sectors in Denmark leads to an 85% reduction in transportation-related CO₂ emissions. Several studies have highlighted that using EVs leads to a reduction in CO₂ emissions compared to ICEVs, even when wind energy is not part of the generation mix [44].

A comprehensive evaluation of the sustainability benefits of PV-based EV charging infrastructure requires consideration of lifecycle assessments (LCA) of the integrated systems. LCAs analyze environmental impacts across all phases from raw material extraction and manufacturing of PV panels and EV charging equipment to operational use and end-of-life recycling or disposal. Recent studies demonstrate that although PV systems entail embodied energy and emissions during production, their deployment in EV charging significantly reduces net greenhouse gas emissions over the system's lifetime compared to conventional fossil-fuel-based charging. Energy payback times for modern PV installations typically range between 1 and 4 years, depending on technology and location, supporting their long-term environmental advantages. Furthermore, advances in PV recycling and durable system designs contribute to minimizing ecological footprints. Incorporating such lifecycle perspectives strengthens the argument for PV-EV infrastructure as a key enabler of sustainable transportation and energy transitions.

Studies conducted in Virginia and the Carolinas regions where fossil fuel-based power plants constitute nearly two-thirds of electricity generation demonstrated that even basic EV charging strategies can lead to a reduction in CO₂ emissions of around 10% compared to conventional gasoline-powered vehicles [45]. In a separate analysis, ref. [46] examined a combined wind and thermal power system, revealing that under a simple charging scheme, there was a slight rise in CO₂ emissions; they decreased with intelligent charging and V2G integration. In China, CO₂ reductions from EV use were observed across three regions, even in areas heavily dependent on coal power [47].

A key point of discussion in the literature is the emission intensity (gCO₂e/kWh) assigned to electricity used for EV charging. Numerous studies adopt the typical grid emission rate, which assumes widespread EV adoption and integration into the regular demand profile. However, some researchers argue for using marginal intensity, where the emissions from the marginal generation unit (often a natural gas or coal plant during peak demand) are attributed to the electricity consumed by EVs, leading to higher carbon emissions. Despite this, works that apply the differential mix still find a net reduction in carbon emissions when using EVs as compared to ICEVs [48–50]. Overall, EVs contribute

to a reduction in CO₂ emissions, even in electricity systems dominated by fossil fuel generation, because of the performance of electric motors over ICEVs.

5. Impact of EVs on the Grid

Table 1 elaborates a summary of the impacts of EV integration on the power grid. In [51], the researchers investigated how Time-of-Use (ToU) pricing affects EV charging behavior within the electricity distribution network. As EV charging contributes to increased grid demand, ToU pricing serves as an effective strategy to reschedule charging to off-peak periods. The study demonstrated that implementing ToU tariffs can influence user behavior, leading to a reduction in peak load by up to 5%. Additionally, research in [52] introduced a compensation-based technique to mitigate harmonic distortion caused by EV charging, successfully decreasing THD from 4.88% to 4.03%.

Table 1. Impact EV integration on the grid.

Reference	Parameter	Description
[51]	ToU rates	Peak-load ToU rates led to a 5% reduction in peak demand.
[52]	Harmonics	An active compensation-based harmonic minimization approach decreased THDI caused by EV charging from 4.88% to 4.03%.
[53]	Voltage, transformer	Effect of uncontrolled charging, intelligent and V2G strategies on a domestic electrical grid in the Netherlands.
[54]	domestic demand of load	The real-world assessment of the grid effect from in-home EV charging varied from the forecasts provided by current simulation models, mainly due to factors like consumer behaviors.
[55]	Harmonics, voltage	With 1 EV, 20.30% of THD is generated; low voltage is observed when multiple EV chargers are related to the same phase.
[56]	Load demand, power losses, voltage profile	A pioneering model to provide the profiles of EV charging needs in Saudi Arabia and to examine the effect of charging on the grid.
[57]	Compensation for discharging	Bottleneck model evaluating the trade-off between waiting time costs and the benefits from discharging.
[58]	Tariff, peak power, carbon footprint	By implementing residential intelligent charging, the end-of-day peak load for EVs can be decreased by 30% to 50%.
[59]	Voltage profile, harmonics, stability, power quality factor, voltage profile	EVs are represented as variable loads and employed as adaptable energy units. Simulated the effect of EV chargers on the low-voltage domestic network.
[60]	Load demand, frequency	Nonlinear EV loads are linked to various phases, resulting in phase imbalance within the network. This imbalance can be minimized through effective grid planning. The switching of EV chargers may influence the power factor, which can be addressed through reactive power compensation.
[61]	Voltage profile, power quality,	Adding EV load to the already constrained section in the grid and unsystematic charging could negatively affect the seamless operation of the grid.
[62]	Voltage profile, transformer Loading,	Line and transformer overloading would occur when the proportion of EVs exceeds 20% in the grid of Norway.

Table 1. Cont.

Reference	Parameter	Description
[63]	Load demand, waiting time in the charging station	The charger placement issue was modeled using a game theory approach, and the effects of charger placement on load demand and waiting times at charging points were analyzed.
[64]	Load demand, frequency deviation	An adaptive particle swarm optimization (PSO)-based management technique minimized EV charging power, accounting for the net charging power need and frequency fluctuations, to guarantee the stable operation of the grid.
[65]	Harmonics, thermal limit, peak load	The voltage profile of the buses of the distribution grid was elevated as it increased to assess the capacity of the buses at specific THD levels.
[66]	Voltage sag, load demand, power quality	The domestic grid voltage sag decreased from approximately 1.96% to 1.77%, remained at 2.21%, decreased from 1.96% to 1.52%, and remained at 1.93% across the four EV-charging profiles.

The effect of EV chargers on residential voltage distribution networks was examined in [53], adopting online-world data from public chargers in the Netherlands. The study considered three charging strategies: uncontrolled, intelligent, and bidirectional V2G. Results showed that while network performance remained acceptable even with a high EV density per charger, excessive EV connections to a single charger led to increased wait times and user dissatisfaction. Additionally, smart charging approaches were found to elevate transformer load levels.

In [54], researchers evaluated the ecological effect of domestic EV charging in Arizona, USA, based on smart meter data from approximately 1600 homes. Findings indicated a 7–14% increase in residential load during summer peak hours (6–8 p.m.). Most households responded to ToU pricing by shifting charging to off-peak periods. However, discrepancies between actual grid impact and simulation models highlighted the importance of consumer behavior in forecasting.

Ref. [55] explored the effect of EV charging on harmonics. The authors noted that as the number of EVs increased, so did the THD, from 20.30% with one EV to 27.56% with three. Voltage drops were also noted when multiple EVs were connected to the same phase.

In [56], a new method for modeling EV charging demand was proposed, incorporating driving behavior, energy use, and charging schedules. This model was applied to Saudi Arabia's grid to simulate the impact of EV charging on the electricity distribution system.

Reference [57] introduced a bottleneck model to assess the trade-off between waiting time and the benefits of discharging EVs via V2G. The study quantified both the delays caused and the potential energy gains from bidirectional discharging.

The benefits of smart charging were further discussed in [58], which showed that peak evening loads could be reduced by 30–50% with at-home smart charging. Moreover, workplace charging could achieve a 10% reduction in carbon emissions through valley filling.

In [59], EVs were modeled as mobile, flexible loads, and their impact on voltage stability, power quality, and harmonics was assessed. The study emphasized the potential of EVs to serve as grid support resources.

Reference [60] assessed the readiness of existing systems for widespread EV integration. Simulations on a low-voltage (LV) residential grid revealed issues like transformer

overloading, power factor degradation, voltage drops, and phase imbalance due to uneven EV load distribution. For this, the authors proposed improved grid planning and reactive power compensation to mitigate these issues.

Authors in [61] used data from urban Indian distribution networks to evaluate how EV charging affects voltage profiles and power quality. They concluded that uncoordinated charging, particularly at weak points in the grid, could destabilize operations.

Study [62] analyzed various charging scenarios—uncontrolled, coordinated without constraints, and coordinated with network limitations—for the Norwegian grid. It was found that EV penetration exceeding 20% could overload lines and transformers.

Using a game-theoretic approach, the authors of [63] examined how charger placement influences load demand and waiting time, using the city of Guwahati in India as a case study.

In [64], a self-learning PSO method was proposed to control EV charging power, optimizing both load demand and frequency deviation to maintain grid stability.

Reference [65] investigated the impact of increasing EV loads on Qatar's distribution network through Simulink simulations, focusing on voltage profile changes and harmonic distortion at different EV penetration levels.

Lastly, in [66], the authors studied the effects of fast charging on low-voltage networks, considering variables like charging time and vehicle characteristics. Results showed notable voltage sags ranging from 1.77% to 2.21% across different charging profiles.

Impact on Power Quality

The evaluation of the grid network primarily involves assessing the characteristics of power delivery. Uncertainty in electric vehicle charging introduces several issues, such as grid overvoltage, power quality degradation, increased risk of line damage, and a higher incidence of current faults. The grid's vulnerability to harmonics is due to the use of high-frequency converters, which are necessary for converting AC electricity into DC power for EV charging. These harmonics may bring overloads in distribution transformers, ultimately shortening their lifespan [67,68].

Harmonics refer to the sinusoidal components of a periodic waveform whose frequency is an integer multiple of the fundamental power frequency [69]. Power waveform harmonic distortion arises when a mixture of the first-, second, third, and higher-order harmonics is present. The non-sinusoidal voltage and current waveforms are represented by Equations (1) and (2):

$$v(t) = v_{dc} + \sum_{n=1}^{n_{\max}} v_{rms}^n (\cos nw_0(t) + \phi_n) \quad (1)$$

$$i(t) = i_{dc} + \sum_{n=1}^{n_{\max}} i_{rms}^n (\cos nw_0(t) + \phi_n) \quad (2)$$

In this context, n represents the harmonic order, w_0 denotes the fundamental frequency, and ϕ_n indicates the phase shift in voltage and current for the harmonics. The components of Total Harmonic Distortion (THD) help calculate the effective value of harmonic content in a distorted waveform, enabling the quantification of harmonic components present in such waveforms [70]. THD can be given as a percentage for both voltage and current.

$$THD_i = \frac{\sqrt{\sum_{n=2}^{n_{\max}} i_n^2}}{i_1} \quad (3)$$

$$THD_v = \frac{\sqrt{\sum_{n=2}^{n_{\max}} v_n^2}}{v_1} \quad (4)$$

Supraharmonics describe distortions in current waveforms that arise within the frequency band of 2 kHz to 150 kHz. The rapid expansion of EVs and their associated charging systems, particularly those utilizing power electronic converters functioning at frequencies higher than 2 kHz, has led to a notable increase in supraharmonic disturbances affecting both current and voltage profiles [71]. These high-frequency anomalies can interfere with the performance of sensitive equipment in smart grid environments and contribute to elevated thermal stress, ultimately reducing the operational lifespan of such devices [72].

Because EVs typically require high-power charging and are more susceptible to supraharmonic distortions than other consumer electronics, their impact is especially noticeable in low-voltage installations. Supraharmonics can cause various detrimental effects on low-voltage networks and the electronic devices connected to them. In networks with high impedance, the system current often contains significant supraharmonic devices, which can further intensify voltage distortion [73].

To complement the qualitative assessment, quantitative evaluations have shown that harmonic distortion caused by EV chargers can reach THD levels of up to 27.5% when multiple units operate simultaneously on the same phase. This is particularly critical during fast-charging sessions, which intensify the generation of higher-order harmonics and supraharmonic frequencies. Temporal analyses indicate that THD values fluctuate throughout the day, peaking during high-demand evening hours. Voltage fluctuations of ± 5 –7% have also been observed in low-voltage distribution feeders under uncontrolled charging scenarios. Simulation studies using MATLAB/Simulink confirm that employing multistage charging topologies with active power filters can reduce THD by up to 65%, bringing it below the 5% IEEE 519 recommended threshold. Moreover, harmonic compensation using advanced inverter control strategies—such as synchronous reference frame (SRF) and instantaneous reactive power theory (p-q)—effectively stabilizes voltage and mitigates current distortion in real-time. These findings highlight the necessity of combining hardware-based solutions (e.g., passive/active filters) with algorithmic controls to ensure grid stability and power quality in high-EV-penetration contexts.

6. Status and Progress of EV Deployment and Renewable Energy Worldwide

6.1. EV Adoption Statistics

This section presents the latest global statistics on EV sales, market share, and charging infrastructure from 2021 to early 2025, based on data from authoritative global sources [74–78]. In 2021, global EV sales approached 6.6 million units, accounting for about 9% of total car sales. This number rose sharply to 10 million in 2022 and further to nearly 14 million in 2023, representing 18% of global car sales. By 2024, EV sales exceeded 17 million, and early 2025 figures show continued momentum, with 1.8 million units sold globally in January alone, a 17.7% increase compared to January 2024. China leads the market with over 60% of global EV sales in 2023, followed by Europe and the United States. In terms of models, the Tesla Model Y was the best-selling EV in 2022, but by 2024, BYD, a Chinese manufacturer, surpassed Tesla in overall EV deliveries. Alongside sales, EV infrastructure has expanded rapidly. By 2023, the number of public charging points worldwide approached 4 million, with China alone accounting for 70% of them. The ratio of EVs per public charging point was most favorable in China (fewer than 10 EVs per charger), while countries like Norway continued to report high EV-to-charger ratios due to strong adoption rates. Projections indicate that by 2030, the global demand for public

chargers is expected to exceed 15 million units. Overall, the global EV ecosystem, both in vehicle deployment and supporting infrastructure, has shown robust and accelerating growth between 2021 and 2025, driven by policy support, consumer demand, and advances in technology.

Figure 2 presents a comparative analysis of EV market statistics across nine countries for the years 2024–2025, focusing on BEV sales, PHEV sales, and the corresponding EV market share as a percentage of total new vehicle registrations. The chart reveals that Germany, the United Kingdom, and France lead in both BEV and PHEV adoption, with Germany achieving the highest number of BEV registrations (approximately 380,000) and the UK recording the largest market share (close to 20%). In contrast, Japan and Korea show moderate EV penetration, with relatively lower sales volumes and market shares, below 10%. Canada demonstrates steady progress, with a balanced mix of BEV and PHEV sales and an EV share around 10%. Notably, North African countries Tunisia, Egypt, and Morocco remain at an early stage of adoption, with minimal sales and market shares below 1%, reflecting infrastructural limitations and policy gaps. Overall, the figure underscores the global disparity in EV adoption and highlights the urgent need for supportive policies and infrastructure development in emerging markets.

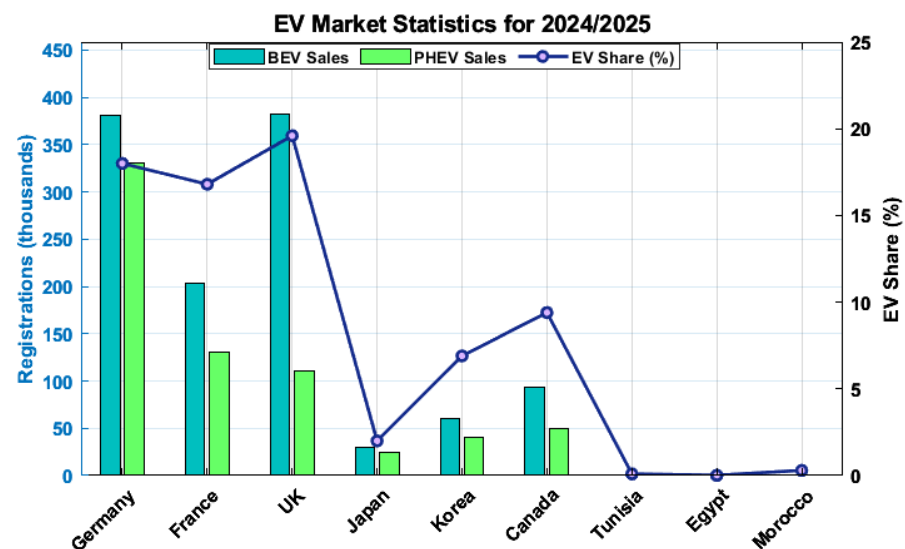


Figure 2. EV market statistics for 2024–2025 [79].

Figure 3 illustrates the global sales performance of the top electric vehicle (EV) models in the years 2024–2025. The data highlights a significant dominance by Tesla and BYD in the global EV market. The Tesla Model Y leads all models with approximately 1.15 million units sold, followed by the Tesla Model 3 with 620,000 units, reflecting Tesla's strong brand recognition, wide market reach, and consistent production scale. Chinese manufacturer BYD occupies the next three positions with its Song Plus EV (570,000 units), Qin Plus EV (510,000 units), and Dolphin (490,000 units), showcasing the company's rapid rise and competitiveness in both domestic and international markets. In the mid-range, the Volkswagen ID.4 recorded 280,000 units, followed by the Hyundai Ioniq 5 (250,000), Kia EV6 (210,000), BMW i4 (190,000), and Audi Q4 e-tron (180,000), indicating solid sales performance among established European and Korean automakers. This figure underscores a market trend where Tesla and BYD dominate the EV sector, while legacy manufacturers are gradually scaling their production and adoption rates. The strong presence of BYD models further emphasizes China's pivotal role in the global transition to electric mobility.

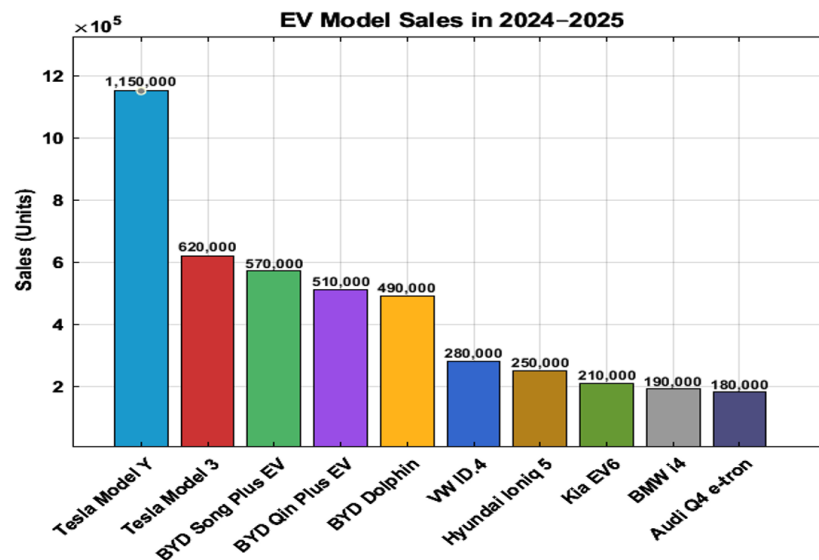


Figure 3. EV model sales in 2024–2025 [80].

Figure 4 presents the evolution of the global availability of fast public EV chargers between 2020 and 2025, highlighting regional disparities and growth trajectories in charging infrastructure. The data shows that China leads the world by a considerable margin, with the number of fast chargers increasing from 310,000 in 2020 to a projected 1,000,000 units in 2025, indicating a strong national policy emphasis on charging accessibility and EV support infrastructure. In contrast, Europe exhibits steady growth, from 40,000 chargers in 2020 to 130,000 in 2025, reflecting coordinated EU efforts to meet the rising demand for electrified transport. The United States shows moderate progress, growing from 20,000 to 55,000 chargers over the same period, which suggests that while EV adoption is increasing, infrastructure expansion is comparatively lagging. Other countries, a category representing regions outside the top three, have doubled their charger counts from 15,000 in 2020 to 40,000 in 2025, showing a slower but positive trend in global electrification. Overall, the figure underscores a global acceleration in fast charger deployment, driven primarily by China, with other regions scaling up efforts at varying rates. It also emphasizes the critical importance of infrastructure development in supporting the broader transition to electric mobility, especially in regions still at early stages of EV market maturity.

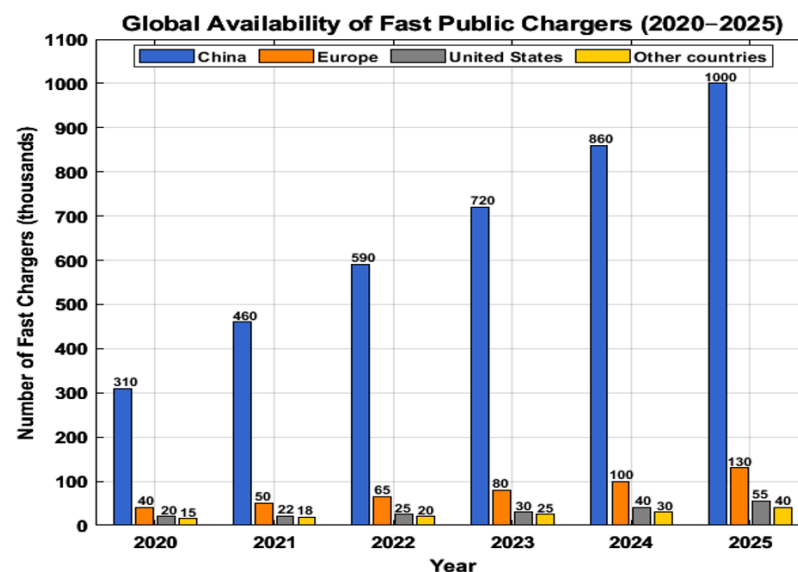


Figure 4. Global availability of fast public chargers 2024–2025 [81].

Figure 5 compares the ratio of EVs per public charging point across selected countries and at the global level between the years 2021 and the projected period 2024–2025. This ratio serves as a key indicator of charging infrastructure adequacy, with lower values reflecting better accessibility to public chargers. The figure reveals that Norway, despite being a global leader in EV adoption, continues to experience the highest ratio, rising slightly from 33 EVs per charger in 2021 to an estimated 35 in 2025, indicating persistent strain on its charging infrastructure relative to the size of its EV fleet. The United States sees a substantial increase from 15 to 22 EVs per charger, highlighting the accelerating EV adoption outpacing infrastructure growth. Japan improves slightly, with a decrease from 14 to 13 EVs per charger, suggesting incremental investments in charging infrastructure. China, meanwhile, maintains a stable ratio of 8, showcasing a balanced approach to infrastructure deployment in line with its rapidly growing EV market. In Europe, the Netherlands and Korea both show slight increases in EV density per charger from 4 to 5 and 2 to 4, respectively, indicating continued infrastructure expansion but still being under pressure from growing demand. Globally, the average increased from 7 to 9, emphasizing the need for accelerated deployment of public chargers worldwide. Overall, the figure highlights a critical challenge: while EV sales continue to rise globally, infrastructure development, especially fast and public charging, must scale proportionally to avoid bottlenecks and maintain user confidence in electric mobility.

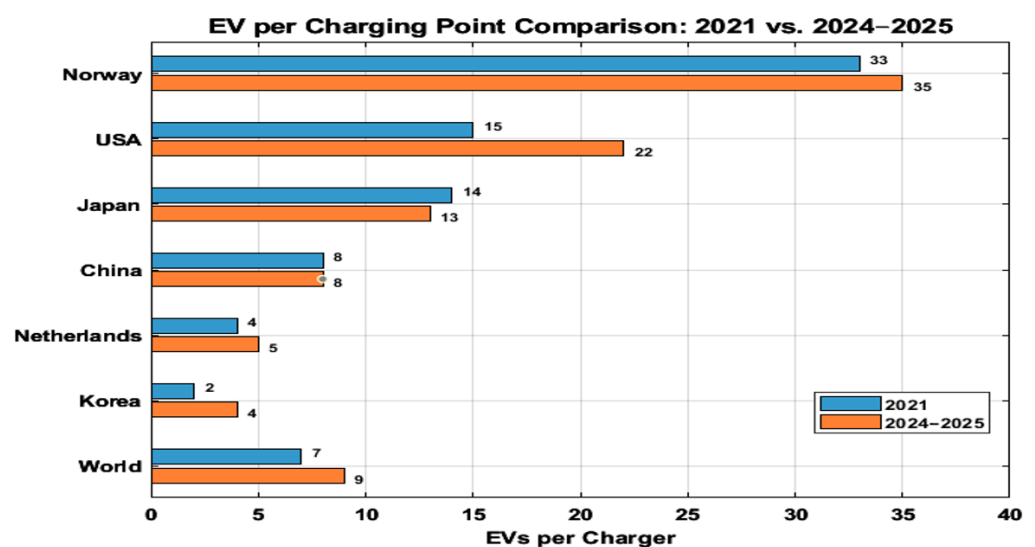


Figure 5. EV per charging point comparison 2021 vs. 2024–2025 [82].

6.2. RES Adoption Statistics

This section highlights the latest global statistics and projected trends in RES generation, based on data from reputable international databases such as [83]. Figure 6 illustrates the annual changes in renewable energy across various countries between 2000 and 2021, serving as a reference to assess expected developments through 2025. China exhibits the most significant increase, with annual growth surpassing 600 TWh by 2021, and is projected to maintain this rapid pace in the coming years. The dataset also covers major economies including the United States, India, Australia, Spain, Norway, Finland, Belgium, France, the United Kingdom, Germany, and Tunisia. While larger economies lead in absolute figures, Tunisia has steadily expanded its renewable capacity particularly in photovoltaic and wind energy and is expected to continue increasing its share in line with national sustainable energy strategies. Notably, China leads annual solar and wind growth with increases exceeding 160 TWh and 400 TWh, respectively, by 2021, with continued expansion

forecasted through 2025. Similarly, countries like Tunisia are anticipated to strengthen their renewable contributions, especially within the North African and Mediterranean regions.

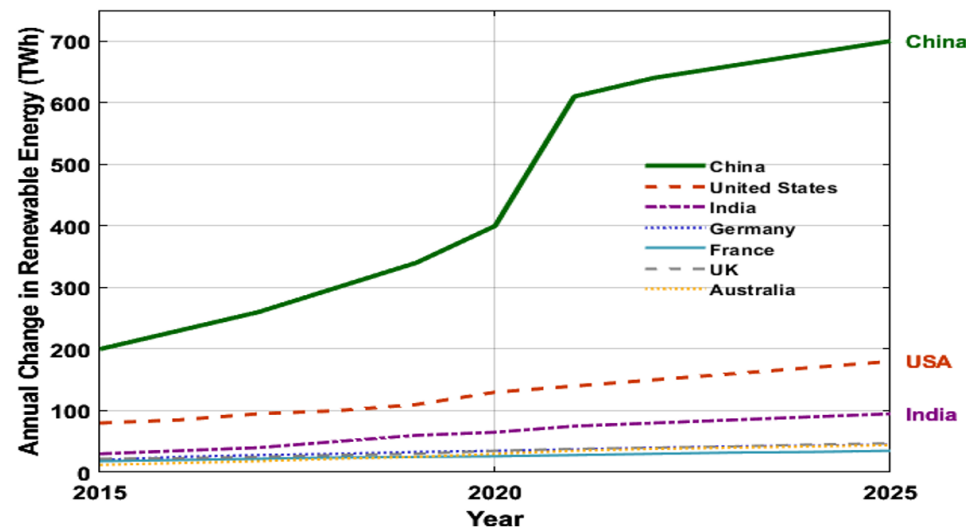


Figure 6. Annual change in renewable energy 2015/2025 [84].

The following regards the annual increase in RES generation, measured in terawatt-hours (TWhs), across seven major countries between 2015 and 2025. The data reveals a remarkable acceleration in renewable energy development, particularly in China, which stands out as the global leader. China's renewable generation increases steadily from around 200 TWh in 2015 to 500 TWh in 2020, followed by a dramatic leap to over 600 TWh in 2021 and a continued upward trend reaching 700 TWh by 2025. This significant expansion reflects China's aggressive national policies, large-scale solar and wind deployments, and grid modernization efforts. The United States follows as the second-largest contributor, with a consistent and moderate growth from approximately 80 TWh in 2015 to around 140 TWh in 2025, indicating a steady investment in renewables, particularly in wind and solar power. India also shows positive momentum, increasing from 30 TWh to nearly 100 TWh, underscoring its growing commitment to decarbonization despite infrastructure and policy challenges. Meanwhile, Germany, France, the United Kingdom, and Australia contribute more modestly, with their annual changes ranging between 30 and 70 TWh by 2025. These countries demonstrate stable progress, aligned with their long-term sustainability strategies and regional decarbonization targets. Overall, the figure highlights the global disparity in renewable energy growth, with China taking a commanding lead, followed by progressive but uneven developments in other regions. It underscores the urgent need for accelerated investments and international cooperation to achieve a balanced and effective global energy transition.

7. Impact of RES Integration on Grid

The panel smoothing strategy for transition regression captures the local impacts of integrating RES into the grid, as explored in [85]. In both energy production zones and load centers, higher voltage levels generally enhance RES output and utilization, although this is not universally observed. Ultra-high voltage (HV) systems appear to be largely unaffected by RES integration, highlighting a critical issue: the absence of extra-HV lines as the backbone of the national utility limits the feasibility of fully leveraging renewable sources. This underscores the urgent need for grid modernization.

Reference [86] presents an optimization model to determine the ideal routing, power transfer capability, and advancement timeline for six inter-local power lines. By 2039,

delivery of power from the northwest to eastern locations is projected to rise by 265%, and from the north to the central region by 160%. The current 400 kV DC (5 GW) standard will be upgraded to 800 kV DC (10 GW) by 2033, peaking between 2036 and 2039. RE generation in central and eastern China, mainly wind and PV, is expected to triple by 2039. Strategic disconnection of lines 2–6 and 7–9, coupled with ES and power need-side feedback, may enhance RES penetration by 1.7% and 2.6%, respectively. According to [87], marine RESs exhibit greater consistency and availability on an hourly basis compared to wind and solar throughout the year. There is also potential for wave energy to reduce grid balancing requirements.

In [88], a novel method combines the advantages of Gaussian distribution modeling with probabilistic failure analysis within a fuzzy fault tree framework. This approach can detect system switch faults and low-power component issues often missed by conventional fault tree analysis. Additionally, it addresses the often-overlooked risk of power disruptions. A significant challenge remains in the lack of reliable data, which increases uncertainty in predicting failures and performance issues in grids related to wind energy systems and EV installations.

To evaluate the potential of RE village grids in alleviating poverty in off-grid rural and island communities in Indonesia, the researchers of [89] performed an extensive study. The research investigates how renewable off-grid electrification can address both poverty and security issues in remote regions, where energy production is often limited by geographic constraints. Using a Difference-in-Differences approach, the study compares outcomes between treated and untreated groups across 217 remote Indonesian villages. The findings revealed that the program failed to benefit 91 individuals from disadvantaged socio-economic backgrounds. However, the provision of electricity to small local businesses contributed significantly to poverty reduction. Overall, off-grid renewable electrification has had a positive impact on poverty alleviation across Indonesian islands.

In [90], the authors simulate a scenario in which all Western European countries rely entirely on RES as wind, water, and solar. They analyze the effects of interconnected versus isolated energy networks on energy costs and demand. Weather-based models are used to forecast wind, solar, thermal, and refrigeration loads, enabling effective balancing of power, heat, cold, hydrogen, and storage systems. Countries such as the UK, France, Germany, Spain, Italy, Luxembourg, and Gibraltar demonstrate reliable WWS integration. Interconnected networks reduce energy costs, overbuilding of generation/storage, energy shedding, and land/water use. Regional cooperation could lower electricity costs in Western Europe by up to 13%. The greatest emission reductions are seen when Denmark (20.6%) and Northwestern Europe (13.7%) are connected to Norway's hydropower resources. Furthermore, strategic connections—such as those involving Luxembourg and larger neighboring countries—yield mutual benefits. Economically robust nations like France and Germany are well-positioned to transition to 100% WWS grids.

The integration of utility-scale PV and wind farms is essential for building sustainable energy systems. Unlike conventional power plants, PV and wind systems generate electricity independently [91]. In Lesotho, RES intermittency has contributed to grid instability. Most PV and wind installations are concentrated near Ha-Ramarothole and Letseng substations. To analyze the dynamic effects of renewable energy fluctuations, researchers introduced a short-circuit fault at the busbar with the lowest critical clearing time, measuring the resulting voltage, frequency, and rotor angle variations. Additionally, a steady-state voltage analysis was conducted using hourly load data, IREG data, and Muela Hydropower generation for 2018. The findings were evaluated against the Lesotho Grid Code, focusing on grid stability indicators.

With the ongoing global energy crisis, RESs are expected to gradually replace traditional power plants in the coming decades, as noted in [92]. Consequently, current research prioritizes integrating RESs into smart grids. The study outlines various control strategies each with their own advantages and drawbacks that support efficient renewable energy integration into smart grid infrastructures.

Reference [93] provides a comprehensive overview of how integrating RES technologies affects power network performance, along with common mitigation approaches. RESs can be sourced from PV, wind, biomass, geothermal, and renewable hydrogen or fuel cells. However, some global forecasts overestimate the capacity of renewables due to constraints in actual deployment. This review highlights the main technical barriers and offers practical solutions to enhance renewable integration.

In previous years, RESs could have been prevalent. However, their integration poses technical challenges. The absence of conventional synchronous generators reduces system inertia, complicating regulation. RESs are also associated with high levels of uncertainty, limited fault ride-through capacity, increased fault current, constrained generation reserves, and poor power quality. Solar and wind power are susceptible to variability. To address these challenges, researchers have developed advanced technologies for control, optimization, energy storage, and fault current limitation [94].

8. Photovoltaic-Based EV Charging Infrastructures

Prior to the installation of a PV system for EV charging, it is important to evaluate the social acceptance of the infrastructure, its potential effects on society, and the additional services it will provide. PV-based EV charging stations have already influenced society and are being increasingly accepted, providing new services that benefit users, particularly those outside urban areas and early adopters. Integrating solar energy with EV charging infrastructure offers substantial potential to reduce carbon emissions, enhance energy security, and promote energy mobility [95]. Nevertheless, the integration process encounters various issues that need to be resolved to ensure effective integration. The planning and deployment of PV systems for EV charging infrastructure require careful optimization to ensure maximum efficiency. Site selection for solar panels is particularly challenging, as it involves considerations such as sun exposure and available space. Additionally, ensuring that solar panels generate enough energy to charge EVs efficiently is critical. The integration of PV into existing power grids presents technical challenges, particularly in handling the variability of PV output and the dynamic nature of EV charging demand. Addressing these fluctuations necessitates the deployment of advanced energy management techniques [96]. One of the major obstacles is the substantial capital investment required to implement EV charging infrastructure powered by solar energy. Securing financial support remains difficult due to high upfront expenditures and long return-on-investment timelines. To ensure the long-term success of such initiatives, it is vital to develop business models that are both economically viable and environmentally sustainable. Despite ongoing reductions in the cost of PV technologies, financial hurdles continue to slow large-scale adoption. Moreover, for seamless integration with the power grid, the establishment of standardized connection protocols for solar-based EV charging systems is crucial. Simplifying regulatory frameworks and accelerating permitting procedures are also key to reducing administrative burdens and facilitating timely project execution. Promoting the expansion of solar-powered EV infrastructure requires addressing these multifaceted technical, financial, and regulatory barriers, it is necessary to develop clear and supportive regulatory frameworks [97].

8.1. Adoption and Integration of PV in Environmentally Protected Areas Technical and Economic Implications Within the Tunisian Context

The integration of PV-based EV charging infrastructure in Tunisia presents unique technical and economic challenges that must be carefully considered. Technically, Tunisia's existing grid infrastructure requires significant modernization to effectively manage the variability introduced by photovoltaic generation and the increasing load from EV charging stations. Grid stability concerns, such as voltage fluctuations, harmonics, and phase imbalance, are exacerbated by the limited deployment of advanced battery energy storage (BESS) and real-time energy management tools. Furthermore, the relatively low penetration of smart grid technologies constrains the effective implementation of bidirectional V2G services, which are essential for optimizing energy flows and grid support.

Economically, the high upfront investment costs for PV arrays, BESS, and EV charging infrastructure pose significant barriers, particularly in a developing country contexts where financial resources and incentives are limited. The regulatory framework in Tunisia is still evolving, with challenges related to permitting, interconnection standards, and policy incentives that affect the scalability and attractiveness of PV-powered EV infrastructure projects. Additionally, socioeconomic factors, including consumer awareness and acceptance, impact demand growth and thus the viability of large-scale deployments.

Addressing these challenges requires coordinated efforts combining grid upgrades, targeted policy development, and innovative financing models tailored to local conditions. Pilot projects and data collection initiatives are crucial for informing scalable solutions and demonstrating technical feasibility and economic benefits. By focusing on these aspects, Tunisia can leverage its abundant solar resources to foster a sustainable and resilient EV charging ecosystem, aligned with national renewable energy and climate goals.

To strengthen the regional applicability of our modeling framework, pilot project outcomes and benchmarking data from comparable solar-rich regions have been reviewed. In Morocco, the Green Energy Park in Ben Guerir has launched demonstration projects on PV-powered EV charging integrated with smart grids and storage systems, providing valuable technical and economic insights applicable to North African markets. Similarly, Egypt's Benban Solar Park, one of the largest in Africa, has incorporated localized charging infrastructure studies and public-private partnership models to support green mobility. These examples confirm the viability of high-irradiance countries implementing hybrid PV-EV systems at scale. Although Tunisia currently lacks large-scale deployments, such regional benchmarks offer relevant technical parameters, financing schemes, and policy frameworks that can inform pilot programs. Drawing on these analogs enhances the credibility of our modeling assumptions and supports a phased approach to implementation, starting with localized testbeds in cities such as Tataouine, Tozeur, and Sfax.

PV systems are playing an increasingly significant role in shaping architectural and urban spaces, thanks to innovative module designs and their incorporation into both new constructions and building renovations, as well as urban areas, energy communities, and preserved landscapes. Beyond enhancing energy efficiency, PV technologies contribute to minimizing GHGE, lowering electricity costs, and fostering economic growth. Recent advances in the visual design of PV panels allow for better integration of esthetics, technological performance, and energy production. In addition, PV systems offer multifunctional uses and open new opportunities for creative and sustainable architectural solutions [98,99].

However, the adoption of PV systems in cities remains a topic of debate. Social preferences driven by perceived benefits, cultural values, and societal priorities play a significant role in determining community acceptance of PV systems. The transition from buildings to landscapes for PV integration increases design complexity, requiring careful coordination between urban planning, architecture, energy planning, heritage conservation,

and environmental protection. To address this, research has aimed at assessing openness to PV technology and its acceptance in landscapes with protected heritage and natural values. A study on PV systems in such landscapes revealed high acceptance rates, with 90% of respondents showing support, divided into 46.5% fully accepting and 43.5% partially accepting. Partial acceptance generally reflects the need for customized PV designs. Only a small percentage (7%) of respondents considered PV technology unsuitable, while 3% expressed reservations about its implementation. These findings align with previous research on incorporating PV technology into historic structures, with similar patterns of total and partial acceptance [100].

8.2. Technical and Operational Issues of Energy Coordination in PV Charging Stations

EV users typically recharge their vehicles using residential connections, which results in significant system losses within the power sector, ultimately reducing profitability. Many EV chargers also introduce power quality issues due to their nonlinear response. These grid reliability issues arise from poorly coordinated and inefficient charging patterns. Solutions to these issues include reconfiguring charging schedules, ameliorating inverter designs, incorporating RES, and implementing EMS.

To provide a more structured perspective, the technical challenges of PV-based EV charging systems can be classified into three main categories: grid-level, load-level, and control-level issues. Grid-level challenges primarily include voltage instability and harmonic distortion caused by the intermittent nature of PV generation and the nonlinear characteristics of EV chargers. Load-level concerns involve phase imbalance and peak demand spikes, particularly during uncontrolled mass charging. Control-related challenges center on the complexity of coordinating bidirectional power flows and dynamically managing energy from multiple sources in real time. In response, advanced EMS leveraging intelligent algorithms have been proposed. For instance, active power filtering based on SRF theory has been shown to reduce THD by up to 65%, maintaining values within IEEE 519 recommended limits. To mitigate load-level issues, smart scheduling strategies can reduce evening peak loads by 30–50% by distributing EV charging more evenly across off-peak hours. At the control level, optimization techniques such as PSO and GA are employed to manage power exchange between PV arrays, storage systems, and EVs. Simulation studies have demonstrated that PSO-based EMS can enhance PV utilization by 12–18%, while GA approaches improve energy efficiency and reduce battery degradation by optimizing charging patterns. This systematic combination of tailored mitigation strategies and intelligent EMS technologies significantly contributes to the stable and scalable deployment of PV-based EV infrastructure.

Leveraging available RE is considered the most effective technique from both a financial and ecological perspective, as it eases the load on the network and enhances grid reliability. EMS maximizes RE use while minimizing charging costs. The optimization of hybrid RE-based EV charging stations may be reached through algorithms like PSO, genetic algorithms (GAs), and a combination of both (GA-PSO), leading to improved performance. Additionally, new energy transfer systems, like the bidirectional V2G technique, allow EVs to supply power back to the grid during blackouts or peak demand periods. This greatly supports the sustainability of power systems and the mobility sector, offering multiple techno-economic and environmental benefits [101].

To provide a quantitative perspective on the impact of different PV system configurations on charging station performance and grid stability, various modeling approaches have been developed and validated through simulations and case studies. For instance, standalone PV arrays integrated with EV chargers show improvements in energy self-consumption and reduced grid dependency, but face challenges due to solar intermittency,

which can cause voltage fluctuations and reduce overall charging efficiency. Hybrid configurations that combine PV systems with BESS offer enhanced energy smoothing capabilities, enabling more stable power delivery, improved load matching, and reduced stress on grid infrastructure. Simulation studies reveal that such hybrid systems can increase charging station efficiency by up to 15% and reduce grid voltage deviations by 10–20%, depending on storage capacity and control algorithms. Additionally, advanced smart charging and V2G algorithms that dynamically manage energy flows between EVs, PV arrays, and the grid optimize peak shaving and frequency regulation, thereby supporting grid stability. Case studies from regions with high PV penetration further demonstrate that proper system design and coordination can mitigate power quality issues, lower operational costs, and enhance reliability, confirming the crucial role of quantitative modeling in guiding infrastructure deployment and policy decisions.

Incorporating PV systems into EV charging infrastructure introduces a mix of issues and opportunities. Tackling concerns such as power quality and energy losses requires the deployment of advanced solutions, including hybrid renewable configurations, intelligent energy management approaches, and optimized control algorithms. With ongoing advancements in PV technology, its role in EV charging systems becomes increasingly important for enhancing efficiency, reducing pressure on the power grid, and supporting the shift toward green energy. The integration of V2G technology amplifies this potential by transforming the energy landscape, emphasizing the need for ongoing studies [102].

For effective implementation, selecting optimal locations for solar-powered EV charging stations is key. EV charging takes longer than refueling conventional vehicles, which means a significant increase in the number of stations will be required to provide EV users with the same level of convenience that gasoline stations offer to ICEVs. To facilitate the shift towards electric mobility, numerous governments have introduced measures like tax benefits, vehicle exchange programs, and subsidies for EV purchases. Furthermore, the price of new EVs has fallen significantly in the last ten years [103].

Site selection for PV-powered EV charging stations can benefit from novel approaches, such as using Geographic Information Systems for optimal placement. Recent works have employed GIS and Multi-Criteria Decision-Making techniques for identifying optimal sites for PV plants. However, there has been limited attention on integrating RE and determining the best sites for PV-generated EV charging stations [104].

Prior to the deployment of PV for EV charging, assessing the societal acceptance and potential social impacts of this infrastructure is a fundamental step. Recognizing how the public perceives PV-powered EV charging stations, along with the additional services they can provide, is key to ensuring their successful integration. The combination of PV technology with electric vehicle charging offers promising benefits, including limited GHGE, ameliorated energy resilience, and the advancement of sustainable mobility. Nevertheless, several issues require attention to ensure effective integration. These include improving system design and installation practices for greater performance, carefully. It is also critical to establish interconnection standards and navigate complex utility regulations to ensure seamless grid integration. The development of supportive regulatory frameworks and the continued advancement of energy management systems, like PSO and GA, will be essential for maximizing the performance of these systems. The introduction of V2G techniques further presents emerging possibilities for energy exchange and grid stabilization during critical events such as power outages and periods of peak demand. Overcoming the associated challenges while leveraging the advantages of PV integration in EV charging infrastructure will necessitate ongoing innovation and research efforts [105].

To further quantify the influence of PV variability on grid performance, simulation-based evaluations were conducted to assess voltage stability and power quality under

different PV generation profiles. The results reveal that during peak solar generation periods, voltage fluctuations can exceed acceptable thresholds, especially in low-inertia grids without energy buffering. However, the integration of hybrid systems combining PV arrays with BESS significantly mitigates these effects. Simulation models show that such configurations can reduce voltage deviation by 10–20%, depending on the storage capacity and control strategy employed. Additionally, adaptive control algorithms such as PSO and GA demonstrate effectiveness in dynamically managing energy dispatch between PV, storage, and EV load, thereby improving load matching and minimizing grid stress. Advanced forecasting techniques, when integrated with smart energy management systems, also help anticipate and smooth out PV intermittency. These quantitative insights emphasize the critical role of intelligent coordination strategies and hybrid system design in maintaining power quality and grid stability in PV-based EV charging infrastructures.

Energy charging capacity levels, charger topologies, communication protocols, and implementation guidelines are also critical considerations in the advancement of EV charging infrastructure. The performance of EV batteries can be influenced by the type of charging infrastructure used. Charging power is categorized into three levels: Levels 1, 2, and 3. Unidirectional charging (on-board) is easier to manage for hardware issues, reduces battery wear, and is constrained by size, weight, and cost. Bidirectional charging (off-board), however, allows energy to flow from the grid to the battery and vice versa. A comparison of various EV charging infrastructures, based on factors like location, power capacity, and equipment, reveals the need for improved power management, standardization, and resolution of infrastructure-based challenges for wider EV acceptance [106].

This comparative Table 2 highlights the distinct characteristics of EV charging technologies. While Level 1 and Level 2 chargers exert minimal to moderate impact on the grid and battery systems, Level 3 chargers, especially fast DC types, introduce significant power quality concerns due to high THD levels (up to 27%) and thermal stress on both transformers and batteries. Bidirectional V2G chargers, though complex, offer the potential to alleviate grid stress through smart coordination and ancillary services. This analysis underscores the importance of aligning charger deployment with grid capacity and intelligent control mechanisms to ensure safe, efficient, and sustainable integration.

Table 2. Comparative analysis of EV charger types based on power capacity, directionality, and grid/battery impact.

Charger Type	Power Capacity	Charging Time	Directionality	Use Case	Grid Impact	Power Quality	Battery Health
Level 1 (AC)	1.4–2.4 kW	8–20 h	Unidirectional	Home/residential	Minimal, low load	Negligible harmonics	Minimal degradation
Level 2 (AC)	3.3–22 kW	3–8 h	Uni/Bidirectional	Public/residential	Moderate impact	Mild THD increase	Slightly higher wear
Level 3 (DC Fast Charging)	50–350 kW	15–45 min	Mostly Unidirectional	Highways, fleet charging	High peak demand	Significant THD (up to 27%)	Accelerated degradation (20–30% after 500 cycles)
V2G (Bidirectional)	3.3–50 kW	Variable	Bidirectional	Grid support, smart homes	Load balancing, ancillary services	May mitigate or inject harmonics	Requires intelligent control to protect battery

Lastly, the social impacts of PV-powered EV charging stations cannot be overlooked. A critical initial phase in deploying a PV-based EV charging system involves evaluating public acceptance of the infrastructure and examining its broader social implications. PV-based

EV charging infrastructure not only affects how society receives this technology but also offers new services, particularly to users in rural or less urbanized areas and early adopters.

8.3. PV-CS Social Impacts

Prior to deploying a PV system for EV charging, it is essential to evaluate public acceptance of the infrastructure and its effect on society, as well as the updated services it may introduce.

Empirical studies underline that social acceptance is a pivotal factor influencing the adoption of PV-powered EV charging infrastructure. Survey data from various regions reveal high levels of community support, with acceptance rates often exceeding 90% when the benefits of reduced emissions, cost savings, and enhanced energy autonomy are clearly communicated. For example, a recent study in European communities showed that 46.5% of respondents fully accepted PV integration in urban and semi-urban environments, while an additional 43.5% expressed conditional acceptance depending on design customization and impact mitigation. Key drivers of acceptance include environmental awareness, perceived economic benefits, and trust in renewable technology. Conversely, concerns related to visual impact, upfront costs, and system reliability remain significant barriers, as highlighted by focus group analyses and behavioral surveys. Understanding these behavioral and perceptual factors is essential to tailor outreach, policy frameworks, and infrastructure design, thereby facilitating more effective deployment and broader community engagement.

Recent empirical studies support the importance of public perception in the deployment of PV-powered EV charging stations. A survey conducted across 11 European urban and semi-urban regions found that 90% of respondents expressed support for PV integration, with 46.5% fully approving and 43.5% conditionally accepting the systems, depending on design and environmental integration. A pilot project in Germany also revealed that public satisfaction increased significantly when stations included transparent information on energy sources and environmental benefits. However, case studies in Spain and Italy noted recurring concerns over visual impact, lack of awareness, and doubts about return on investment as barriers to adoption. In Tunisia, while large-scale data are limited, small-scale interviews in solar pilot regions such as Tataouine and Sfax have indicated growing interest, particularly among youth and tech-literate users, although concerns remain about upfront costs and local grid readiness. These findings highlight the importance of context-specific engagement strategies, educational campaigns, and inclusive planning processes to strengthen social acceptance and support the expansion of PV-based EV infrastructure.

The integration of PV-based EV charging infrastructure has already influenced public perception and acceptance, offering services that benefit not only urban residents but also users in rural areas and early adopters. Four conceptual case studies, all solar-powered, are presented to illustrate these innovative services: a PV-powered luggage vehicle, a solar-equipped train station, a solar-powered bus terminal, and a portable charging unit [107].

8.4. Impact of Photovoltaic-Based EV Charging Infrastructure on Sustainability and the Economy

EV charging stations powered by PV systems offer a range of benefits for both the economy and the environment. Economically, these stations reduce dependence on the power grid, which lowers operating charge and provides long-term savings for both consumers and businesses. By harnessing solar energy, they foster greater control over energy supply and mitigate the impact of increasing fuel prices. Environmentally, PV-powered charging stations reduce pollution and GHGE, further enhancing the sustainability of EV. When combined with PV systems, EV charging stations improve grid stability and efficiency through optimized charging schedules. Moreover, these stations are indepen-

dent of the grid, boosting transportation system resilience and providing backup power during outages.

The viability of on-site energy storage for EV charging stations, powered by PV, has been explored in simulations conducted in both the United States and China. These studies discuss the findings, with energy balance serving as the foundation for evaluating ecological and financial metrics. The economic analysis factors in PV array investment costs, BESS, electricity sales to the grid, and grid electricity purchases to calculate a yearly operating cash flow. Additionally, the remediation charge of GHGE is assessed by fusing both green and investment practicality evaluations [108].

8.5. Technical Standards and Protocols

The successful deployment and operation of PV-powered EV charging infrastructure relies heavily on adherence to established technical standards and communication protocols that ensure interoperability, safety, and efficient integration with the grid. Key standards include International Electrotechnical Commission (IEC) 61850 [109], which defines communication networks and systems for power utility automation, facilitating seamless data exchange between grid components and charging stations. The International Organization for Standardization (ISO) 15118 protocol governs the communication between EVs and charging stations [110], enabling features such as plug-and-charge, smart charging, and bidirectional energy flow in V2G systems. Interconnection standards such as Institute of Electrical and Electronics Engineers (IEEE) 1547 and Underwriters Laboratories (UL) 1741 standard specify requirements for integrating distributed energy resources, including PV systems, to ensure grid stability and safety [111]. Compliance with these standards supports standardized control, monitoring, and protection functions, which are critical for scaling PV-EV infrastructure. Furthermore, ongoing developments in cybersecurity standards are increasingly important to safeguard communication channels against potential threats. Incorporating these technical frameworks into design and policy considerations provides clear guidance to practitioners and regulators, fostering reliable and resilient PV-based EV charging networks.

While standards such as IEC 61850, ISO 15118, IEEE 1547, and UL 1741 provide a foundation for PV and EV system integration, several technical and regulatory gaps remain. For example, IEC 61850 enables substation automation and communication, but its implementation across distributed PV-EV systems is still limited. ISO 15118 supports smart charging and V2G communication, yet lacks widespread compatibility across EV brands and charger types. IEEE 1547 defines interconnection requirements for distributed energy resources, but does not fully address the dynamic behaviors of V2G-enabled EV chargers. Regulatory inconsistencies further complicate deployment: many regions lack unified guidelines for bidirectional energy flows, cybersecurity requirements, or streamlined permitting. To facilitate seamless integration, it is crucial to establish globally harmonized standards for charger communication, enforce minimum cybersecurity protections for grid-interfaced systems, and develop fast-track permitting processes tailored to PV-based EV charging stations. These improvements will accelerate deployment, enhance interoperability, and ensure grid reliability as EV and PV adoption expands.

8.6. Regulatory, Technical, and Social Barriers

The successful integration of PV-powered EV charging infrastructure faces several regulatory, technical, and social barriers that require deeper consideration. From a regulatory standpoint, varying policies across regions create challenges for scalability. For example, the EU Renewable Energy Directive and U.S. Clean Energy Standards have established frameworks that encourage the adoption of EVs and PV systems through financial incen-

tives, grid integration standards, and emission reduction targets. However, regions with less mature regulatory environments, such as Tunisia, face slower implementation due to gaps in interconnection policies and lack of standardized permitting processes for renewable energy systems. On the technical side, hardware compatibility remains a significant hurdle, particularly in integrating various EV models, PV systems, and energy storage units. Interoperability issues, including mismatched charging protocols and differing inverter technologies, can hinder efficient energy exchange and grid stability. To address these, universal standards and smart grid technologies are crucial. Socially, public acceptance and cultural factors play a significant role in adoption rates. Regions with higher environmental awareness, like Scandinavian countries, show faster adoption of PV-EV systems, while areas with lower awareness face resistance to new technologies. Additionally, cultural perceptions about the reliability and esthetics of PV infrastructure can also affect adoption, especially in urban areas where space and visual appeal are important considerations. Overcoming these barriers requires tailored policy development, technical innovation, and community engagement to ensure the success of PV-powered EV infrastructure globally.

9. Conclusions and Future Trends

The integration of EVs into existing power grids is essential for advancing sustainable transportation and reducing greenhouse gas emissions. This review underscores the significant impacts of EVs on power quality, grid stability, and infrastructure planning, particularly when combined with renewable energy sources like PV systems. Despite ongoing technological progress addressing challenges such as voltage imbalance, harmonic distortion, and energy storage, strategic planning and supportive policy frameworks remain critical.

While PV-powered EV charging infrastructure offers significant environmental and economic benefits, several key hurdles impede its large-scale deployment. Primary challenges include the variability of solar energy, which necessitates advanced energy storage and smart grid management to ensure consistent power supply; high upfront capital costs for PV systems, batteries, and charging stations limit widespread adoption, especially in developing regions with constrained financial resources; additionally, technical issues such as hardware interoperability and the lack of standardized communication protocols hinder seamless integration. Social acceptance and regulatory uncertainties further complicate deployment, as supportive policies and clear guidelines are still evolving in many markets. Overcoming these barriers requires continued technological advancements in high-efficiency PV panels, durable and cost-effective energy storage solutions, and intelligent charging algorithms that optimize energy flow and battery health. Equally important are the development of universal standards and scalable business models that encourage investment and consumer confidence. By addressing these multifaceted challenges through coordinated innovation, policy support, and stakeholder engagement, PV-EV infrastructure can achieve practical, sustainable scalability.

Despite significant progress in integrating PV systems with EV charging infrastructure, several critical research gaps remain. Future investigations should focus on the development of advanced energy management algorithms that dynamically optimize the balance between PV generation variability and EV charging demand to enhance grid stability and efficiency. Furthermore, resilience strategies need to be designed to ensure reliable EV charging during power outages, including the exploration of V2G capabilities and hybrid energy storage solutions. Additionally, integrated urban planning approaches that coordinate PV-EV infrastructure deployment with city energy and transportation systems are essential to maximize socio-economic and environmental benefits. Targeted pilot projects in

developing regions, such as Tunisia, could provide valuable data to refine these strategies, enabling scalable and sustainable deployment of PV-based EV charging networks globally.

In Tunisia, with its high solar irradiance, the transition to EVs and renewable energy presents both an environmental imperative and a strategic opportunity for regional leadership. However, limited infrastructure and the need for grid modernization pose challenges to large-scale EV adoption.

Future research should focus on integrating advanced energy storage systems to manage PV variability and balance supply–demand dynamics, especially during peak solar generation. Optimizing storage sizing, hybrid solutions, and intelligent controls will enhance system reliability and cost-effectiveness. Parallel efforts in grid modernization—deploying smart grid technologies tailored to Tunisia’s unique energy profile—are necessary to enable real-time monitoring, adaptive energy management, and efficient V2G operations.

Equally vital is the formulation of clear, supportive policies that streamline interconnection, simplify permitting, and incentivize investment in PV-powered EV infrastructure. Collaborative frameworks involving utilities, regulators, industry, and communities will foster social acceptance and equitable access. Encouraging local R&D and academic partnerships will further enable context-specific solutions, particularly for rural and semi-urban regions.

By capitalizing on its solar potential and prioritizing sustainable infrastructure, Tunisia can emerge as a model for clean mobility and decentralized renewable energy integration in North Africa.

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Abbreviations

BEV	battery electric vehicle
BESS	Battery Energy Storage Systems
EV	Electric vehicles
EMS	energy management strategies
G2V	Grid to vehicles
GA	Genetic algorithm
GHGE	greenhouse gas emission
GIS	Geographic Information Systems
ICEVs	internal combustion engine vehicles
PQ	Power quality
PHEV	plug-in hybrid electric vehicle
PV	Photovoltaic
RES	Renewable energy source
SRF	synchronous reference frame
MISO	Midwest ISO

THD	Total harmonic distortion
TUO	Time of Use
UPQC	unified power quality conditioners
HV	high voltage
V2G	Vehicle to grid

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