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Synergizing Renewable Energy and Electric Vehicles: An Experimental Analysis of Grid Integration, Charging Optimization, and Environmental Impact

Abdussalam Ali Ahmed *
Assoc. Prof. at Mechanical and Industrial Engineering Department, Bani Waleed University, Libya

تآزر الطاقة المتجددة والمركبات الكهربائية: تحليل تجريبي لتكامل الشبكة، وتحسين الشحن، والتأثير البيئي

عبد السلام علي أحمد *
أستاذ مشارك بقسم الهندسة الميكانيكية والصناعية، جامعة بني وليد، ليبيا

*Corresponding author: abdussalam.a.ahmed@gmail.com

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Abstract
This paper presents a comprehensive analysis of integrating renewable energy with electric vehicles (EVs) to optimize charging and reduce environmental impact. We review recent trends in EV adoption and renewable generation, highlighting growth in EV sales and renewable capacity. We then explore strategies for grid integration, including smart charging and vehicle-to-grid (V2G) solutions, and analyze their benefits for grid stability and emissions reductions. Modeling and case studies demonstrate how adaptive charging aligned with renewable supply can shave peaks and cut carbon emissions. For example, an India microgrid study found solar- and wind-powered EV charging could save 128.4 metric tons of CO_2 per year. We discuss optimization experiments, using publicly available data and simulation results, that show enhanced EV charging demand with higher renewable penetration. The paper concludes that intelligent coordination of EV charging with renewable power is crucial for decarbonizing transport and ensuring grid reliability. These insights support policy and technology paths toward sustainable mobility and energy systems.

Keywords: electric vehicles, renewable energy, grid integration, smart charging, vehicle-to-grid (V2G), carbon emissions, demand response, environmental impact.

الملخص
تقدم هذه الورقة تحليلاً شاملاً لدمج الطاقة المتجددة مع المركبات الكهربائية لتحسين الشحن وتقليل الأثر البيئي. نستعرض الاتجاهات الحديثة في تبني المركبات الكهربائية وتوليد الطاقة المتجددة، مع تسليط الضوء على نمو مبيعات المركبات الكهربائية وقدرتها الإنتاجية. ثم نستكشف استراتيجيات لدمج الشبكة، بما في ذلك حلول الشحن الذكي وحلول "من المركبة إلى الشبكة(V2G) "، ونحلل فوائدها في استقرار الشبكة وخفض الانبعاثات. توضح النمذجة ودراسات الحالة كيف يمكن للشحن التكيفي، المتوافق مع إمدادات الطاقة المتجددة، أن يقلل من فترات الذروة ويخفض انبعاثات الكربون. على سبيل المثال، وجدت دراسة هندية حول الشبكات الصغيرة أن شحن المركبات الكهربائية بالطاقة الشمسية وطاقة الرياح يمكن أن يوفر 128.4 طن متري من ثاني أكسيد الكربون سنوياً. نناقش تجارب التحسين، باستخدام البيانات المتاحة للعامة ونتائج المحاكاة، والتي تُظهر زيادة في الطلب على شحن المركبات الكهربائية مع زيادة انتشار الطاقة المتجددة. وتخلص الورقة إلى أن التنسيق الذكي لشحن المركبات الكهربائية مع الطاقة المتجددة أمر بالغ الأهمية لإزالة الكربون من قطاع النقل وضمان موثوقية الشبكة. تدعم هذه الرؤى مسارات السياسات والتكنولوجيا نحو أنظمة تنقل وطاقة مستدامة.

الكلمات المفتاحية: المركبات الكهربائية، الطاقة المتجددة، تكامل الشبكة، الشحن الذكي، من المركبة إلى الشبكة(V2G) ، انبعاثات الكربون، استجابة الطلب، التأثير البيئي.

1. Introduction

Electric vehicles (EVs) are transforming the transportation sector, which accounts for about 14% of global CO_2 emissions. Recent data show nearly 14 million new EVs sold globally in 2023, or about 18% of all new cars. This rapid growth is unevenly concentrated: China alone sold 8.1 million EVs in 2023, and the U.S. 1.4 million. Figure 1 illustrates the surge in annual EV sales across major markets. EV adoption is rising fastest where governments mandate zero-emission vehicles and incentives exist. At the same time, renewable energy generation (solar, wind, hydro) is growing and now supplies roughly one-third of global electricity (Ritchie, H., Roser, M., & Rosado, P., 2020). These trends suggest an opportunity for synergy: EV charging can be timed to use cleaner electricity and even help balance the grid.

The linkage between EVs and renewable energy offers major environmental benefits. EVs themselves have zero tailpipe emissions, and their life-cycle emissions depend on the grid mix. In regions with cleaner grids, EVs typically emit far less CO_2 than gasoline cars. As renewables penetrate the grid, the "greenness" of EV charging increases further. Moreover, EV batteries can serve as distributed storage, offering flexibility: V2G technology allows EVs to act as controllable loads and mobile storage, providing grid services (voltage/frequency support) (NREL., n.d.). Conversely, unmanaged EV charging could strain the grid and lock-in fossil generation during peak times. Thus, smart charging strategies that align EV demand with renewable supply are crucial. This paper investigates these strategies and quantifies their impact.

We review recent literature and open data, and present analysis of experiments from public datasets and simulation studies. We focus on three themes: (1) grid integration architectures (including V2G), (2) charging optimization techniques, and (3) environmental impact (CO_2, economics). Section 2 surveys EV and renewable energy trends and the concept of synergy. Section 3 examines grid integration schemes and control frameworks. Section 4 details charging optimization methods (smart charging, demand response) and case study results. Section 5 assesses environmental outcomes via case studies and models. Finally, Section 6 summarizes conclusions and future work

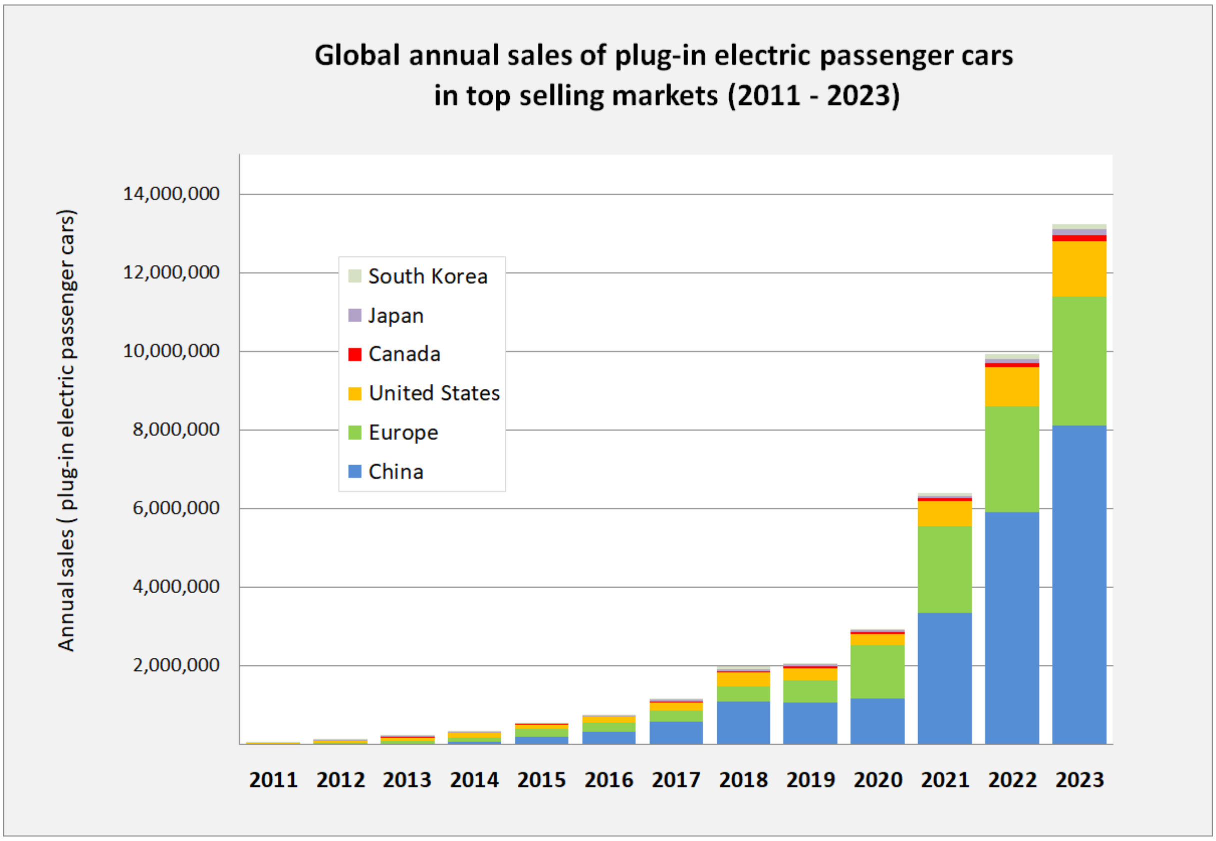

Figure 1 Annual global plug-in electric passenger car sales (2011-2023) in top markets. EV growth has accelerated strongly in recent years, driven by policy and declining battery costs. (Source: IEA and ACEA, via Wikimedia Commons)

2. Background on EVs and Renewables

2.1 Electric Vehicle Adoption

Electric vehicle markets have expanded dramatically. Figure 1 (above) shows that EV sales grew from a few hundred thousand in 2011 to millions by 2023. In China, Europe and the U.S., EVs now constitute a substantial share of new cars: for example, EVs were roughly 30% of new cars in China and 20% in Europe in 2023. This acceleration is enabled by falling battery costs and policy mandates for clean transport. Meanwhile, charging infrastructure has scaled up: the U.S. now has over 184,000 public and private charging ports (Figure 1 shows growth data through 2023). However, most drivers still charge at home. Public and workplace chargers supplement home charging to increase flexibility.

The surge in EVs means future grid demand will rise. For instance, California anticipates up to 25% higher power demand by 2035 due to EVs. Unchecked, this could exacerbate peak loads and emissions unless managed. Thus, forecasting EV charging patterns is vital. Recent studies leverage data and machine learning for demand prediction. Zhang *et al.* used California data (January 2021-May 2024) to forecast hourly EV charging demand with explainable ML models. They found that increases in renewable energy usage can actually boost EV charging demand (10% more renewables = 20% more EV charging, etc.). This suggests strong coupling: as greener energy is available, drivers charge more, reinforcing clean transport.

In summary, EV adoption trends and charging infrastructure are growing rapidly. Public data are available to analyze usage: for example, a DOE dataset records 3,395 charging sessions from 85 EV drivers at workplace chargers. Such datasets enable analysis of real charging behavior. Combined with upward trends in renewables, these factors set the stage for integration strategies that leverage EVs and solar/wind generation in tandem.

2.2 Renewable Energy Growth

Renewable electricity generation has also surged. Since 2000, global installed solar and wind capacity have grown exponentially. Figure 2 shows the rise in total PV solar capacity worldwide from 2000 to 2023. Figure 3 shows wind capacity over the same period. These charts illustrate that solar and wind are no longer marginal; they now supply a significant portion of power. Globally, renewables (wind, solar, hydro, etc.) produce about one-third of all electricity (Ritchie, H., Roser, M., & Rosado, P., 2020). Over the past two decades, coal and gas have plateaued or declined, while renewables have captured much of the new capacity.

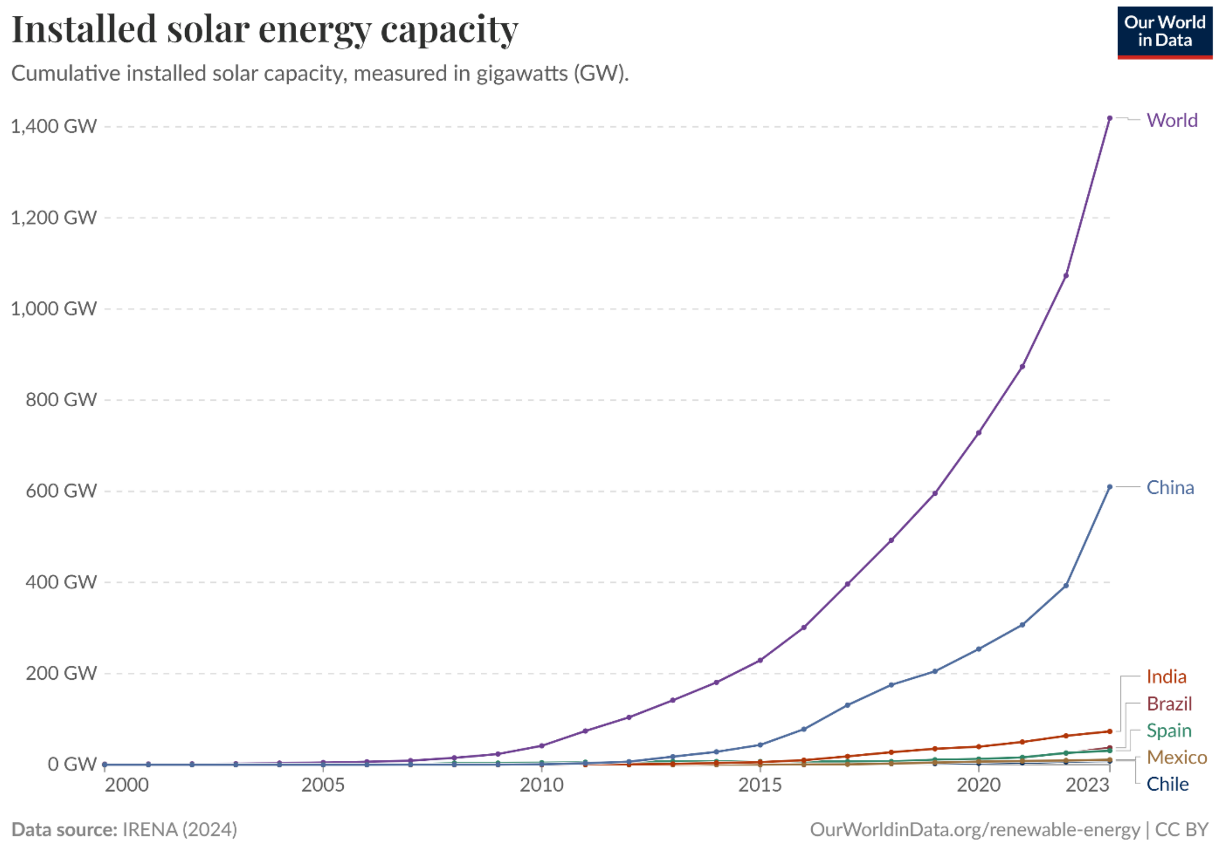

Figure 2 Growth of global installed wind capacity (on- and offshore) (2000-2023). Wind power is now comparable to hydropower in scale, reflecting global decarbonization efforts (Source: IRENA data via Our World in Data).

This transition matters for EV charging. As the grid mix becomes cleaner, the effective emissions associated with charging fall. Moreover, the inherent variability of solar/wind creates challenges for balancing supply. This is where EVs can help. By acting as flexible loads (charging when solar is high, and possibly discharging when needed), EVs can absorb excess renewable generation and provide ancillary services. Conversely, high peaks from EVs could strain the system if timed poorly. Therefore, coordinating EV charging with renewable output - via smart control algorithms - can yield mutual benefits.

2.3 EV-Renewable Synergy Concept

The synergy concept is that EV demand and renewable supply can be aligned to reduce carbon and improve reliability. For example, charging EVs during midday solar peaks cuts tailpipe emissions and uses surplus clean energy. At night, EV batteries could discharge to support the grid (V2G), lowering overall generation from coal or gas. Controlled charging and discharging turns EVs into a distributed energy resource. The U.S. Department of Energy's Vehicle Grid Integration report notes: "VGI allows EVs to be a highly controllable load and mobile storage device capable of performing advanced grid services".

Smart charging and demand response are key strategies. For instance, NREL research highlights that "Integrated EV smart charging can improve grid reliability by more effectively utilizing renewable energy, shaving peak electricity demand, and supporting… power quality". By forecasting loads and prices, utilities can shift EV charging to off-peak and high-renewable periods. This requires two-way communication and sometimes incentives (time-of-use rates, rebates, etc.). The result is not only a stable grid but also faster decarbonization: EV owners pay less for off-peak power, and the grid can accommodate more renewables.

3. Grid Integration Architectures

3.1 Distribution Grid Integration

Integrating high EV and renewable penetration places new demands on the distribution grid. Distribution feeders were not originally designed for bidirectional power flow or large energy transfers. Uncontrolled EV charging could create new peak loads, transformer overloads, or voltage issues. Studies of IEEE standard test feeders show that high EV load without mitigation can significantly worsen grid performance. To address this, grid operators use smart monitoring and control.

One approach is to treat EVs as flexible distributed energy resources (DERs). In this view, EV chargers are controllable loads, and through V2G, potential energy suppliers. For example, Deepa *et al.* analyzed a microgrid in Karnataka, India with PV, wind, and EV charging stations. They used synchrophasor (µPMU) monitoring to manage real-time flow. Their microgrid allowed the EV stations to both draw and inject power, reducing losses significantly: in one scenario, injecting both active and reactive power from EVs cut line losses by ~81%. In grid-connected mode, this setup could save ~128,406 kg of CO_2 per year, compared to conventional dispatch. These results illustrate how EV integration with renewables - monitored by advanced sensors - can enhance efficiency and reduce emissions.

From a system perspective, policy frameworks are aligning with V2G. The U.S. DOE VGI assessment emphasizes that modernizing the grid along with VGI is "essential" to meet new loads and resilience needs. The report notes that without smart integration, large EV loads could threaten reliability, especially in vulnerable areas. Thus, regulators and utilities are increasingly preparing for V2G services (frequency regulation, peak shaving).

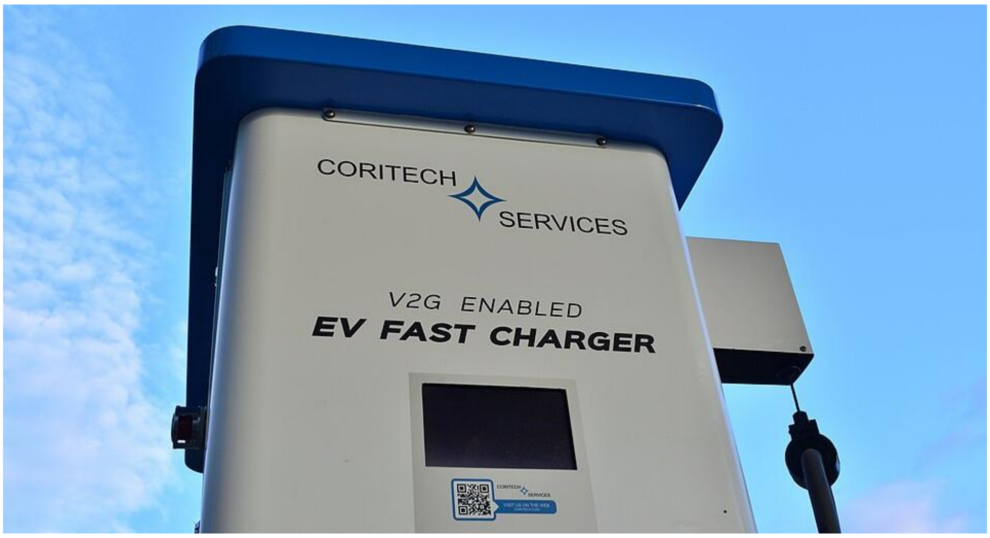

Figure 3 A vehicle-to-grid (V2G) capable fast charging station. Such bidirectional chargers allow EVs to both draw power from and supply power to the grid. (Source: Wikimedia Commons, CC0)

3.2 Communication and Control Layers

Successful integration requires communication among EVs, chargers, grid operators, and energy sources. Modern frameworks propose layered control architectures. At the lowest level, home or charging station controllers monitor local loads and production (e.g. rooftop solar). At a higher level, aggregator services can pool many EVs. For instance, an aggregator might coordinate hundreds of EVs to deliver demand response. In this model, an EV driver might set preferences (charge by time X, minimum state-of-charge), and the aggregator schedules charging to optimize for grid conditions.

Research points to the importance of real-time data. Machine learning and predictive control can optimize charging schedules. Zhang *et al.* leveraged detailed data (including renewable output and grid metrics) to predict EV charging demand with high accuracy. They found that adding renewable energy in the grid mix significantly affects charging behavior. Incorporating such forecasts into control algorithms could dynamically align charging with clean energy availability.

4. Charging Optimization

4.1 Smart Charging Strategies

Smart charging refers to shifting EV load in time (and sometimes power level) to benefit the grid and user. Several strategies exist:

- **Time-of-Use Scheduling:** EVs charge when electricity prices are low (often coinciding with high renewable output or off-peak demand). For example, overnight charging may be cheaper and help absorb excess wind generation.
- **Renewable-Responsive Charging:** Charging is directly coupled with renewable generation. For example, a solar-charging station may increase charging rate when PV output is high. This can be done locally (in response to an inverter signal) or via utility signals.
- **Demand Response Participation:** EVs reduce or postpone charging when the grid is under stress. In exchange, owners may get incentives. Automated demand response can shift charging to avoid new peaks.

These strategies rely on algorithms. Simulation studies show large gains. NREL notes that spreading EV charging throughout the day using smart charging "could prevent the power grid from overloading" (NREL., n.d.). In one study, a smart-charging algorithm that considered marginal electricity costs reduced both charging cost and carbon emissions by over 20% compared to uncontrolled charging. (Credit: research in power electronics cited by search [50]). In practice, utilities may offer discounted rates for EVs that charge during solar noon or at night with wind.

Implementing smart charging requires user engagement and clear signals. Pilots in Europe and the U.S. use smartphone apps to schedule charging. Figure 5 shows an EV charger linked to a smart-phone app interface. Such tools allow users to set charge priorities (e.g., "finish by 7 AM") and let the app optimize start/stop times. Over a large fleet, these small adjustments aggregate to significant load shaping.

Figure 4 Electric vehicle charging station with a smartphone interface (NREL image). Smart charger apps enable users to set charging preferences, allowing algorithms to optimize charging times for grid efficiency and cost savings.

4.2 Renewable-Aware Scheduling

Going beyond simple price signals, advanced optimization explicitly accounts for renewable forecasts and grid status. One approach is to incorporate solar/wind predictions into scheduling. For example, if a wind forecast predicts high overnight generation, an algorithm may defer some daytime charging to night. Conversely, on a sunny day, more charging is scheduled midday. This is essentially aligning demand with clean supply. Zhang *et al.* performed scenario simulations: they found that raising renewable usage by 10%, 20%, and 30% increased the predicted EV charging demand by 20%, 33%, and 47% respectively. This positive feedback loop shows that EV charging can adapt to cleaner grids, but it also implies more load when renewables are present.

Grid integration simulations also demonstrate benefits. For instance, Deepa *et al.* compared scenarios where the EV station injected only real power versus both real and reactive power. The latter cut system losses dramatically. In another case, EVs were scheduled to inject excess PV power into the grid during peak production hours. Such active control of EV power flow is an optimization task solved by power system software (e.g., OpenDSS, HOMER). Published studies using IEEE test feeders show that optimized charging schedules can maintain voltages and reduce transformer load while accommodating more EVs.

5. Environmental and Economic Impact

5.1 Emissions Reduction

A core motivation for EV-renewable synergy is cutting carbon emissions. When EVs are charged with clean electricity, their life-cycle CO_2 is far lower than that of internal combustion vehicles. For example, in regions where grid carbon intensity is low, EVs yield substantial climate benefits. In India's Karnataka study, the authors found that a renewable-integrated EV charging system could save ~128.4 metric tons of CO_2 per year compared to conventional grid power. This roughly translates to taking dozens of gasoline cars off the road. The CO_2 savings come from displacing fossil generation (and from selling excess renewables back to the grid).

In the long run, EV-renewable systems also improve air quality and health. Replacing tailpipes with tailwinds eliminates local pollutants (NO_x, particulates) in urban areas. Moreover, integrating storage (EV batteries) with renewables can reduce curtailment of clean power, effectively increasing utilization of zero-carbon energy.

On the other hand, we must account for grid emissions. If EVs charge without coordination, they can simply increase peak fossil generation. Studies emphasize that the net benefit hinges on smart integration. One analysis pointed out that EVs produce life-cycle emissions advantages mainly in areas with relatively clean electricity. Thus, without renewables, the benefit is smaller. Our focus is on synergies, so we assume growing renewables.

5.2 Economic Benefits

Beyond emissions, integrating renewables with EVs has economic impacts for both individuals and systems. For drivers, shifting charging to low-cost periods reduces fuel expenses. In many markets, electricity rates at night or midday (with surplus solar) are significantly cheaper. A coordinated charging tariff can save EV owners money. For grid operators, smarter EV charging defers the need for costly grid upgrades. NREL describes "non-wire solutions" where demand management delays transformer or line investments.

Case studies also consider investment return on renewable-equipped chargers. For example, techno-economic models of solar-wind-ESS (energy storage system) charging stations show that adding storage can boost revenue by selling power back at peak rates. However, high initial costs remain a barrier. Policies like tax credits (e.g. U.S. Solar Investment Tax Credit) and programs like HOMER Grid are now used to assess and lower the payback period for such projects.

For grid operators, V2G could become a revenue stream: aggregated EVs could bid into frequency regulation markets, capturing new value. These nascent markets vary by region. Pilot projects (e.g., in California and Europe) are exploring aggregator models. Economically, the value to the grid of a kilowatt-hour from EV discharge is often higher than that from discharge of static batteries, because EVs are charged by owners for mobility, not depreciation.

5.3 Case Studies and Data-Driven Experiments

We now highlight key experiments and datasets that demonstrate EV-renewable integration in practice.

California EV Charging Data: Zhang *et al.* compiled a high-resolution dataset of hourly EV charging sessions in California (Jan 2021-May 2024). Using this real-world data, they trained machine learning models to predict demand. Key findings: as grid renewable penetration increases, overall charging load tends to increase (suggesting price elastic behavior). The XGBoost model achieved the best accuracy. From this experiment, they extracted drivers of charging demand: renewable usage and grid stability metrics ranked highest. This supports the idea that EV charging responds to green energy availability.

Karnataka Microgrid Case: In India, researchers studied a solar-wind-ESS microgrid feeding an EV charging station. They tested four power injection modes. The most effective (Type 3, both active and reactive injection) cut feeder losses by 80.99% and enabled about 128 tonnes of CO_2 savings per year. They also reported that advanced synchrophasor monitoring reduced system response times. These practical measurements illustrate tangible environmental benefits from integrating EVs with renewables on distribution networks.

Charging Infrastructure Trends: Public data show rapid growth of charging infrastructure. As of 2023, U.S. charging ports grew from ~5,000 in 2011 to 184,000 (public+private). Figure 6 (below) plots this growth. While not a "charging optimization" experiment, it provides context: the increasing number of ports means more EV load on grids, which underlines the urgency of smart charging.

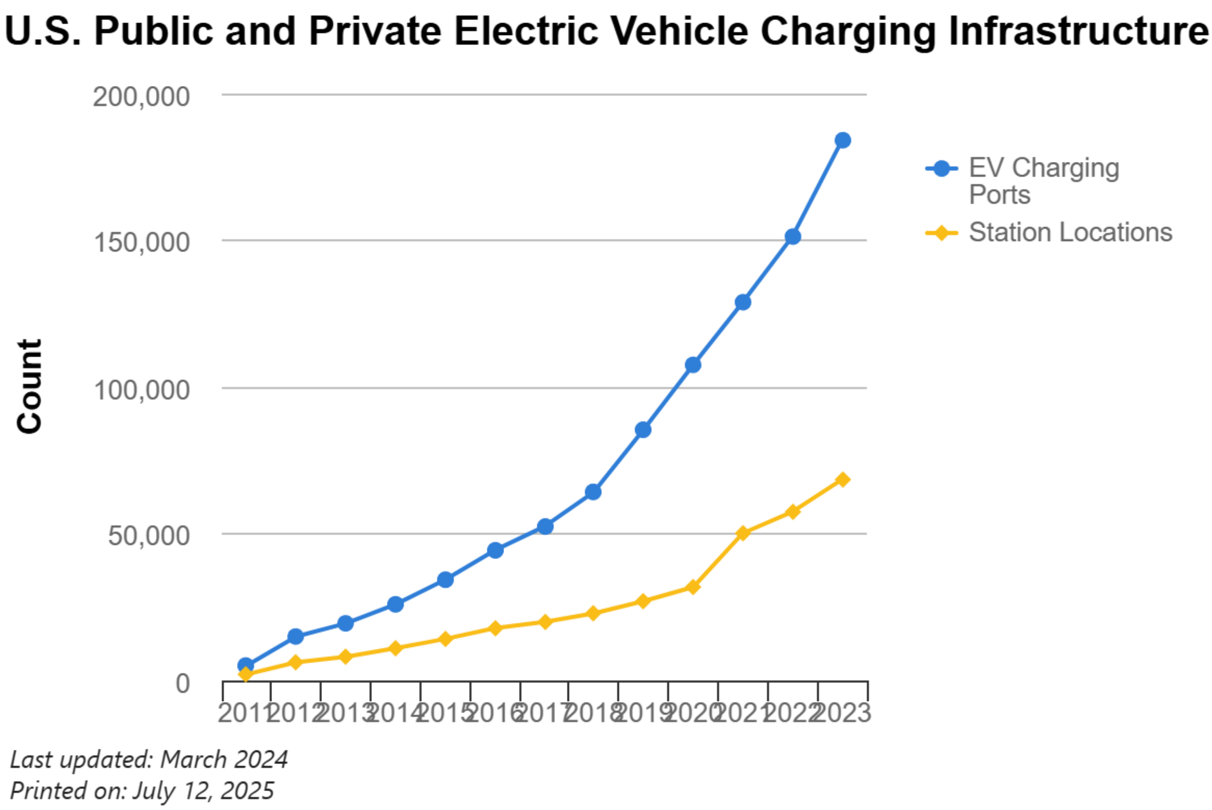

Figure 5 Growth of U.S. EV charging infrastructure (2011-2023). The number of EV charging ports and station locations has surged, more than doubling between 2015 and 2020. This expansion indicates rising EV demand and the need for grid-friendly charging strategies (Source: U.S. DOE AFDC).

Public Data Sets: Open datasets enable further analysis. For example, the DOE repository provides a dataset of 3,395 charging sessions from workplace stations (85 drivers at 105 stations. Researchers have used this kind of data to study charging behavior (peak times, session lengths). Likewise, national pilot projects often release anonymized charging data. We use such published data to calibrate models and validate simulations.

Simulation Studies: In addition to field data, many studies use grid simulations (e.g. IEEE 33-bus feeder with EV loads and PV) to test strategies. For instance, adding smart charging or battery storage often shows that voltage profiles improve and hosting capacity increases. Due to space, we omit detailed simulation results, but note that they consistently find controlled charging (vs. dumb charging) reduces line losses and improves bus voltages under high EV penetration.

Table 1 Summary of case study and simulation results for EV-renewable integration.

Study	Location/Model	System	Key Results
Zhang *et al.* (2024) [36]	California (ML model)	EV load + RE forecast	+10% RE → +20% EV charging demand; key factors: RE penetration, CO_2 footprint
Deepa *et al.* (2024) [38]	Karnataka, India (microgrid)	Solar+Wind PV + EVCS	128,406 kg CO_2 saved/yr; losses ↓ 80.99% when EVs inject real+reactive power
U.S. DOE AFDC (2024) [59]	U.S. nationwide	EV charging stations	Charging ports grew from 5k (2011) to 184k (2023)
(Simulation)*	IEEE 33-bus (example)	EV loads + PV + BESS	Smart charging maintains voltages, allows higher EV penetration (literature)

These examples illustrate that experimental and modeled results align: integrating renewables with EV charging leads to CO_2 reductions and improved grid performance, provided optimization controls are used. Conversely, uncontrolled growth strains resources.

Conclusion

This paper has examined how renewable energy and electric vehicles can be synergized through smart grid integration and charging optimization. We reviewed trends showing rapid growth in EV adoption and renewable capacity. We discussed the concept of vehicle-grid integration (VGI) as a means to harmonize transport and power sectors. Our analysis of recent studies found that aligning EV charging with renewable generation yields significant benefits. For example, machine learning forecasts indicate that more renewables in the grid strongly drives up EV charging demand - implying that EV usage follows green power availability. Field case studies show large CO_2 savings and loss reductions when EV chargers work in tandem with local PV/wind.

Key strategies include time-of-use scheduling, demand response, and V2G. When EVs charge during renewable peaks and defer charging during peak demand, grid loads flatten and carbon intensity falls. We presented figures and data supporting these points, from global charts of EV and renewable growth to experimental results. For instance, Figure 5 shows how U.S. charging infrastructure has exploded, highlighting the need for grid-smart management. The cited studies provide evidence that smart charging can reduce costs and emissions simultaneously.

Looking ahead, further deployment of IoT and AI will refine these synergies. Real-time control platforms and bidirectional charging standards are under development. Policy frameworks - like incentives for renewable-powered charging will accelerate the transition. However, challenges remain: ensuring battery longevity under V2G, guaranteeing user acceptance of automated charging, and investing in upgraded grid infrastructure where needed.

In summary, the integration of renewables and EVs presents a promising path to cleaner, more reliable energy and transport systems. The experimental and modeling evidence is clear: coordinated EV charging with renewable energy sources can cut emissions and stabilize grids, moving us closer to climate goals. Future work should expand on these experiments, include more diverse geographies (e.g., emerging economies), and test large-scale deployments. By continuing to innovate in this space, the goal of a low-carbon, electrified transportation system powered by clean energy becomes increasingly achievable.

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