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Unlocking the Decarbonization Potential of Large-Scale Electric Vehicle Integration: A Cross-Domain Review of Grid Strategies, Consumer Behavior, and Policy Mechanisms

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Abstract. The rapid growth of electric vehicles (EVs) is reshaping both transportation and power systems worldwide. While EVs offer a promising solution to reduce greenhouse gas emissions from the transportation sector, their widespread adoption also presents significant challenges to grid stability, efficiency, and economics due to large-scale charging demands. This paper reviews technical pathways for EV-grid integration, focusing on smart charging, vehicle-to-grid (V2G), and synergies with renewable energy systems. By synthesizing recent studies on microgrids, distribution networks, and transmission systems, the review highlights how controlled charging and V2G mitigate peak demand, enhance grid flexibility, and lower system costs. EVs can also act as distributed energy storage units, enabling higher renewable energy penetration and improved system resilience. However, current challenges remain, including user behavior uncertainties, infrastructure readiness, and policy support. The study concludes that EV-grid integration holds substantial promise for low-carbon transitions, while addressing battery degradation, interoperability standards, and large-scale validation will be critical for its future success.

Keywords: Electric Vehicles, Smart Charging, Vehicle-to-Grid, Renewable Energy Integration

1. Introduction

The global shift toward low-carbon energy has made the transport sector a key focus of decarbonization. Electric vehicles (EVs), seen as a cleaner option than conventional cars, are now growing rapidly around the world. The International Energy Agency estimates that the number of EVs could pass 200 million by 2030, which shows both the promise and the challenges of adopting them on a large scale. On the one hand, EVs can cut direct emissions from road transport; on the other hand, connecting so many of them to power grids raises issues such as higher peak demand, voltage problems, and system reliability.

Research has pointed out that if charging is left unmanaged, the extra load can put more pressure on the grid, while coordinated charging can help flatten peaks and make better use of renewable energy [1]. V2G technologies go further by allowing two-way power flow, so EVs can act like small

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storage units, providing services such as frequency support and helping the grid stay flexible [2,3]. EV integration can also contribute to wider changes in the energy system, especially when combined with renewable generation and local energy management [4,5]. Still, how much EVs can actually help reduce emissions depends not only on the technology but also on how consumers behave, whether the charging infrastructure is ready, and what policies are in place. Studies have shown that the benefits—like lower costs and fewer emissions—can look very different depending on the region and charging patterns [5,6].

This paper reviews current approaches, including smart charging, V2G, and renewable energy integration. The study contributes to understanding their impact and guiding the design of future low-carbon power systems.

2. Technical pathways for EV-Grid integration

2.1. Smart charging strategies

Traditional charging, where EV users connect to the grid immediately upon arrival, typically leads to instant demand peaks, creating pressure on the distribution network and increasing reliance on fossil-based peaking plants. Smart charging, on the other hand, means managing when and how fast EVs are charged, based on system conditions, electricity prices, or the availability of renewable energy. Figure 1 illustrates how different smart charging and control scenarios impact the contribution of various energy sources to the grid, highlighting the potential for optimizing renewable energy integration and reducing reliance on fossil fuels.

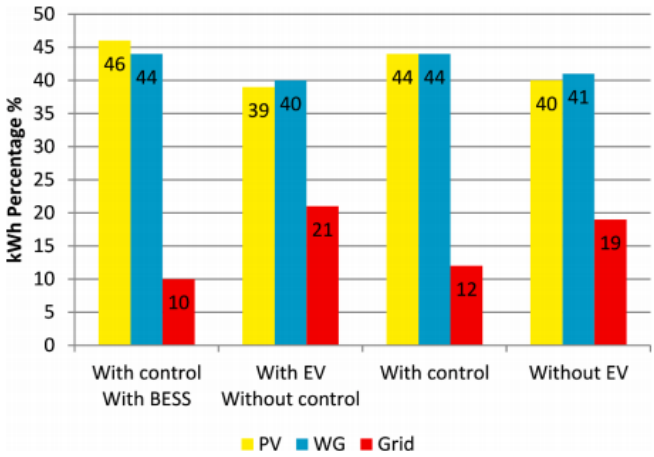


Figure 1. Energy source contribution under different smart charging and control scenarios [2]

Many studies have shown that smart charging helps flatten the load curve and lower operating costs. For example, simulations on European transmission grids found that moving EV charging away from peak hours could save up to 1.1 billion euros each year and cut carbon emissions by 3.2 million tons of CO_2 [2]. In developing countries like Indonesia, optimized charging was also reported to improve renewable energy use by about 4% and bring down system costs by 9% compared to uncontrolled charging [5].

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2.2. Vehicle-to-Grid (V2G) technology

Expect controlled charging, bidirectional vehicle-to-grid (V2G) technologies enable EVs both consume electricity and to discharge stored energy back into the grid. By acting as distributed energy storage units, EVs can provide ancillary services like frequency regulation, spinning reserve, and peak shaving.

Studies on residential microgrids showed that, compared to cases without EV control, controlled V2G integration cut total system costs by $0.728 million and prevented 213 kg of CO_2 emissions each year. Similarly, when combined with battery energy storage systems (BESS), controlled V2G achieved even greater savings, reducing costs by $0.835 million and CO_2 emissions by 361 kg [2]. The primary advantages of V2G include grid stability through frequency and voltage regulation, economic value for EV owners who can earn revenues by selling electricity back to the grid during high-price periods, and environmental gains by supporting the integration of renewable energy sources and reducing reliance on peaking plants.

However, challenges remain regarding battery degradation, charging infrastructure investment, and user participation. Studies highlight that battery lifespan and interoperability standards will strongly affect the feasibility of widespread V2G adoption [3].

2.3. Synergy with renewable energy sources

The integration of EVs with renewable energy sources (RES) presents a critical pathway toward sustainable energy systems. Given the variability of solar and wind power, EV batteries can function as flexible storage assets, absorbing excess generation during periods of high renewable output and discharging during demand peaks. Figure 2 compares different EV charging patterns—morning, daytime, evening, and optimized—showing their impacts on grid stability, energy cost, and renewable integration. Case studies show that coupling EVs with combined heat and power (CHP) and district heating and cooling systems reduced primary energy consumption by 32% and achieved a payback period of approximately six years [4]. Similarly, Indonesia’s national-scale modeling found that V2G integration reduced the need for stationary battery storage by 84%, while simultaneously reducing emissions by 23.7% and boosting renewable penetration by 10% [5]. These findings highlight EVs' potential to enhance renewable energy utilization when aligned with broader energy system optimization frameworks.

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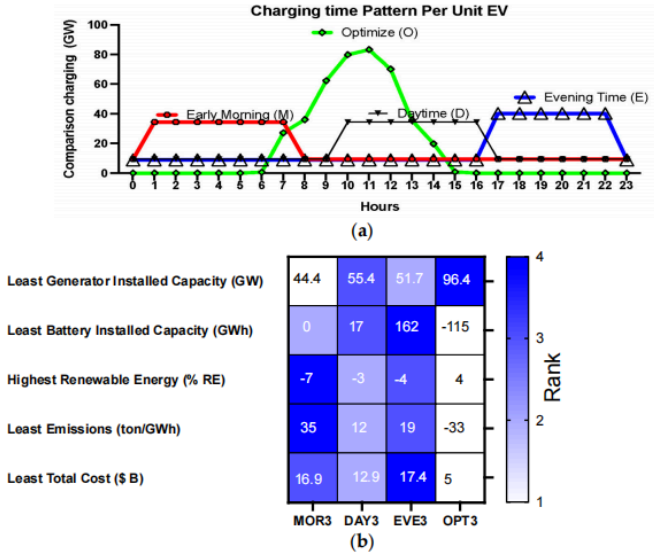


Figure 2. Comparison of EV charging patterns (morning, daytime, evening, optimized) and their impacts on system indicators. Data adapted from [5]

To sum up, smart charging addresses demand peaks, V2G supports active grid management, and renewable synergies leverage EVs as distributed storage to boost clean energy. Together, these strategies form a comprehensive framework for integrating EVs into low-carbon power systems.

3. System-level impacts

The large-scale use of electric cars (EVs) in the power system have many multiple effects, covering technical, environmental and also economic dimensions. Unmanaged charging can significantly increase evening peak demand, straining generation and distribution networks. European studies show that uncontrolled charging can raise peak load by over 30%, necessitating costly investment in new generation capacity [1]. In contrast, smart charging and V2G can make the load curve more flat and give extra help like frequency and voltage support [2,7]. For example, Sadeghian et al. looked at smart charging and said that coordinated charging could make grid costs lower about 10% and reduce wasted renewable energy by almost 40% [8]. Similarly, city-scale case studies also demonstrate that aligning EV charging with solar PV and combined heat and power (CHP) operations enhances system flexibility. Figure 3 illustrates that smart and optimized charging strategies significantly reduce peak demand stress and flatten the load curve, improving overall grid stability. EV adoption inherently reduces tailpipe emissions compared to conventional vehicles. However, the net environmental benefit depends on the generation mix. Charging from coal-dominated grids may even offset emission gains, while coupling EVs with renewable resources can achieve substantial reductions. Amiruddin et al. conducted a national-level case study for Indonesia, where different EV penetration scenarios were evaluated [5]. Results showed that under smart charging and V2G, the share of renewable utilization increased and carbon emissions declined significantly compared to unmanaged charging. In parallel, a European review estimated that smart charging could reduce CO_2 emissions by 600,000 tons per year by 2030 relative to uncontrolled charging [8].

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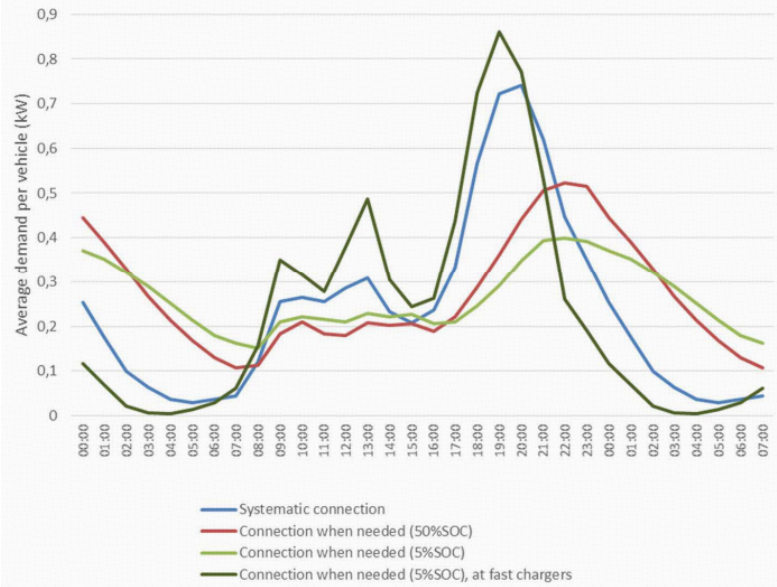


Figure 3. BEV demand curve on working days by connection behavior [5]

The economic implications of EV-grid integration are context-dependent. Unmanaged EV growth can increase total costs due to the need for new peaking capacity, network reinforcement, and higher fossil fuel consumption. In the UK, Logan et al. argued that the national grid could face substantial cost escalations without flexible charging policies [6]. Conversely, coordinated strategies shift charging to off-peak periods, reducing strain on the system and lowering marginal generation costs. Empirical case studies show that smart charging reduced system operating costs by 9% in Indonesia, while V2G integration cut costs by USD 3.4 billion over the study horizon and reduced the need for stationary battery storage by 84% [5]. At the microgrid scale, Aziz et al. found that controlled V2G in residential systems reduced total system costs by USD 0.728 million annually and avoided 213 kg of CO_2 emissions, while the combination of V2G and battery storage achieved even larger cost savings and emission reductions [2]. These localized results reinforce the broader conclusion that EVs can provide economic value when integrated through smart coordination.

From a policy perspective, Oshnoei et al. and Alsharif et al stressed that the economic viability of EV-grid integration depends not only on technical optimization but also on user participation and market frameworks [8,9]. Aggregator-based V2G models, where fleets of EVs are managed collectively to participate in ancillary service markets, are emerging as promising business models. However, challenges remain in ensuring fair compensation for users and managing uncertainties in participation.

Overall, EV-grid integration can provide significant cost savings and environmental benefits, particularly in systems with high renewable penetration. Policy and regulatory frameworks must align user incentives with system-level benefits to maximize these advantages.

4. User behavior and acceptance

The successful implementation of EV-grid integration strategies is highly dependent on user behavior and acceptance. Unlike traditional grid assets, EVs are privately owned and operated, and their flexibility can only be realized if users are willing to modify charging habits or participate in V2G programs.User charging preferences strongly influence system impacts. Most EV drivers tend to plug in after work, creating evening peaks. Smart charging strategies require users to accept

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delayed or shifted charging, which may be perceived as inconvenient. Surveys cited in Oshnoei et al. revealed that while up to 70% of users are open to time-shifted charging if properly incentivized, only 20–30% are comfortable with their vehicles discharging into the grid under V2G programs [8]. Economic incentives are critical to encourage user participation. Time-of-use tariffs, real-time pricing, and aggregator-based compensation mechanisms have been shown to increase acceptance. For example, European pilot projects demonstrated that users could save 15–25% on charging costs through participation in managed charging programs [7]. However, inadequate or unclear compensation for battery degradation in V2G remains a barrier.

User behavior introduces uncertainty into system modeling. Charging demand is influenced by lifestyle, travel distance, and vehicle type. Models that assume full compliance with charging schedules may overestimate benefits. As Alsharif et al. highlighted, future research should incorporate probabilistic user models to better capture behavioral variability [9].

In summary, user participation is both the greatest opportunity and the greatest challenge for EV-grid integration. Without widespread behavioral alignment, the technical and economic benefits of smart charging and V2G cannot be fully realized.

5. Policy and infrastructure

Technical solutions must be supported by policy frameworks and adequate infrastructure. Governments play a central role in enabling EV-grid integration through regulation, incentives, and long-term planning.National decarbonization strategies and EV adoption targets provide a foundation for EV-grid integration. The UK government, for instance, has announced a ban on new internal combustion engine vehicles by 2030 [6]. Such policies accelerate EV adoption, but without parallel charging strategies, they risk destabilizing the grid. Carbon pricing and renewable portfolio standards also indirectly strengthen the value proposition of V2G and smart charging. The expansion of charging infrastructure is essential to accommodate EV growth. Distribution networks must support both fast-charging stations and residential charging points. Logan et al. warned that insufficient charging infrastructure in the UK could result in localized congestion and uneven adoption [6]. Smart meters and bidirectional chargers are also necessary to enable dynamic pricing and V2G.Case studies highlight the role of policy and infrastructure in shaping outcomes. In Europe, coordinated regulation and cross-border electricity markets enhance the feasibility of large-scale smart charging. In Indonesia, Amiruddin et al. showed that infrastructure expansion, combined with optimized charging, could reduce costs and emissions while enhancing renewable integration [5]. These examples demonstrate that technical pathways are deeply intertwined with policy environments.

6. Conclusion

This paper reviews the integration of electric vehicles into power grids, focusing on three key technical pathways—smart charging, V2G, and renewable energy synergy—and their system-level impacts. To sum up, smart charging helps cut down peak loads and saves money, while also making better use of renewables. V2G goes a step further by helping balance the grid and reducing the need for extra batteries. Moreover, the combination of EVs and renewable energy can significantly cut carbon emissions, although it requires good planning to connect with things like electricity, heating, and cooling systems. It is important to note that economic and environmental outcomes are highly context-dependent, shaped by grid composition, user behavior, and policy support.

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However, this review is limited by its reliance on secondary literature rather than original simulation or empirical data, which may restrict the depth of quantitative insights.Future work could incorporate real-world pilot projects, broader geographic comparisons, and more detailed modeling of user behavior to provide a more comprehensive understanding of EV-grid integration. Ultimately, EV-grid integration represents both a challenge and an opportunity for the transition to low-carbon energy systems. The benefits are not automatic; they depend on the deployment of intelligent charging strategies, user engagement, and enabling policy frameworks. With continued technological advancement, supportive regulation, and growing EV adoption, EVs can evolve from passive consumers to active assets that underpin a resilient and sustainable energy future.

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