

INTEGRATED GRID-TO-VEHICLE AND VEHICLE-TO-GRID ARCHITECTURES FOR HIGH-RENEWABLE POWER SYSTEMS: OPTIMIZATION PARADIGMS, UNCERTAINTY, AND SYSTEM-LEVEL IMPLICATIONS

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Article received: 02/01/2026, Article Accepted: 30/01/2026, Article Published: 01/02/2026

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ABSTRACT

The accelerating global transition toward low-carbon energy systems has positioned electric vehicles as both a major new load and a flexible distributed energy resource within modern power grids. Beyond their conventional role as transportation devices, electric vehicles increasingly participate in grid-to-vehicle and vehicle-to-grid interactions, enabling bidirectional energy exchange, demand-side flexibility, and ancillary service provision. This research article develops a comprehensive and theoretically grounded investigation of integrated grid-to-vehicle and vehicle-to-grid architectures, with a particular emphasis on optimization techniques, uncertainty management, and large-scale system implications under high renewable energy penetration. Drawing strictly on the existing scholarly literature, the article synthesizes insights from foundational smart grid studies, contemporary vehicle-to-grid modeling frameworks, photovoltaic-electric vehicle co-optimization research, profitability analyses under uncertainty, and system-level case studies from diverse geographical contexts.

The study advances the argument that grid-to-vehicle and vehicle-to-grid strategies must be conceptualized not merely as technical charging schemes, but as socio-technical coordination mechanisms embedded within evolving energy markets, regulatory environments, and renewable-dominated power systems. Methodologically, the article adopts a qualitative-analytical synthesis of optimization paradigms, including deterministic scheduling, stochastic optimization, information gap decision theory, and hybrid frameworks that account for uncertainty in renewable generation, vehicle availability, battery degradation, and market prices. Particular attention is devoted to the modeling of electric vehicle batteries, driving behavior, and state-of-health dynamics, recognizing their critical influence on the long-term feasibility of bidirectional grid participation.

The results section presents an integrated descriptive analysis of how coordinated charging, vehicle-to-grid aggregation, and virtual power plant configurations reshape load profiles, mitigate network congestion, and enhance renewable energy utilization across distribution and transmission levels. The discussion critically examines economic viability, battery aging trade-offs, and the role of policy and market design in enabling scalable deployment. Limitations associated with model assumptions, data uncertainty, and real-world behavioral variability are explored in depth, alongside future research pathways involving multi-energy systems, advanced forecasting, and digitalized grid control. The article concludes that electric vehicles, when systematically integrated through optimized grid-to-vehicle and vehicle-to-grid frameworks, constitute a cornerstone technology for resilient, renewable-intensive power systems, provided that technical, economic, and institutional challenges are addressed in a coordinated manner.

Keywords: Electric vehicles; Vehicle-to-grid; Grid-to-vehicle; Smart grids; Renewable energy integration; Optimization; Energy systems.

INTRODUCTION

The global energy landscape is undergoing a profound transformation driven by the dual imperatives of

decarbonization and electrification. Electricity systems that were historically designed around centralized, dispatchable generation are increasingly dominated by

variable renewable energy sources such as wind and solar power. At the same time, the electrification of end-use sectors, most notably transportation, is introducing new patterns of demand that challenge conventional grid planning and operation. Electric vehicles occupy a unique position at the intersection of these trends, acting simultaneously as mobile loads, distributed storage units, and potential providers of grid services.

Early research into electric vehicle integration focused primarily on the risks associated with uncontrolled charging, including peak load amplification, voltage deviations, and transformer overloading in distribution networks. Foundational studies on coordinated charging emphasized the necessity of management procedures to mitigate these impacts, particularly in residential settings where clustering effects can exacerbate local constraints (Lopes, Soares, and Almeida, 2009; Clement, Haesen, and Driesen, 2009). As electric vehicle penetration increased, attention gradually shifted from defensive strategies aimed at avoiding grid stress toward proactive approaches that leverage electric vehicle flexibility to support system objectives.

The emergence of vehicle-to-grid concepts marked a pivotal shift in this discourse. Vehicle-to-grid refers to the bidirectional exchange of energy between electric vehicles and the power grid, enabling vehicles to discharge stored energy back into the system during periods of high demand or low renewable generation. In contrast, grid-to-vehicle encompasses controlled charging strategies that align vehicle charging with grid conditions, renewable availability, or price signals. Together, these paradigms form an integrated framework for electric vehicle-grid interaction that has been explored across technical, economic, and policy dimensions.

Comprehensive reviews of grid-to-vehicle and vehicle-to-grid technologies highlight a rapidly expanding body of research addressing power electronics, communication architectures, aggregation mechanisms, and optimization techniques (Thorat and Bhatt, 2023). These reviews underscore the complexity of electric vehicle integration, which spans multiple temporal and spatial scales, from real-time frequency regulation to long-term capacity planning. Moreover, they emphasize that successful implementation depends not only on technological readiness but also on market structures and regulatory incentives.

Parallel to these developments, studies on renewable-dominated power systems have demonstrated the growing need for flexible resources capable of balancing variability and uncertainty. Early smart grid initiatives in wind-rich regions illustrated how advanced control, demand response, and distributed resources could enable high shares of renewable generation without compromising reliability (Xu et al., 2009).

Electric vehicles, with their inherent storage capacity and controllable charging behavior, have since been recognized as a natural complement to such systems.

Despite substantial progress, several gaps persist in the literature. First, many studies examine grid-to-vehicle or vehicle-to-grid strategies in isolation, without fully capturing their integrated system-level interactions. Second, optimization models often rely on simplifying assumptions regarding vehicle availability, user behavior, and battery degradation, limiting their real-world applicability. Third, economic analyses frequently focus on short-term profitability without adequately addressing long-term uncertainty and infrastructure impacts. Finally, the transferability of findings across different geographic and regulatory contexts remains underexplored, particularly for emerging economies and islanded or archipelagic systems.

This article addresses these gaps by offering an extensive, theory-driven synthesis of grid-to-vehicle and vehicle-to-grid integration within renewable-intensive power systems. By drawing on a diverse set of peer-reviewed studies, it aims to articulate a coherent conceptual framework that connects optimization techniques, uncertainty management, and system-level outcomes. In doing so, it seeks to contribute to both academic understanding and practical decision-making in the evolving field of electric vehicle-grid integration.

Methodology

The methodological approach adopted in this research is qualitative and analytical, centered on an in-depth synthesis of established models, optimization frameworks, and empirical findings reported in the peer-reviewed literature. Rather than introducing new numerical simulations or mathematical formulations, the study systematically interprets existing methodologies to extract generalizable insights and theoretical implications. This approach is particularly appropriate given the objective of developing a comprehensive, publication-ready article that consolidates knowledge across multiple domains of electric vehicle-grid interaction.

A central methodological pillar is the comparative analysis of optimization techniques employed in grid-to-vehicle and vehicle-to-grid studies. Deterministic optimization approaches are examined first, as they form the historical foundation of coordinated charging research. These methods typically assume perfect foresight regarding vehicle arrival times, departure schedules, and energy requirements, enabling the formulation of optimal charging profiles that minimize peak demand or energy costs. While such approaches offer valuable baseline insights, their limitations in handling uncertainty are critically assessed.

To address these limitations, the methodology incorporates stochastic optimization frameworks that explicitly model uncertainties in renewable generation, electricity prices, and vehicle behavior. Studies employing stochastic programming demonstrate how probabilistic scenarios can be used to balance expected costs against risk exposure, particularly in systems with high shares of wind and solar energy (Ahrabi et al., 2021). Information gap decision theory further extends this perspective by focusing on robustness under severe uncertainty, enabling decision-makers to identify strategies that remain acceptable across a wide range of unknown conditions.

Hybrid optimization approaches that combine deterministic, stochastic, and robust elements are also examined, especially in the context of virtual power plants and multi-energy systems. These frameworks integrate electric vehicles alongside other flexible resources, such as stationary storage and controllable loads, to achieve zero-carbon or low-emission objectives (Alabi, Lu, and Yang, 2021). The methodological analysis emphasizes how such integrated models capture interdependencies between energy carriers and temporal scales.

Another critical methodological dimension concerns the modeling of electric vehicle batteries and driving behavior. Comprehensive vehicle models that account for battery capacity, efficiency, degradation, and user constraints are essential for realistic vehicle-to-grid strategy development (Rücker et al., 2022). Driving pattern analysis provides empirical grounding for assumptions about vehicle availability, highlighting the diversity of usage profiles across regions and user groups (Wu et al., 2010). The methodology therefore pays particular attention to how behavioral data are incorporated into optimization models.

Finally, the article adopts a systems analysis perspective to contextualize methodological findings within broader energy system transformations. Case studies from national and regional contexts, including high-wind power systems and archipelagic grids, are interpreted to illustrate how methodological choices influence real-world outcomes (Xu et al., 2009; Herlambang, 2025). Through this multi-layered methodological synthesis, the article constructs a robust analytical foundation for the subsequent results and discussion.

Results

The synthesis of existing research reveals a consistent pattern of results demonstrating the transformative potential of integrated grid-to-vehicle and vehicle-to-grid strategies. Across diverse system configurations and geographic contexts, coordinated electric vehicle integration emerges as a key enabler of flexibility, efficiency, and renewable energy utilization.

One of the most prominent results concerns load profile reshaping. Coordinated grid-to-vehicle charging significantly reduces peak demand compared to uncontrolled charging, particularly in residential distribution networks with high electric vehicle penetration. By shifting charging to off-peak hours or periods of high renewable generation, these strategies alleviate stress on local infrastructure and defer costly grid reinforcements (Clement, Haesen, and Driesen, 2009; Lopes, Soares, and Almeida, 2009).

Vehicle-to-grid participation further enhances these benefits by allowing electric vehicles to actively supply power during peak periods or system contingencies. Aggregated fleets of vehicles can provide ancillary services such as frequency regulation and reserve capacity, effectively functioning as distributed power plants. Profitability analyses indicate that, under favorable market conditions, vehicle-to-grid services can generate additional revenue streams for vehicle owners and aggregators, although returns are sensitive to price volatility and participation rates (Bianchi et al., 2023).

The integration of electric vehicles with on-site renewable generation, particularly rooftop photovoltaic systems, yields synergistic results. Scheduling optimization studies demonstrate that co-optimizing vehicle charging and photovoltaic output increases self-consumption, reduces grid imports, and enhances overall energy efficiency at the building or community level (Lv et al., 2023). These results underscore the importance of localized optimization in complementing system-wide strategies.

At the transmission level, electric vehicle parking lots and aggregated fleets contribute to congestion management and unit commitment optimization. Hybrid stochastic and robust approaches reveal that electric vehicles can mitigate the impacts of transmission constraints by providing localized flexibility, thereby improving system reliability under uncertainty (Ahrabi et al., 2021).

Battery modeling results highlight a nuanced trade-off between economic benefits and degradation costs. While frequent vehicle-to-grid cycling increases revenue potential, it also accelerates battery aging, potentially offsetting financial gains. Advanced state-of-health estimation and remaining useful life prediction models provide critical insights into this trade-off, enabling more informed optimization strategies that balance short-term profitability against long-term asset value (Li et al., 2021).

System-level case studies demonstrate that electric vehicle integration is particularly valuable in renewable-rich systems. In power systems with high wind penetration, electric vehicles contribute to balancing

variability and reducing curtailment, supporting ambitious renewable targets without compromising reliability (Xu et al., 2009). In emerging economies and archipelagic systems, electric vehicles and renewables jointly offer pathways to reduce dependence on imported fossil fuels and enhance energy security (Herlambang, 2025).

Collectively, these results paint a compelling picture of electric vehicles as multifunctional assets whose value extends far beyond transportation. When integrated through optimized grid-to-vehicle and vehicle-to-grid frameworks, they enhance system flexibility, economic efficiency, and sustainability across multiple scales.

Discussion

The results synthesized in this article invite a deeper discussion of their theoretical and practical implications. At a conceptual level, grid-to-vehicle and vehicle-to-grid strategies challenge traditional distinctions between supply and demand in power systems. Electric vehicles blur these boundaries, embodying a hybrid role that necessitates new analytical frameworks and governance models.

One critical implication concerns market design. The profitability of vehicle-to-grid services depends heavily on access to ancillary service markets, compensation mechanisms, and aggregation rules. Without appropriate market structures, the technical potential identified in optimization studies may remain unrealized. This observation aligns with findings that uncertainty and regulatory barriers significantly influence investment decisions and participation levels (Bianchi et al., 2023).

Another key discussion point relates to user behavior and acceptance. Optimization models often assume rational, compliant participants, yet real-world behavior is shaped by convenience, trust, and perceived risk. Driving pattern analyses reveal substantial heterogeneity in vehicle usage, suggesting that one-size-fits-all strategies may be ineffective (Wu et al., 2010). Incorporating behavioral insights into optimization frameworks remains a critical research frontier.

Battery degradation emerges as both a technical and economic constraint. While advanced modeling techniques improve state-of-health estimation, uncertainty regarding long-term degradation under vehicle-to-grid operation persists. This uncertainty complicates cost-benefit analyses and underscores the need for conservative, robust optimization approaches that protect user interests (Li et al., 2021; Rucker et al., 2022).

From a system perspective, electric vehicle integration must be evaluated alongside other flexibility options,

including stationary storage, demand response, and grid reinforcement. Hybrid virtual power plant models illustrate how electric vehicles can complement these resources, but they also highlight the complexity of coordination in multi-energy systems (Alabi, Lu, and Yang, 2021).

Geographic context plays a decisive role in shaping outcomes. Lessons from wind-dominated systems may not directly translate to regions with different resource profiles or infrastructure constraints. Case studies from islanded and developing systems emphasize the importance of tailored solutions that account for local conditions, institutional capacity, and socio-economic priorities (Herlambang, 2025).

Despite these challenges, the overarching trajectory is clear. Electric vehicles, when strategically integrated, offer a scalable and versatile flexibility resource that aligns with long-term decarbonization goals. Future research should prioritize interdisciplinary approaches that bridge technical optimization with behavioral science, policy analysis, and real-world pilot projects.

Conclusion

This article has presented an extensive, theory-driven exploration of integrated grid-to-vehicle and vehicle-to-grid architectures within renewable-intensive power systems. By synthesizing a diverse body of peer-reviewed research, it has demonstrated that electric vehicles are not merely passive loads but active system components capable of delivering substantial technical, economic, and environmental benefits.

The analysis reveals that optimized charging and discharging strategies mitigate grid constraints, enhance renewable energy utilization, and create new value streams through ancillary services. At the same time, it highlights the importance of uncertainty management, realistic battery modeling, and user-centric design in ensuring long-term feasibility.

Ultimately, the successful integration of electric vehicles into future power systems depends on coordinated advancements in optimization methodologies, market design, and policy frameworks. As renewable penetration continues to rise, electric vehicles will play an increasingly central role in shaping resilient, flexible, and sustainable energy systems. This article contributes to that ongoing discourse by offering a comprehensive conceptual foundation for both academic inquiry and practical implementation.

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