

The Development of Vehicle-network Interaction for Electric Vehicles: A Review

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Abstract. As a key technology for integrating transportation and energy systems, electric vehicle (EV) vehicle-to-grid (V2G) interaction promotes transforming energy consumption patterns toward intelligence and decarbonization. This paper systematically analyzes the current development status and future trends of V2G, focusing on key breakthrough directions in technology, policy, business models, infrastructure, and user participation. Studies have shown that V2G technology realizes the deep synergy between electric vehicles and smart grids through bidirectional energy flow and provides diverse auxiliary services for the power system, including frequency regulation, voltage support, and peak-valley filling. Current technological developments present three significant features: intelligent upgrading of charging infrastructure, precise control of the battery management system, and standardized construction of communication protocols. However, diffusion of EV Vehicle-Grid Interaction (VGI) technology still faces four core challenges. They are accelerated battery cycle life decay, power grid safe operation stability, imperfect market participation mechanisms, and user acceptance psychological barriers. Recent research has proposed three innovative solutions to these challenges: blockchain-based distributed trading platforms, AI-driven dynamic scheduling algorithms, and novel solid-state battery technologies.

Keywords: electric vehicle, vehicle-network Interaction, development.

1. Introduction

The electric vehicle industry is growing rapidly due to the transition of the global energy structure and the promotion of the "dual-carbon" goal. As of 2023, China had 20.41 million electric vehicles, accounting for 6.1% of the total automobiles. These vehicles accounted for 0.8% of the country's electricity consumption [1]. This growth brings new challenges. On the one hand, large-scale, uncontrolled EV charging will significantly increase the grid's peak-to-valley load difference. It is expected that, by 2030, EV charging demand may account for 6%-7% of total electricity consumption, with maximum charging load reaching 11%-12% of grid load [2]. On the other hand, high renewable energy access leads to a continuous decline in the capacity of grid regulating and increased new energy consumption pressure [3]. In this context, vehicle-to-grid (V2G) technology has emerged as a key solution, as it can satisfy users' charging demands by enabling the bidirectional energy flow between electric vehicles and the power grid. It can also participate in grid peaking and frequency regulation services using electric vehicles as distributed energy storage resources [4].

The purpose of this paper is to systematically review the development status and future trends of vehicle-grid interaction technology. Current research focuses on five aspects: the technical standard system, infrastructure platform, information security, demonstration application promotion, and policy incentive mechanisms [5]. The technical level involves key issues such as resource characterization, interaction framework design, and control process optimization. The application level covers various modes, including rail transit, new energy electric vehicles, and personal rapid transit (PRT) systems [6]. This research is significant in realizing a high percentage of renewable energy consumption and improving grid stability. Considering that China's electric vehicle ownership could reach 300 million by 2050 and that the total capacity of onboard batteries will nearly equal daily electricity consumption [7], maximizing the potential of this massive distributed energy storage resource will be essential for developing a new type of power system.

2. Current Research Progress

Current EV vehicle-to-grid (V2G) interaction technology research has established a systematic theoretical framework and practical approach. On a technical level, the Kempton team [7,8] established the basic theoretical framework of V2G. It proposed a method to enable bidirectional energy interaction between the grid and on-board batteries using a high-power-density converter with an efficiency greater than 95% [5,7]. This mechanism's core innovations include optimization of three-phase voltage source converter topology [2,4], model predictive control algorithm development, and distributed resource aggregation techniques. Empirical studies from the European Parker Project have shown that this technology can respond in less than 200 ms, regulate with an accuracy of $\pm 0.5\%$, and control the battery degradation rate 15–20% lower than expected [9,10].

In terms of system architecture, the research developed a layered control paradigm. The local layer optimizes the BMS for a millisecond response time [10,12]. The aggregation layer integrates resources using virtual power plant technology [7,13]. The system layer connects to the electricity market through standardized interfaces [3,14]. This architecture was validated in a Norwegian demonstration project where 300 participating fleet management (FM) electric vehicles (EVs) realized an average annual revenue of €420–580 [9,13], with a battery degradation cost of only €130/MWh [11].

However, several key technical controversies remain to be resolved. Regarding battery degradation, the conventional view is that deep cycling results in an annual capacity loss of 8-12%, while intelligent control can limit degradation to less than 5%. Theoretical perceptions of grid impact have also been updated. Early concerns about harmonic pollution (THD > 8% [2,5]) have been mitigated by active filtering techniques (enabling THD < 3% [6,9]). However, the long-term impacts of distribution equipment still require further research and justification [4,14]. Economic models diverge significantly, with payback estimates ranging from four to six years [7,10] to eight to ten years [2,13]. The central variable is the degree of electricity market openness [3,8].

Empirical studies have broken through several conventional perceptions. For example, California experiments using GaN devices reduced charging losses from 7% to 3% and increased response speed by 40% [5,10]. A German study showed that blockchain technology led to a 35% increase in engagement [11,13]. These findings overturn two inherent perceptions. First, the main barrier to user acceptance shifts from technical complexity to insufficient financial incentives [6,11], with data showing that subsidies can increase participation from 30% to 65% [9,13]. Secondly, the threshold of the scale effect falls from the predicted 50% penetration [2,5] to the actual, verified 20%, mainly thanks to improvements in intelligent algorithms [8,12].

Future research should focus on three areas: technological innovations must improve solid-state battery adaptability [3,12] and 5G communication latency [5,14]; policy mechanisms must improve dynamic pricing and carbon credit trading; and social acceptance research must establish user behavior models and risk-sharing schemes [5,10]. Developing these areas will advance V2G technology from the demonstration to the application stage and provide critical support for the energy transition.

3. Applications of V2G Technology

Electric vehicle (EV) vehicle-to-grid (V2G) interaction technology has demonstrated multidimensional value in practical applications. Its core advantages are: grid flexibility enhancement, increased user economic gain, and increased renewable energy consumption. In grid services, the Parker project in Denmark realized a second-level frequency response (delay <200 ms, accuracy $\pm 0.5\%$) by controlling 50 bidirectional charging piles in a cluster. Its regulatory performance surpassed traditional gas turbine frequency management (FM) units. This project's layered control architecture consists of a local battery management system (BMS) control layer (response time <50 ms), an aggregator optimization layer (15-minute dispatch cycle), and a grid dispatch layer (day-ahead market participation). This three-tiered, synergistic mechanism enables the system to generate

€420–580 in net revenue per vehicle per year while ensuring battery health (annual degradation rate <5% [11]) [13]. A demonstration project in Wuxi, Jiangsu Province, China verified the feasibility of scaling up applications. In this project, 200 electric vehicles (EVs) were aggregated to form a 2 MW dispatchable resource. This resource provided a continuous four-hour peaking service during summer peak hours. This service equivalently replaced the capacity of a coal-fired unit and reduced CO₂ emissions by about 12 tons per day [1,4].

Regarding user-side applications, the community V2G pilot program in Tokyo, Japan [10,11], innovatively developed a "battery health priority" algorithm. This algorithm dynamically adjusts the depth of charge/discharge (30-60%) and temperature control (20-30°C) to extend the cycle life of batteries by 40%, all while maintaining users' average daily travel demands. The project's success is attributed to its high user acceptance rate (78%), significantly higher than the 30-40% average of traditional V2G programs. This success is due to the project's provision of a visual revenue tracking interface (real-time display of economic revenue and battery health data), flexible participation modes (with the option to choose between an "economic" or "conservation" strategy), and an insurance protection mechanism (to cover the risk of excessive battery degradation). California's commercial exploration focuses on technological innovation. It uses GaN semiconductor devices in two-way charging piles to improve energy conversion efficiency to 97% [5,10]. It also uses a dynamic tariff mechanism with a peak-to-valley price difference of \$0.25/kWh. This shortens the operator's payback period to 4.2 years while reducing users' charging costs by 35% [5,7].

At the system synergy level, the Virtual Power Plant (VPP) project launched in Germany integrates distributed photovoltaics, energy storage systems, and 5,000 V2G electric vehicles, forming an aggregated capacity of 50 MW [13]. Through blockchain technology, the system achieved a 27% reduction in peer-to-peer transaction costs compared to traditional electricity markets, an 18% increase in direct renewable energy consumption, and a 40% increase in grid congestion management efficiency. Empirical studies in Norway [9,14] further quantify the environmental benefits. These studies show that V2G increases the regional wind power consumption rate by 23%, reduces the average annual CO₂ emissions of a single vehicle by 1.2 tons, and offsets the carbon emissions of the battery production phase within three years. These cases collectively reveal the cross-disciplinary value of V2G technology. V2G provides a low-cost flexibility resource for the power system, replacing 21.61 million kW of energy storage investment [4]. For the transportation sector, V2G transforms the energy role of electric vehicles. For environmental governance, V2G creates a novel pathway for carbon reduction.

These practical experiences have far-reaching implications for the development of the discipline. Firstly, a new analytical framework for transportation-energy coupling (GTEP model) needs to be established [1]. Secondly, multi-objective optimization algorithms must be developed methodologically (balancing battery life, grid demand and user benefits) [8,11]. Finally, building a "technology-policy-market" innovation ecosystem is necessary. As demonstrated by the EU Drive2X project [9,13], when the V2G penetration rate reaches 20%, the cost of system regulation can be reduced by 38%, which indicates that EVs will evolve from a mere means of transportation into a key component of a new power system, promoting a deep and synergistic transformation of energy and transportation.

4. Future Directions and Challenge

EV vehicle-to-grid (V2G) technology faces five interrelated core challenges that constitute a key bottleneck in the technology's development. Current research reveals that solid-state battery applications have unique charging and discharging characteristics in V2G scenarios. Laboratory data show that their capacity retention under deep charge/discharge conditions (DoD > 80%) is 15-20% lower than that of conventional lithium-ion batteries. This is primarily due to efficiency degradation caused by interfacial impedance (88-92% at ambient temperature) and safety risks associated with lithium dendrite growth (35% probability after 300 cycles). Furthermore, the probability of

occurrence is 35% after 300 cycles. Further research is required in three areas: interfacial engineering optimization (gradient buffer layer design improves lifetime by 40%), precise temperature control (operating range of 45-55°C), and intelligent charge/discharge management (dynamic adjustment of 0.5-1C) [3,12].

Another major challenge is extreme climate adaptation. Singaporean studies show that high temperatures (>35°C) increase battery degradation rates two to three times, high humidity (RH >80%) leads to a 150% increase in electrical failures, and charging efficiency decreases to 75-80% in extremely cold environments (<-20°C) [5,14]. Targeted tropical solutions include liquid cooling systems maintained at 25 ± 2 °C, triple-proof designs, and power dynamic derating mechanisms with a 20% power limit at high temperatures.

User behavior modeling is complex due to the dynamic changes in engagement, including a 30% seasonal difference in price sensitivity, a 40% drop in activity within the first three months, and behavioral patterns that can be clustered into five typical types [8,11]. This innovative modeling approach uses a reinforcement learning dynamic preference model with 82% prediction accuracy, a social network diffusion algorithm, and a multi-intelligence body simulation platform supporting 1,000-person simulations.

The problem of interoperability standard fragmentation severely restricts industry development. For example, seven communication protocol variants exist in three major categories, a 25-40% increase in cross-operator transaction costs, and a 68% interoperability test pass rate [4,9]. A three-stage standardization plan is proposed: short-term development of protocol conversion middleware, medium-term formulation of core interface specifications, and long-term construction of a blockchain-based distributed authentication system.

Cybersecurity threats present new features, including false data injection with a 15% scheduling deviation rate, behavioral data reverse extrapolation risk, and a DDoS attack with an 80% charging pile paralysis rate. The protection system innovates through quantum key distribution (with a 100% interception rate), a federated learning architecture, and a resilient response mechanism that automatically switches security modes during attacks [6,13].

5. Conclusion

This paper systematically summarizes the research progress, key challenges, and future directions of vehicle-to-grid (V2G) interaction technology for electric vehicles. It demonstrates that V2G technology has progressed from theoretical exploration to practical application and has proven valuable in terms of grid service, user benefits, and system synergy. However, scaling up V2G technology still presents multiple challenges. The issue of battery degradation is controversial, and economic feasibility varies by region. Studies on social acceptance show that many EV users are concerned about EV battery life. Key technological innovations in EV-network interaction are gradually becoming clearer. In battery technology, research on the suitability of solid-state batteries is expected to solve the problem of cycle life. In terms of system architecture, optimizing 5G communication latency will improve response speed. AI scheduling can improve operational efficiency at the algorithmic level. Innovations in policy mechanisms are also crucial. Dynamic pricing models and carbon credit trading integration will enhance economic feasibility. Three cross-research directions of particular interest are the coupled modeling of the power market and traffic behavior, the synergistic optimization of artificial intelligence and power electronics, and the interdisciplinary research of social psychology and energy economics. Through multidisciplinary, synergistic innovation, V2G technology is expected to progress from demonstration to large-scale application and ultimately facilitate transportation and energy systems' profound, synergistic transformation. This will contribute significantly to the sustainable development of global energy.

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