

Review

Vehicle-to-Grid Systems for Renewable Energy Integration: Scheduling, Economics, and User Engagement

Peiying Zhang ^{1,2} , Xiangguo Zheng ^{1,2} , Yujie Yuan ^{3,*} , Xi Chen ^{4,5}  and Chun Sing Lai ⁶ 

¹ Qingdao Institute of Software, College of Computer Science and Technology, China University of Petroleum (East China), Qingdao 266580, China; zhangpeiying@upc.edu.cn (P.Z.); z24070095@s.upc.edu.cn (X.Z.)

² Shandong Key Laboratory of Intelligent Oil & Gas Industrial Software, Qingdao 266580, China

³ The School of Air Traffic Management, Civil Aviation University of China, Tianjin 300300, China

⁴ Department of Artificial Intelligence, China Electric Power Research Institute, Beijing 100192, China; xc@ieee.org

⁵ GEIRI North America, 250 W Tasman Dr., San Jose, CA 95134, USA

⁶ State Key Laboratory of Smart Power Distribution Equipment and System, Tianjin University, Tianjin 300072, China; cslai@tju.edu.cn

* Correspondence: yjyuan@cauc.edu.cn

Abstract

With the rapid growth of electric vehicles (EVs) and renewable energy generation, Vehicle-to-Grid (V2G) technology has emerged as a promising approach for transforming EVs from passive charging loads into flexible distributed energy storage resources. By enabling bidirectional power exchange between EV batteries and the power grid, V2G can support renewable energy accommodation, peak shaving, demand response, ancillary services, and local grid balancing. This review provides a systematic synthesis of recent advances in V2G systems for renewable energy integration, with particular emphasis on coordinated scheduling, economic mechanisms, battery degradation, and user engagement. First, the technical foundations of V2G are introduced, including Vehicle-to-Everything operating modes, bidirectional charging architecture, aggregation mechanisms, grid-support services, and renewable accommodation pathways. Second, major scheduling strategies are reviewed, including price-based, load-based, renewable-forecast-driven, centralized, distributed, and hybrid approaches. Third, the economic feasibility of V2G is examined from the perspectives of revenue streams, pricing mechanisms, business models, battery aging costs, and compensation schemes. In addition, user participation barriers, such as range anxiety, battery lifetime concerns, loss of control, uncertain financial returns, and data privacy, are discussed. Key challenges related to communication standards, interoperability, cybersecurity, market access, policy design, and pilot-scale validation are also summarized. Finally, future development directions are identified, including AI-based scheduling, aggregator platforms, fleet-scale V2G, degradation-aware optimization, carbon-aware electricity markets, and user-centered participation mechanisms. This review highlights that large-scale V2G deployment requires the integrated coordination of technical scheduling, economic incentives, battery health protection, and user acceptance in renewable-rich power systems.

Keywords: vehicle-to-grid; electric vehicles; renewable energy integration; coordinated scheduling; economic incentives; battery degradation; user engagement



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1. Introduction

The rapid electrification of road transportation is changing the interaction between mobility systems and electric power systems. Electric vehicles (EVs) are widely regarded

as an important pathway for reducing transport-related emissions and improving energy efficiency. However, the large-scale integration of EVs also introduces new operational challenges for power grids, particularly at the distribution level. When EV charging is uncoordinated, charging demand may coincide with existing peak-load periods, resulting in increased transformer and feeder loading, voltage deviations, higher peak-to-valley differences, and reduced distribution network hosting capacity [1]. These impacts are especially relevant in residential communities, workplace charging areas, fast-charging stations, and fleet depots, where charging behavior is closely related to travel patterns, charging convenience, and electricity price signals.

Meanwhile, power systems are undergoing a transition toward higher shares of renewable energy, especially solar photovoltaic and wind power. Although renewable energy is essential for electricity-sector decarbonization, its variability and uncertainty create additional requirements for system flexibility [2]. Solar generation may be abundant during midday but decline rapidly in the evening, while wind generation can fluctuate over different time scales. Such mismatches between renewable generation and electricity demand may lead to renewable curtailment, increased ramping pressure, and greater balancing needs [3]. Therefore, the simultaneous growth of EVs and renewable energy presents both a challenge and an opportunity: unmanaged EV charging may aggravate grid stress, whereas coordinated EV charging and discharging can provide flexible resources for renewable energy integration.

Vehicle-to-Grid (V2G) technology has emerged as a promising solution to this problem. Unlike conventional unidirectional charging, V2G enables bidirectional power exchange between EV batteries and the power grid through bidirectional chargers, communication systems, and coordinated control strategies. In this framework, EVs are not only electricity consumers but also distributed energy storage resources that can support grid operation [4]. When aggregated at scale, EVs can provide multiple grid services, including peak shaving, valley filling, demand response, frequency regulation, voltage support, congestion management, and renewable energy accommodation [5]. In particular, V2G can charge EVs during periods of renewable energy surplus and discharge electricity during periods of high demand or renewable shortfall, thereby improving renewable energy utilization and reducing curtailment [6].

However, the flexibility provided by V2G is not always available. EVs are primarily mobility assets, and their participation in grid services is constrained by travel schedules, state-of-charge requirements, charging infrastructure availability, user preferences, and battery health considerations [7]. Therefore, realizing the potential of V2G for renewable energy integration requires more than bidirectional charging hardware. It also depends on effective scheduling strategies, economically viable incentive mechanisms, and user-centered participation designs.

Coordinated scheduling is a key technical requirement for V2G deployment. A V2G scheduling strategy determines when EVs should charge or discharge and how much battery capacity should be allocated to mobility needs and grid services. Existing studies have proposed various approaches, including price-based scheduling, load-based scheduling, renewable-forecast-driven scheduling, centralized aggregator-based scheduling, and distributed user-oriented scheduling [8]. Price-based strategies encourage EVs to charge during low-price periods and discharge during high-price periods. Load-based strategies aim to reduce peak demand and smooth load profiles. Renewable-forecast-driven strategies coordinate EV charging and discharging with predicted wind and solar generation. Centralized scheduling can improve system-level optimization through aggregators, while distributed scheduling may better preserve user autonomy, privacy, and local decision-making flexibility.

Despite these technical advances, scheduling optimization alone is insufficient for large-scale adoption of V2G. Economic feasibility remains a decisive factor for EV owners, aggregators, charging operators, and grid companies. Potential V2G revenue streams include energy arbitrage, ancillary service payments, demand response incentives, capacity payments, and congestion management compensation [9]. However, these benefits must be balanced against the costs of bidirectional charging infrastructure, communication systems, aggregator operation, battery degradation, and user inconvenience. Battery degradation is particularly important because additional charge–discharge cycles may accelerate capacity fade and reduce battery lifetime [10]. Therefore, fair and transparent compensation mechanisms should explicitly account for battery aging costs and user opportunity costs.

User participation is another critical factor in practical V2G deployment. Unlike stationary batteries, EVs are owned or operated by users whose primary concern is mobility. Private EV owners may be concerned about range anxiety, battery lifetime, loss of control, uncertain financial returns, and data privacy. Commercial fleets, buses, taxis, logistics vehicles, and shared mobility fleets may provide more predictable schedules and larger aggregate capacity, but they also face stricter operational constraints. Recent studies indicate that realistic V2G potential assessment should consider user behavior, willingness to participate, compensation expectations, and battery degradation impacts [11]. Thus, effective V2G deployment requires participation mechanisms that ensure sufficient departure state of charge, transparent revenue sharing, flexible opt-out options, and battery health protection.

Although V2G technology has been widely investigated, the existing literature is still largely organized around separate research streams, including grid services, smart charging, renewable energy integration, aggregator-based scheduling, battery degradation, business models, and user acceptance. As shown in Table 1, several recent reviews have already provided broad and valuable discussions of V2G-related topics, such as charging infrastructure, grid impacts, power electronic interfaces, battery cycle aging, technological trends, behavior modeling, and reliability assessment. However, their comprehensiveness is mainly reflected in the coverage of multiple topics, whereas the coupling mechanism among these topics remains less explicitly synthesized. In particular, few reviews use renewable energy integration as the central organizing perspective to explain how renewable variability creates flexibility demand, how scheduling converts uncertain EV availability into grid services, how battery degradation and infrastructure costs affect net economic value, and how compensation, trust, and mobility protection determine whether this flexibility can actually be mobilized from users. Therefore, the distinctive contribution of this review is not simply to add another broad survey of V2G technologies but to connect scheduling, economics, battery degradation, and user engagement as an integrated deployment chain for renewable-rich power systems. Table 1 summarizes representative V2G-related references and clarifies the specific identified gaps addressed in this review by using systematic comparison criteria, including renewable energy integration, scheduling strategies, economics, battery degradation, user participation, standards/interoperability, and future development directions.

The references listed in Table 1 can be broadly grouped into several categories. Some works focus on V2G implementation, grid impacts, renewable energy integration, and smart-grid applications [12–17]. Several papers emphasize charging/discharging scheduling, optimization methods, and distribution-network operation [18–23]. Other publications concentrate on economic value, market participation, battery degradation, and green energy utilization [24–26]. In addition, standards, charging-station grid integration, power-electronic interfaces, user behavior modeling, and reliability assessment are addressed

in [27–32]. This classification shows that the existing literature provides valuable insights into individual dimensions of V2G, whereas this review connects renewable energy integration, scheduling, economics, battery degradation, user participation, and standards/interoperability within one integrated review framework. The main contributions of this review are summarized as follows:

- Explanation of the technical foundation of V2G systems and how bidirectional charging, aggregation, and grid interaction enable electric vehicles to support the integration of renewable energy.
- Review and comparison of the main V2G scheduling strategies, including price based, load based, renewable energy prediction driven, centralized, and distributed methods.
- Analysis of the economic and behavioral factors that affect V2G deployment, including revenue streams, battery degradation costs, stakeholder business models, compensation mechanisms, and user engagement barriers.
- An integrated framework that links scheduling strategies, economic mechanisms, battery degradation, and user engagement for renewable energy-rich power systems.

The remainder of this paper is organized as follows. Section 2 introduces the fundamentals of V2G systems and their mechanisms for renewable energy integration. Section 3 reviews coordinated scheduling strategies for V2G systems. Section 4 discusses economic incentives, user participation, stakeholder business models, and battery degradation considerations. Section 5 summarizes communication standards, deployment challenges, and future development directions. Finally, Section 6 concludes the review and highlights the role of V2G in building a more flexible, low-carbon, and user-centered energy–transportation system.

Table 1. Representative research on V2G system and related identified gaps.

Ref.	Year	Main Contribution	Identified Gaps
[12]	2021	Reviewed V2G implementation, grid impacts, renewable energy and smart-grid integration, and scholarly literature and projects.	Although it covered V2G implementation, renewable energy and smart grid integration, and related projects, it failed to systematically integrate scheduling strategies, economics, battery degradation, user participation, standards/interoperability, or future directions.
[18]	2021	Developed a stochastic optimization framework for optimal scheduling of EV charging/discharging power and user patterns in V2G systems.	Focused on random scheduling of electric vehicle charging/discharging power and user modes but did not account for renewable energy integration, economy, battery degradation, or standards/interoperability.
[27]	2022	Reviewed EV integration and V2G operation in active distribution grids, including power architectures, grid connection standards, and typical applications.	Reviewed EV integration and V2G operation in active distribution grids, including power architectures, grid connection standards, and typical applications, but economics, battery degradation, user participation, and renewable-energy-oriented scheduling were not systematically synthesized.
[19]	2022	Presented a comprehensive state-of-the-art review of EV smart charging, systematically categorizing and summarizing relevant solutions, scheduling strategies and key enabling technologies.	Although this review systematically summarizes EV smart charging solutions, scheduling strategies, and enabling technologies, its emphasis is mainly on smart charging rather than bidirectional V2G operation. Economics, battery degradation, user participation, standards/interoperability, and future development directions are not integrated within a renewable-energy-centered V2G framework.
[20]	2022	Reviewed V2G connected technologies and charging strategies, including operational principles, control approaches, key challenges, and optimization recommendations.	It covered V2G related technologies, charging strategies, control methods, challenges, and optimization suggestions but did not discuss renewable energy integration, economics, battery degradation, user participation, or interoperability issues.

Table 1. Cont.

Ref.	Years	Main Contribution	Identified Gaps
[28]	2022	Systematically reviewed international and regional standards and best practices for EV charging station-utility grid integration.	This work provided a valuable review of standards and best practices for EV charging station-utility grid integration. However, its main focus was on grid-integration standards and technical requirements, while renewable-energy-oriented V2G scheduling, economics, battery degradation, user participation, and future deployment directions were not systematically compared.
[13]	2022	Reviewed the progress and perspectives of using EVs for V2G services, including grid services, aggregation, challenges, and market penetration.	Reviewed V2G services, aggregation, challenges, and market penetration, but scheduling strategies, economics, battery degradation, and user participation were not systematically connected within a renewable-energy-centered framework.
[21]	2023	Studied charging-dispatch strategies and V2G technologies for EVs in distribution networks.	Focused on charging-dispatch strategies and V2G technologies for EVs in distribution networks, but economics, degradation-aware compensation, user participation, standards/interoperability, and renewable-energy-centered deployment pathways were not comprehensively compared.
[22]	2023	Investigated charging/discharging control of aggregated EVs for frequency regulation and discussed its contribution to V2G-based grid-support services.	This work contributed to charging/discharging control for aggregated EVs in frequency regulation. However, it focused on a specific grid-service application and did not systematically address renewable energy integration, broader scheduling strategies, economics, battery degradation, user participation, standards/interoperability, or future development directions.
[24]	2023	Explored the economic potential of V2G applications in the electricity market.	Explored the economic potential of V2G application in the electricity market but did not integrate the scheduling of renewable energy, the impact of battery degradation on net economic returns, or user participation.
[2]	2023	Reviewed renewable-energy-enabled EV charging infrastructure, smart charging approaches, utility interests, and technical challenges.	Reviewed the charging infrastructure, intelligent charging methods, and technical challenges of electric vehicles driven by renewable energy, but bidirectional V2G discharge, economy, and battery degradation have not been systematically integrated as interrelated V2G deployment factors.
[29]	2023	Systematically reviewed and classified bidirectional converter topologies for V2G systems, analyzing their operational principles, performance characteristics and application suitability.	Focused on bidirectional converter topologies for V2G systems and their operational principles, performance characteristics, and application suitability.
[14]	2024	Reviewed EV charging technology, grid integration impacts, policies, challenges, and future trends.	Reviewed EV charging technology, grid integration impacts, policies, challenges, and future trends, but renewable-energy-oriented V2G scheduling, economic compensation, battery degradation, user participation, and interoperability were not systematically compared within one integrated framework.
[30]	2024	Critical review and classification of mainstream power electronic interface topologies for V2G technology.	Focused on power electronic interface topologies for V2G technology.
[25]	2024	Reviewed V2G applications and battery cycle aging, including aging mechanisms, degradation models, simulations, and mitigation strategies.	Provided a battery-centered review of V2G applications and cycle aging, including aging mechanisms, degradation models, simulations, and mitigation strategies.
[26]	2024	Investigated EV integration optimization with V2G technology, exploring the effects of price disparity and battery costs on market adoption, economic profits and green energy utilization.	Investigated EV integration optimization with V2G, including price disparity, battery costs, market adoption, economic profits, and green energy utilization, but user participation, standards/interoperability, and broader future deployment directions were not systematically reviewed.
[15]	2024	Reviewed V2G integration schemes for power grid security enhancement, including grid stability regulation, emergency support and load balancing strategies.	Reviewed V2G integration solutions for enhancing grid security, including grid stability regulation, emergency support, and load balancing but did not consider economics, battery degradation, user engagement, or renewable-energy-centric dispatch strategies.
[16]	2025	Reviewed the technological advancements, practical challenges, and developmental future trends of V2G systems covering core technologies, application scenarios and research hotspots.	Reviewed the progress, application scenarios, practical challenges, and research hotspots of V2G technology but did not consider the integration with renewable energy, economy, battery degradation, and user participation.
[23]	2025	Explored the optimization of V2G systems using artificial bee colony algorithm, including system modeling, multi-objective scheduling and algorithm performance verification.	Focused on optimization of V2G systems using an artificial bee colony algorithm, including system modeling, multi-objective scheduling, and algorithm performance verification, but economics, battery degradation compensation, user participation, standards/interoperability, and practical deployment readiness were not comprehensively reviewed.

Table 1. Cont.

Ref.	Years	Main Contribution	Identified Gaps
[17]	2025	Reviewed a decade of V2G research progress and key achievements, including technical evolution, application scenarios, research hotspots and future development directions.	Reviewed a decade of V2G research progress, technical evolution, application scenarios, research hotspots, and future development directions, but renewable-energy-centered scheduling, economic mechanisms, degradation-aware compensation, user participation, and standards/interoperability were not integrated into one comparative framework.
[31]	2026	Reviewed EV behavior modeling for V2G integration, including modeling methodologies, practical challenges, and future research perspectives.	Focused on EV behavior modeling for V2G integration, including modeling methodologies, practical challenges, and future research perspectives, but renewable energy integration, scheduling strategies, economics, battery degradation, standards/interoperability, and grid-service deployment were not comprehensively compared.
[32]	2026	Established a reliability assessment framework for V2G systems integrated with performance sharing.	Focused on reliability assessment of V2G systems integrated with performance sharing, but renewable energy integration, scheduling strategies, economics, battery degradation, user participation, standards/interoperability, and broader future directions were outside the main scope.
This review	2026	Provides an integrated review of V2G systems for renewable energy integration, linking scheduling strategies, economic mechanisms, battery degradation, user participation, standards/interoperability, and future development directions.	Unlike prior publications that mainly focused on one or several separate dimensions, this review organized these elements into an integrated deployment-oriented framework for renewable-rich power systems.

2. V2G Fundamentals and Renewable Energy Integration

V2G systems provide a technical pathway for transforming EVs from passive charging loads into flexible distributed energy storage resources. In renewable-rich power systems, this transformation is particularly important because EV batteries can absorb surplus renewable electricity and release stored energy during periods of high demand or renewable generation shortage [33]. However, the practical contribution of V2G depends on several fundamental elements, including bidirectional charging capability, communication and control infrastructure, aggregation mechanisms, and coordination with distribution networks. This section introduces the basic operating modes of vehicle–grid interaction, the architecture of V2G systems, the main grid-support services enabled by V2G, and the mechanisms through which V2G supports renewable energy accommodation.

2.1. Vehicle-to-Everything Modes and Bidirectional Charging

The vehicle–grid interaction can be classified into several operating modes according to the direction of energy flow and the target application. Vehicle-to-One-Grid (V1G) controls the timing and power level of EV charging without exporting electricity back to the grid. Although V1G does not provide reverse power flow, it can still reduce charging costs, shift demand away from peak periods, and improve the utilization of renewable energy by aligning charging demand with renewable generation availability.

In contrast, V2G enables bidirectional power exchange between EV batteries and the electricity grid. Under V2G operation, EVs can charge when electricity demand is low or renewable generation is abundant, and discharge electricity back to the grid when demand is high or renewable generation is insufficient [34]. This bidirectional capability allows EVs to provide grid-support services such as peak shaving, demand response, frequency regulation, and renewable energy balancing. From the perspective of demand response, V2G can be regarded as a bidirectional active-load resource: EV charging can be shifted, curtailed, or intensified during renewable surplus periods, while controlled discharging can support the grid during peak demand or renewable shortfall. Compared with passive charging loads, coordinated V2G loads can help reduce feeder congestion and network losses by smoothing power flows, increase renewable energy source consumption by aligning charging demand with wind or photovoltaic output, and reduce operating costs

by lowering peak-demand charges, electricity procurement costs, and balancing-service requirements. Recent demand-response optimization work further confirms the value of active-load coordination for improving distribution-system operation, while storage-optimization evidence from renewable-based systems shows that properly scheduled flexible storage can substantially reduce net present cost, improve renewable penetration, and reduce reserve-capacity shortages [35,36]. Therefore, bidirectional charging is the key technical foundation that distinguishes V2G from conventional smart charging.

Other Vehicle-to-Everything modes include Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), and Vehicle-to-Vehicle (V2V). V2H allows an EV battery to supply electricity to a household, typically for backup power, self-consumption of rooftop photovoltaic generation, or residential peak-load reduction. V2B extends this concept to commercial or public buildings, where EV fleets can support building energy management and reduce demand charges. V2V enables energy transfer between EVs, which can be useful in emergency charging, roadside assistance, or fleet-level energy sharing [37]. Although these modes differ in application scope, they share a common requirement: controlled power conversion and reliable communication between vehicles, chargers, users, and energy management systems.

The comparison table for the Vehicle-to-Everything modes is shown in Table 2.

Table 2. Comparison of major Vehicle-to-Everything operating modes.

Mode	Energy Flow and Core Function	Functional Difference	Advantages	Disadvantages and Efficiency-Related Limitations	Typical Application Scenario
V1G	Grid-to-vehicle; controlled unidirectional charging, load shifting, and charging cost reduction.	V1G only adjusts charging time and charging power without exporting electricity from the EV battery to external loads or the grid.	It is technically mature, easy to implement, compatible with most existing charging infrastructure, and does not introduce additional battery discharge cycles.	Its flexibility is limited to demand shifting. Because it cannot discharge power, it cannot directly provide backup supply, peer-to-peer energy transfer, or discharge-based grid services.	Residential charging, workplace charging, smart charging stations.
V2G	Grid-to-vehicle and vehicle-to-grid; bidirectional power exchange, grid support, and renewable energy balancing.	V2G connects EV batteries with the public grid, allowing aggregated EVs to operate as distributed storage resources.	It can support peak shaving, valley filling, demand response, frequency regulation, congestion relief, and renewable energy accommodation.	It requires bidirectional chargers, communication systems, aggregation control, market access, and user permission. Its practical value may be reduced by battery degradation, charger losses, limited plug-in duration, and insufficient compensation.	Demand response, peak shaving, frequency regulation, renewable energy accommodation.
V2H	Vehicle-to-home; household backup power, rooftop PV self-consumption, and residential peak reduction.	V2H limits the discharge target to a household rather than the wider grid or a commercial building.	It improves household energy resilience, provides emergency backup power, increases rooftop PV self-consumption, and can reduce electricity costs during peak-price periods.	Its application scale is small and depends on home energy management, islanding protection, household load demand, and the need to reserve sufficient state of charge for driving.	Home energy management, emergency power supply, rooftop PV integration.
V2B	Vehicle-to-building; building-level energy management, demand-charge reduction, and backup power.	V2B coordinates one or multiple EVs with building loads, building energy management systems, and possibly local PV or stationary storage.	It is suitable for offices, campuses, commercial buildings, and fleet parking areas; it can reduce demand charges, improve local renewable energy use, and support building-level load management.	Its effectiveness depends on parking duration, fleet availability, building load profiles, charger capacity, and coordination between mobility needs and building energy objectives.	Commercial buildings, office parking lots, campus energy systems.
V2V	Vehicle-to-vehicle; direct energy transfer between EVs for emergency charging or local energy sharing.	V2V uses one EV as a mobile energy source for another EV, usually without relying on fixed charging infrastructure.	It can provide emergency charging, roadside assistance, temporary fleet-level energy balancing, and local energy sharing when fixed chargers are unavailable.	End-to-end efficiency is generally lower than that of fixed-interface modes because V2V may involve multiple conversion stages and additional coupling losses. For example, two 95% converters yield about 90.3% wired efficiency, while adding an 80–90% coupling link reduces the efficiency to about 72.2–81.2% before battery losses. Therefore, V2V is more suitable for emergency or auxiliary charging than for large-scale energy balancing.	Fleet operation, roadside assistance, mobile charging services.

Table 3 summarizes representative quantitative evidence from field experiments, measured case studies, and case-based evaluations. These numerical results illustrate the practical value of coordinated EV charging and discharging in terms of peak-load reduction, renewable energy consumption, cost savings, dispatch-cost reduction, and round-trip efficiency.

Table 3. Representative quantitative evidence on the practical value of coordinated EV charging and discharging.

Mode or Application	Evidence Type and Context	Quantitative Findings	Practical Implication
Optimized EV charging and V2G for clean-energy regional grids	Case-based evaluation using regional grid data, EV charging patterns, renewable generation uncertainty, and time-series simulation.	At a 30% EV penetration rate, unmanaged charging may increase regional peak load by about 20%. Optimized charging strategies, including time-of-use pricing, direct load control, and V2G, reduce the peak–valley load difference by 15%, improve clean-energy consumption by about 12%, and reduce dispatching costs by approximately 10% [38].	Coordinated EV charging and discharging can mitigate peak-load stress, improve renewable energy consumption, and reduce operational costs in renewable-rich regional grids.
V2B using EV parking lots in non-residential buildings	Simulation using real-world building power-consumption data and parking-lot occupancy data.	Scheduling EV charging and discharging in a parking lot reduced peak power consumption by approximately 3% in the minimum parking-spot scenario and approximately 20% in the maximum parking-spot scenario [39].	V2B operation can flatten daytime building load profiles and reduce contracted-capacity-related electricity costs.
Smart unidirectional and bidirectional EV charging for campus peak shaving	Case evaluation based on annual measured load data from Saarland University and simulated EV/PV operation scenarios.	Compared with the reference case, PV alone achieved a 3.2% reduction in total electricity costs, smart unidirectional EV charging achieved up to 3.0%, bidirectional EV charging achieved 8.1%, and stationary battery storage achieved 13.3% [40].	Bidirectional EV charging provides stronger peak-shaving and cost-reduction capability than unidirectional smart charging, although stationary batteries may provide higher dedicated peak-shaving potential.
Measured V2G round-trip efficiency	Field experiment measuring V2G charging and discharging for different dates, current rates, and average SOC levels.	Measured V2G round-trip efficiency ranged from 79.1% to 87.8%. Under 25–75% SOC and 3×16 A operation, the average round-trip efficiency was $87.0\% \pm 1\%$ [41].	Efficiency losses should be explicitly considered when evaluating V2G energy arbitrage, renewable-energy shifting, and user compensation mechanisms.

2.2. V2G System Architecture

A typical V2G system consists of four core components: EVs, bidirectional charging infrastructure, aggregators or energy management systems, and the power grid. EVs provide distributed battery capacity, but their availability is constrained by mobility requirements, state-of-charge limits, battery health, and user preferences. Bidirectional chargers serve as the physical interface between EVs and the grid by converting power between alternating current and direct current and by controlling charging and discharging power. Communication systems transmit information such as battery state of charge, charging availability, electricity prices, grid requests, and user constraints [42].

At the electric vehicle charging station (EVCS) or aggregator level, the net charging-station power can be expressed as

$$P_{s,t}^{\text{EVCS}} = \sum_{i \in \mathcal{N}_s} \left(\frac{P_{i,t}^{\text{ch}}}{\eta_s^{\text{ch}}} - \eta_s^{\text{dis}} P_{i,t}^{\text{dis}} \right), \quad (1)$$

where $P_{s,t}^{\text{EVCS}}$ denotes the net power of EVCS s at time t , $P_{i,t}^{\text{ch}}$ and $P_{i,t}^{\text{dis}}$ are the charging and discharging power of EV i , η_s^{ch} and η_s^{dis} are station-side charging and discharging efficiencies, and $\mathcal{N}_s$ is the set of EVs connected to EVCS s . The station-level power exchange is usually limited by the import and export capacity of chargers, transformers, or grid-connection equipment:

$$-P_s^{\text{exp,max}} \leq P_{s,t}^{\text{EVCS}} \leq P_s^{\text{imp,max}}. \quad (2)$$

The aggregator plays a central role in large-scale V2G operation. Since individual EVs usually have limited battery capacity and uncertain availability, it is difficult for a single vehicle to directly participate in electricity markets or grid-support services [43]. Aggregators combine the flexibility of many EVs and coordinate their charging and discharging behavior according to grid requirements, electricity prices, renewable generation forecasts, and user-defined constraints. Through aggregation, EV fleets can behave as a virtual energy storage resource and provide services to distribution system operators, transmission system operators, electricity retailers, or local energy communities [44].

The distribution network is the main grid interface for V2G deployment. Most EVs are connected at low- or medium-voltage distribution levels, where large-scale charging and discharging may affect transformer loading, feeder congestion, voltage profiles, and

local power quality. Therefore, V2G control should not only pursue market revenue or user cost reduction but also respect distribution network constraints [45]. A practical V2G architecture requires coordination among physical power flows, digital communication, market signals, and user participation. Figure 1 illustrates the conceptual architecture of a V2G system.

Recent studies have further extended the discussion of V2G architecture from basic vehicle–charger–grid interaction to grid–vehicle–grid (G2V2G) power transmission and hardware-level validation. G2V2G frameworks emphasize that EVs can not only consume electricity from the grid but also participate in bidirectional power transmission through coordinated charging infrastructure, power electronic interfaces, metering systems, and communication platforms [46]. In addition, experimental validation of V2G chargers based on Combo CCS Type 2 connector standards shows that interoperability between EVs, chargers, and grid-side control systems is essential for practical V2G deployment [47]. These studies indicate that scalable V2G architecture should be designed not only at the control-algorithm level but also at the hardware, connector, communication, and certification levels.

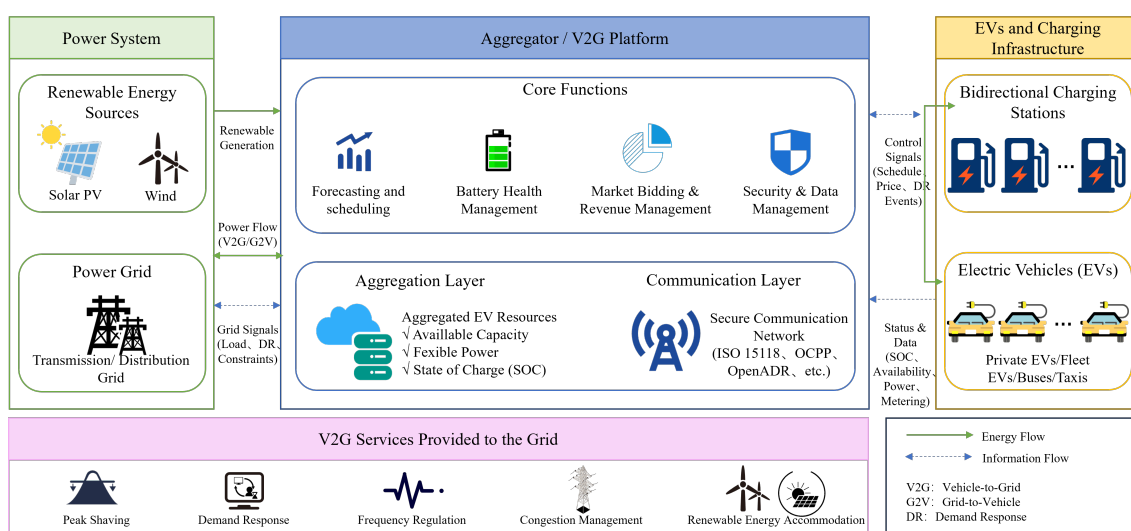


Figure 1. Conceptual architecture of a V2G system for renewable energy integration.

2.3. V2G Services for Grid Support

V2G can provide several types of grid-support services. Among them, peak shaving, demand response, and renewable energy accommodation are the most relevant to the scope of this review.

Peak shaving refers to reducing electricity demand during peak-load periods by discharging EV batteries or by avoiding simultaneous charging. In distribution networks, peak shaving can reduce transformer and feeder loading, delay grid reinforcement, and improve the utilization of existing infrastructure [48]. For EV owners, peak shaving may also reduce charging costs if electricity tariffs include time-of-use prices or demand charges. At the system level, peak shaving helps reduce the need for expensive peaking generation and improves operational flexibility [49].

Demand response is another important service enabled by V2G. In a V2G-based demand response program, EV charging and discharging can be adjusted according to electricity price signals, grid congestion signals, or direct control commands from aggregators [50]. Compared with conventional demand response resources, EVs have the advantage of flexible charging windows and distributed battery capacity. When coordinated properly, EVs can increase charging demand during low-price or renewable-rich periods and reduce or reverse demand during peak or stressed periods [51]. However, demand response per-

formance depends strongly on user availability, incentive design, communication reliability, and the ability of aggregators to forecast EV behavior.

Renewable energy accommodation is the central service considered in this review. High penetration of photovoltaic and wind generation increases the need for flexible resources that can respond to generation variability [15]. V2G can support renewable accommodation in two ways. First, EVs can increase charging demand during periods of renewable surplus, thereby reducing curtailment and improving renewable energy utilization. Second, EVs can discharge during periods of renewable shortfall, thereby reducing the need for fossil-fuel-based balancing resources. Through these mechanisms, V2G can act as a distributed buffer between variable renewable generation and electricity demand [52].

In addition to these three services, V2G can also contribute to ancillary services such as frequency regulation, voltage support, congestion management, spinning reserve, and emergency backup. Frequency regulation requires fast response to short-term power imbalance, which is technically suitable for EV batteries due to their rapid power response [53]. Voltage support and congestion management are especially relevant in distribution networks with high penetrations of EV charging and distributed renewable generation [54]. Recent work has also emphasized the need to validate V2G grid-support functions under dynamic operating conditions. In [55], the authors investigated the effects of various Vehicle-to-Everything applications and charging modes on the service life of electric vehicle batteries. In [56], the authors investigated the regulatory effects of electric vehicles participating in grid auxiliary services. Nevertheless, these services require advanced communication, accurate control, appropriate market rules, and compensation mechanisms that reflect both system benefits and user costs.

2.4. V2G Mechanisms for Renewable Accommodation

The fundamental mechanism through which V2G supports the integration of renewable energy is the temporal shift in electricity consumption and storage. Renewable generation is often mismatched with electricity demand. For example, photovoltaic generation usually peaks around noon, while residential electricity demand and EV charging demand often increase in the evening. Without flexible resources, this mismatch may cause renewable curtailment during surplus periods and high ramping requirements during evening peaks. V2G can mitigate this mismatch by charging EVs during periods of high renewable output and discharging electricity when renewable generation decreases [57].

A second mechanism is the smoothing of fluctuations in renewable generation. Wind and solar output can vary in minutes, hours, and days. Aggregated EV batteries can respond to these fluctuations by adjusting the charge or discharging power. Since individual EV availability is uncertain, aggregation is essential to provide reliable flexibility. A large EV fleet can reduce the uncertainty of individual mobility behavior and provide a more stable aggregate capacity [58]. This makes V2G particularly suitable for supporting renewable-rich distribution networks, microgrids, and virtual power plants.

A third mechanism is the coordination of V2G with renewable forecasting. Forecasts of photovoltaic output, wind generation, electricity demand, and EV availability can be used to develop charging and discharging schedules in advance. When renewable generation is predicted to be high, EV charging can be encouraged through lower prices or direct scheduling. When renewable generation is predicted to be low, EV discharge capacity can be reserved for grid support [59]. Forecasting-driven V2G scheduling therefore provides a bridge between renewable uncertainty and controllable demand-side flexibility.

A fourth mechanism is the enhancement of local energy self-consumption. In residential communities, campuses, commercial buildings, and charging stations with distributed

photovoltaic generation, V2G can increase the local consumption of renewable electricity. Instead of exporting surplus photovoltaic power to the grid at low value or curtailing it due to local constraints, EV batteries can store the surplus and later supply buildings, local loads, or the grid [60]. This mechanism is especially relevant for V2H, V2B, and charging-station-level V2G applications.

Recent studies further show that the contribution of V2G to renewable energy integration can be evaluated through curtailment reduction, ramping mitigation, flexibility capacity, storage substitution, and system-cost savings. In a California 2030 scenario with 3.3 million plug-in electric vehicles and a 60% renewable portfolio standard, V2G-capable managed charging reduced annual renewable curtailment from 7.09 TWh with unmanaged charging to 2.45 TWh, corresponding to a reduction of approximately 65%. The same study showed that bidirectional V2G reduced the maximum three-hour upward ramping requirement from 17 GW to 8.7 GW and provided an equivalent flexibility capacity of 12.5 GW/50 GWh, corresponding to about USD 26.28 billion of stationary storage investment value [61]. In a New England low-carbon power-system case, participation from 13.9% of the light-duty vehicle fleet in V2G displaced 14.7 GW of six-hour stationary storage and generated more than USD 700 million in capital savings [62]. For China's 2030 renewable energy target, bidirectional V2G was found to reduce total power-system cost by 2.08%, reduce annual power-sector carbon emissions by 2.95%, and increase the total share of wind and photovoltaic generation by 1.28% in the power mix [63]. In addition, a regional clean-energy grid study reported that optimized EV-grid coordination strategies, including time-of-use pricing, direct load control, and V2G, reduced the peak–valley load gap by 15% and improved renewable energy consumption by 12% [38]. Despite these benefits, V2G-based renewable accommodation must satisfy several constraints. EVs must retain sufficient state of charge for future trips; battery degradation should be limited and compensated; charging and discharging should not violate network constraints; and users must be willing to allow a portion of their battery capacity to be scheduled. Therefore, V2G should not be viewed only as a technical storage solution but as a cyber-physical and socio-economic system involving vehicles, users, aggregators, charging infrastructure, electricity markets, and power networks. These constraints motivate the need for coordinated scheduling strategies, which are reviewed in Section 3.

3. Coordinated Scheduling Strategies

Coordinated scheduling is essential for converting the theoretical flexibility of V2G systems into practical grid-support capability. Although EV batteries can provide distributed storage capacity, their availability is highly dynamic because it depends on user travel behavior, plug-in time, state-of-charge (SOC) requirements, charging infrastructure, electricity prices, and grid operating conditions [64]. Therefore, V2G scheduling must determine when EVs should charge, when they should discharge, and how much power should be exchanged with the grid while satisfying both mobility and power-system constraints.

In most V2G scheduling formulations, SOC is the key state variable that links battery operation with user mobility requirements. For EV i , the SOC evolution can be described as

$$\text{SOC}_{i,t+1} = \text{SOC}_{i,t} + \frac{\eta_i^{\text{ch}} P_{i,t}^{\text{ch}} \Delta t}{E_i^{\text{bat}}} - \frac{P_{i,t}^{\text{dis}} \Delta t}{\eta_i^{\text{dis}} E_i^{\text{bat}}}, \quad (3)$$

where E_i^{bat} is the battery capacity, η_i^{ch} and η_i^{dis} are charging and discharging efficiencies, and Δt is the scheduling interval. To protect mobility demand and battery health, typical V2G scheduling constraints include

$$\begin{aligned} \text{SOC}_i^{\min} &\leq \text{SOC}_{i,t} \leq \text{SOC}_i^{\max}, \\ \text{SOC}_{i,t_i^{\text{dep}}} &\geq \text{SOC}_i^{\text{req}}, \\ 0 &\leq P_{i,t}^{\text{ch}} \leq x_{i,t}^{\text{ch}} P_i^{\text{ch,max}}, \\ 0 &\leq P_{i,t}^{\text{dis}} \leq x_{i,t}^{\text{dis}} P_i^{\text{dis,max}}, \\ x_{i,t}^{\text{ch}} + x_{i,t}^{\text{dis}} &\leq a_{i,t}. \end{aligned} \quad (4)$$

Here, t_i^{dep} is the departure time, $\text{SOC}_i^{\text{req}}$ is the required departure SOC, $x_{i,t}^{\text{ch}}$ and $x_{i,t}^{\text{dis}}$ are charging and discharging status variables, and $a_{i,t}$ indicates whether EV i is connected to the charger.

In renewable-rich power systems, the objective of V2G scheduling is not limited to reducing charging cost. It should also support load smoothing, renewable energy accommodation, peak reduction, ancillary service provision, and battery health protection. A practical scheduling framework usually needs to consider several constraints, including battery capacity, charging and discharging power limits, SOC boundaries, expected departure SOC, charger availability, distribution network capacity, and user participation preferences. Therefore, coordinated scheduling acts as the operational bridge among EV users, aggregators, charging infrastructure, electricity markets, and power grids. This section evaluates V2G scheduling strategies from multiple practical dimensions, including computational complexity, scalability, communication requirements, privacy protection, renewable energy integration capability, battery degradation impacts, economic performance, and deployment readiness.

Existing V2G scheduling strategies can be broadly divided into price-based scheduling, load-based scheduling, renewable-forecasting-driven scheduling, centralized scheduling, and distributed scheduling. These strategies differ in their optimization objectives, information requirements, control structure, and applicability. Table 4 summarizes the main features of these scheduling approaches.

Table 4. Comparison of major V2G coordinated scheduling strategies

Scheduling Strategy	Scheduling Rationale	Computational Complexity and Scalability	Information Exchange and Privacy	Capability for Renewable Energy Integration	Battery Degradation and Economic Implications	Deployment Maturity
Price-based scheduling [65]	EV charging and discharging are guided by time-of-use tariffs, real-time prices, dynamic prices, or market-clearing signals.	The computational burden is relatively low because the control signal is externally provided. Scalability is high, but simultaneous response to identical price signals may create rebound peaks or local congestion.	Communication requirements are limited to tariff or market-signal dissemination. User privacy is comparatively well preserved because detailed mobility and battery-state data are not necessarily centralized.	Its renewable-integration capability is indirect and depends on whether electricity prices accurately reflect renewable surplus, scarcity, or local network constraints.	It can improve energy-arbitrage value and reduce charging costs, but degradation costs may be underestimated if battery cycling is not explicitly priced.	High, especially in markets with mature time-varying tariffs or dynamic pricing schemes.
Load-based scheduling [66]	EV flexibility is scheduled to reduce peak demand, fill load valleys, smooth net-load profiles, and relieve distribution-network stress.	The computational burden is moderate and increases with network granularity, temporal resolution, and the number of controllable EVs. Scalability is feasible at feeder, community, or station level.	It requires load forecasts, feeder or transformer constraints, EV availability, and charging-state information. Collection of user-level data may introduce privacy and data-governance concerns.	Renewable integration is moderate to high when load valleys overlap with renewable surplus periods or when net-load smoothing reduces renewable-driven ramping stress.	It may reduce demand charges, peak-related operating costs, and network reinforcement needs, but degradation-aware constraints are required to avoid excessive discharge during peak-shaving events.	Medium to high, particularly for residential communities, workplaces, fleet depots, and charging stations with predictable load patterns.

Table 4. Cont.

Scheduling Strategy	Scheduling Rationale	Computational Complexity and Scalability	Information Exchange and Privacy	Capability for Renewable Energy Integration	Battery Degradation and Economic Implications	Deployment Maturity
Renewable-forecasting-driven scheduling [67]	Charging is aligned with predicted renewable surplus, while discharge capacity is reserved for renewable shortfall, net-load ramping, or peak-demand periods.	The computational burden is moderate to high because renewable forecasts, EV availability uncertainty, rolling-horizon updates, and network constraints must be jointly considered.	It requires multi-source information, including PV/wind forecasts, load forecasts, SOC, plug-in duration, charger status, and grid constraints. Secure data exchange is therefore essential.	High, because the scheduling objective is explicitly coupled with renewable accommodation, curtailment mitigation, and net-load flexibility.	It can increase renewable self-consumption and system-level flexibility value, but frequent cycling may accelerate degradation unless aging-aware constraints and compensation mechanisms are embedded.	Medium, with strong potential in renewable-rich distribution networks, microgrids, PV charging stations, and virtual power plants.
Centralized scheduling [68]	An aggregator or system operator optimizes fleet-level charging and discharging decisions using aggregated EV, grid, market, and renewable-generation information.	The computational burden is high for large-scale fleets, especially when binary decisions, network constraints, and high-resolution time steps are included. However, centralized optimization can achieve strong system-level coordination.	Communication requirements are substantial because detailed SOC, availability, departure time, and user-preference data may be collected centrally. This raises privacy, cybersecurity, and data-ownership concerns.	High, since the aggregator can coordinate EV flexibility with renewable forecasts, congestion constraints, ancillary-service requirements, and market signals.	It can maximize fleet-level revenue and grid-support value, but the objective function must incorporate battery aging, user compensation, and mobility guarantees to remain acceptable.	Medium, with near-term applicability to buses, taxis, logistics fleets, fleet depots, and aggregator-operated V2G programs.
Distributed scheduling [69]	Charging and discharging decisions are made by EVs, chargers, or local controllers based on local states and limited coordination signals.	Local computational complexity is low to moderate and scalability is strong. However, the absence of global information may lead to suboptimal system-level outcomes.	Communication burden is reduced because detailed user information can remain local. Privacy preservation is stronger than in fully centralized schemes.	Renewable-integration capability is moderate and depends on whether local incentives or control signals sufficiently represent renewable generation and grid conditions.	It improves user autonomy and may reduce participation barriers, but economic efficiency and grid-service reliability may be lower without adequate coordination.	Medium, suitable for residential EVs, local energy communities, and decentralized charging networks.

3.1. Price and Load-Based Scheduling

Price-based scheduling is a widely used strategy for coordinating EV charging and discharging. Its basic principle is to guide EVs to charge during low-price periods and discharge during high-price periods. Under time-of-use or dynamic pricing conditions, EV users can reduce charging costs, while aggregators can participate in energy arbitrage and demand response by adjusting charging and discharging decisions according to electricity prices, congestion signals, or renewable generation conditions [70]. This strategy is relatively easy to implement because it relies on market-based price signals rather than direct control of individual EVs.

However, price-based scheduling may also create operational problems. If many EVs respond to the same low-price period, charging demand may become concentrated and form a secondary peak [71]. In addition, electricity prices may not fully reflect local distribution network constraints, such as feeder congestion, transformer loading, or voltage deviations. Therefore, price-based scheduling should be combined with grid-aware constraints or aggregator-level coordination to avoid negative impacts on distribution networks.

Load-based scheduling focuses on reshaping the load curve rather than responding only to electricity prices. Its main objective is to reduce peak demand, fill load valleys, and smooth power fluctuations. In V2G systems, EVs can be charged during valley-load periods and discharged during peak-load periods, thereby reducing peak-to-valley differences, improving transformer utilization, and enhancing distribution network reliability. This strategy is particularly suitable for residential communities, workplace parking areas, charging stations, and fleet depots where EV charging demand is concentrated [72].

Nevertheless, load-based scheduling depends on accurate load forecasting and reliable information about EV availability. If user travel patterns, plug-in behavior, or departure SOC requirements deviate from forecasts, the scheduled V2G capacity may not be available when needed. Therefore, practical load-based scheduling should incorporate user-defined SOC requirements, opt-out options, and compensation mechanisms to balance grid-support objectives with user mobility needs.

3.2. Renewable Forecasting-Driven Scheduling

Renewable forecasting-driven scheduling directly links V2G operation with the variability of solar and wind generation. Unlike price-based or load-based scheduling, this strategy uses forecasts of photovoltaic (PV) output, wind power, load demand, electricity prices, and EV availability to determine charging and discharging plans. The basic principle is to schedule EV charging during periods of renewable energy surplus and reserve EV discharge capacity for periods of renewable shortage or peak demand.

For PV-dominated systems, the main challenge is the mismatch between midday solar generation and evening electricity demand. V2G scheduling can shift EV charging to high-PV-output periods and discharge part of the stored energy during evening peaks, thereby improving PV self-consumption and reducing peak-load pressure. For wind-rich systems, wind power uncertainty and multi-time-scale fluctuations are more significant [73]. Aggregated EV fleets can absorb surplus wind power when wind generation is high and provide discharge support when wind output decreases, helping to reduce curtailment and smooth net-load variations [74].

A typical renewable forecast-driven scheduling process includes three steps. First, renewable generation, load demand, and EV availability are predicted over a scheduling horizon. Second, the scheduler identifies renewable surplus and shortage periods and optimizes EV charging/discharging decisions under SOC, charger power, departure time, and distribution-network constraints. Third, the schedule is updated in real time or in a rolling-horizon manner to reduce the impact of forecasting errors [75]. Model predictive control, stochastic optimization, distributionally robust optimization, and deep reinforcement learning have been used to improve scheduling robustness with renewable and EV behavior uncertainties [76].

Although renewable forecasting-driven scheduling can improve renewable energy utilization, its practical performance depends on forecast accuracy, aggregation scale, communication reliability, and user participation. Inaccurate renewable forecasts may lead to inadequate charging or underutilized renewable energy, while inaccurate EV availability forecasts may overestimate scheduled capacity. Moreover, frequent charge–discharge cycles may increase battery degradation [67]. Therefore, renewable-oriented V2G scheduling should jointly consider renewable accommodation, grid constraints, user mobility requirements, battery aging, and economic incentives [77].

Recent studies have further emphasized that renewable-oriented V2G scheduling should be formulated as a multi-constraint optimization problem involving renewable generation uncertainty, EV mobility patterns, distribution network limits, and market signals. In [21], the authors explored the application of electric vehicles as mobile energy storage in the Vehicle for Grid (VfG) mode. In [78], the authors explored the feasibility of electric vehicle V2G operation in different charging scenarios. In [79], the authors investigated the charging and discharging scheduling strategies for electric vehicles in V2G systems. Therefore, future scheduling models should move beyond idealized EV availability assumptions and incorporate real-world mobility data, degradation-aware constraints, and renewable forecasting errors.

Although different scheduling strategies assign different weights to technical and economic objectives, their optimization logic can usually be represented by a cost-minimization or benefit-maximization function. A representative V2G scheduling objective can be written as

$$\min J = \sum_t \left[c_t^{\text{grid}} p_t^{\text{grid}} + c_t^{\text{cur}} p_t^{\text{cur}} + \sum_i C_{i,t}^{\text{deg}} + \sum_i C_{i,t}^{\text{inc}} - r_t^{\text{V2G}} p_t^{\text{dis,agg}} \right] \Delta t, \quad (5)$$

where c_t^{grid} is the grid electricity cost, P_t^{grid} is the exchanged grid power, c_t^{cur} is the renewable curtailment penalty, P_t^{cur} is curtailed renewable power, $C_{i,t}^{\text{deg}}$ is the battery degradation cost, $C_{i,t}^{\text{inc}}$ is the user inconvenience cost, r_t^{V2G} is the V2G service revenue coefficient, and $P_t^{\text{dis,agg}}$ is the aggregated discharge power. This expression shows how V2G scheduling can jointly consider electricity cost, renewable curtailment, battery aging, user inconvenience, and service revenue. Therefore, future scheduling formulations should move beyond idealized EV availability assumptions and incorporate real-world mobility data, degradation-aware constraints, and renewable forecasting errors.

3.3. Centralized vs. Distributed Scheduling

V2G scheduling can also be classified according to its control architecture, mainly including centralized, distributed, and hybrid scheduling. In centralized scheduling, an aggregator, fleet operator, charging service provider, or system operator collects information from EVs, such as plug-in status, SOC, expected departure time, charging power limits, and user preferences. Based on this information, the central controller optimizes the charging and discharging schedules of the EV fleet according to grid requirements, electricity prices, renewable generation forecasts, and market signals [80].

Centralized scheduling can achieve better system-level coordination because the aggregator has access to global information and can allocate EV flexibility according to grid or market objectives. It is particularly suitable for electric buses, taxis, logistics fleets, shared mobility fleets, and charging stations, where vehicle routes, parking duration, and charging locations are relatively predictable. However, centralized scheduling also faces several limitations, including high communication requirements, computational complexity, privacy concerns, and potential single-point failure risks. In addition, excessive central control may reduce user autonomy if mobility requirements and opt-out options are not properly considered.

Distributed scheduling provides an alternative approach in which EVs, chargers, or local controllers make decisions based on local information and coordination signals, such as electricity prices, power limits, or incentive signals. Compared with centralized scheduling, distributed scheduling can reduce communication burden, improve scalability, and better protect user privacy. It is therefore more suitable for residential EVs, community energy systems, and decentralized charging networks [81]. However, purely distributed decisions may not achieve global optimality, especially when many EVs respond similarly to the same price signal, which may lead to secondary peaks or local congestion.

Hybrid scheduling combines the advantages of centralized and distributed approaches. In a hybrid framework, the aggregator provides high-level coordination signals, grid constraints, or market targets, while local EV controllers optimize individual charging and discharging decisions according to user preferences, SOC requirements, and battery conditions. This architecture can balance system-level optimization with user autonomy and privacy protection. Therefore, hybrid scheduling is increasingly suitable for large-scale V2G deployment, especially in renewable-rich distribution networks, virtual power plants, and aggregator-based electricity markets [82]. Figure 2 shows the architecture diagram of centralized vs distributed scheduling, where the solid line represents electricity and the dashed line represents information.

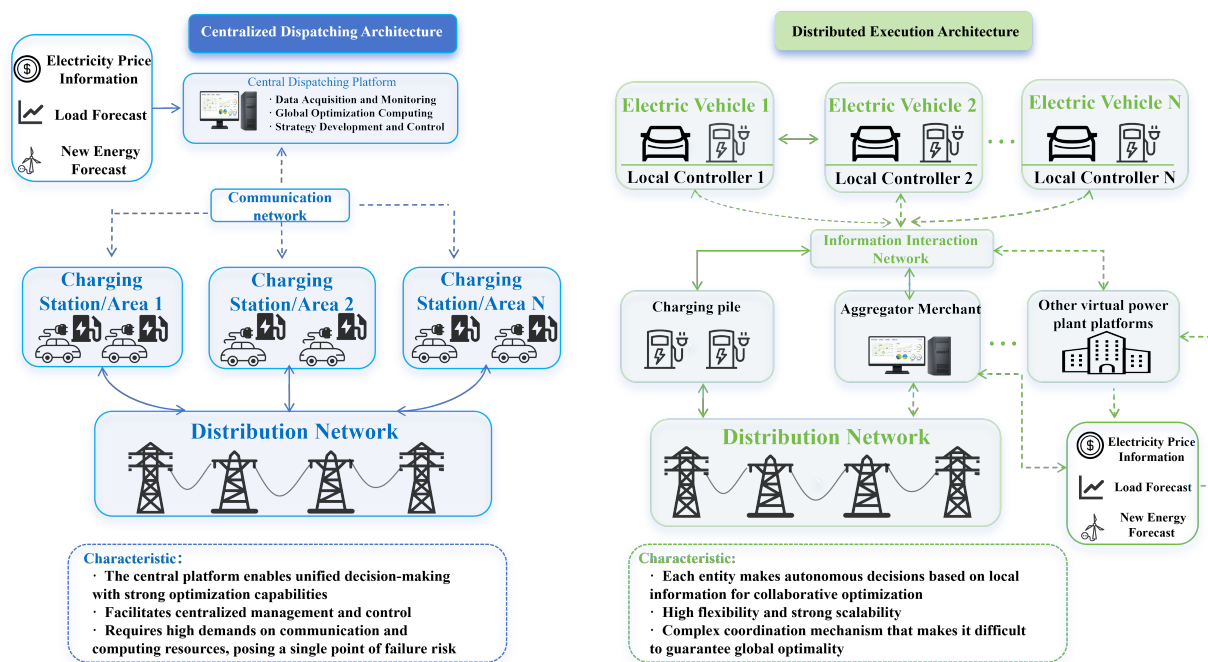


Figure 2. Conceptual architecture of centralized, distributed, and hybrid V2G scheduling.

3.4. Optimization Methodologies for V2G Scheduling

In addition to the classification of scheduling strategies according to control objectives and architectures, V2G scheduling can also be analyzed from the perspective of underlying optimization methodologies. Different methods vary in mathematical tractability, uncertainty modeling capability, scalability, privacy protection, and suitability for real-time deployment. Therefore, the choice of optimization method should be consistent with the scheduling objective, available data, aggregation scale, renewable uncertainty, battery degradation model, and market participation mechanism. Table 5 summarizes representative optimization methodologies used in V2G scheduling and compares their main strengths and limitations.

Overall, no single scheduling or optimization method is universally optimal for all V2G applications. Price-based and distributed approaches are easier to scale and protect user privacy, but they may provide weaker system-level coordination. Centralized, renewable-forecasting-driven, stochastic, and robust optimization approaches can better support renewable integration and grid reliability, but they require more data, communication, and computation. Learning-based and multi-agent methods are promising for real-time and decentralized operation, but their deployment requires validation under safety, cybersecurity, battery degradation, and market-settlement constraints. Therefore, practical V2G scheduling is likely to evolve toward hybrid frameworks that combine renewable forecasting, degradation-aware optimization, user-centered incentives, and aggregator-level coordination.

Table 5. Comparison of representative optimization methodologies for V2G scheduling

Optimization Methodology	Application Scope in V2G Scheduling	Methodological Strengths	Methodological Limitations	Most Suitable Application Context
Mixed-integer linear programming (MILP)	Commonly used for day-ahead or intra-day V2G scheduling with linearized SOC dynamics, charging/discharging limits, binary operating states, electricity prices, and simplified network constraints.	Provides a well-established mathematical structure and can obtain globally optimal solutions when the problem is formulated linearly. It is suitable for representing mutually exclusive charging and discharging decisions.	The number of binary variables increases rapidly with fleet size and time resolution. Nonlinear battery aging, charger efficiency, and AC power-flow relationships often need to be approximated.	Aggregator scheduling, fleet-depot operation, charging-station energy management, and market-oriented dispatch with moderate problem size.
Mixed-integer nonlinear programming (MINLP)	Applied when V2G scheduling needs to include nonlinear battery degradation, nonlinear charger efficiency, voltage constraints, AC power-flow equations, or nonlinear user-utility functions.	Provides a more physically detailed representation of V2G operation and can capture nonlinear interactions among battery behavior, power networks, and charging infrastructure.	Computational tractability is limited for large-scale EV fleets. Global optimality is difficult to guarantee, and solution time may be incompatible with real-time operation.	Offline planning, distribution-network-constrained studies, high-fidelity simulation, and small-scale V2G optimization with detailed physical constraints.
Dynamic programming	Used for sequential decision-making problems in which SOC evolution, electricity prices, renewable generation, and mobility requirements change over time.	Well suited to multi-stage optimization and explicit state-transition modeling. It can provide interpretable policies for charging and discharging over a finite horizon.	The state space expands rapidly with the number of EVs, SOC levels, time steps, and uncertainty variables, resulting in the curse of dimensionality.	Single-EV scheduling, small fleet optimization, benchmark studies, and simplified real-time control problems.
Stochastic optimization	Used to schedule V2G resources under probabilistic uncertainty conditions in renewable output, electricity prices, load demand, EV arrival/departure times, and user availability.	Can explicitly incorporate uncertainty scenarios and optimize expected cost, revenue, emissions, or grid-support value. It is suitable for renewable-rich systems with forecast uncertainty.	Performance depends on the quality of probability distributions or scenario generation. Computational burden increases significantly with the number of scenarios and constraints.	Day-ahead scheduling, renewable-energy accommodation, risk-aware aggregator operation, and electricity-market participation under uncertainty conditions.
Robust optimization	Used when uncertainty in renewable generation, load demand, electricity prices, or available EV capacity is represented through bounded uncertainty sets rather than probability distributions.	Improves operational feasibility with adverse uncertainty realizations and is useful when reliable probability distributions are unavailable.	The resulting schedules may be overly conservative, reducing economic performance and underutilizing EV flexibility. The selection of uncertainty sets strongly affects results.	Reliability-oriented V2G scheduling, grid-support services, distribution-network operation, and applications requiring feasibility guarantees.
Game theory	Used to analyze strategic interactions among EV owners, aggregators, charging operators, electricity retailers, distribution system operators, and market participants.	Provides a structured framework for pricing, incentive design, revenue sharing, competition, and user participation analysis.	Equilibrium outcomes depend on behavioral assumptions, information availability, and market structure. Practical implementation can be difficult when users behave heterogeneously or irrationally.	V2G tariff design, aggregator-user contracts, peer-to-peer trading, demand response markets, and participation incentive mechanisms.
Multi-agent systems	Used for decentralized coordination among EVs, chargers, aggregators, buildings, renewable generators, microgrids, and local energy management systems.	Enhances scalability, autonomy, modularity, and privacy preservation. It is suitable for systems where decision-making is geographically or institutionally distributed.	Coordination, convergence, and stability are challenging. System-level optimality may not be guaranteed without carefully designed communication and consensus mechanisms.	Energy communities, microgrids, virtual power plants, decentralized charging networks, and local flexibility markets.
Reinforcement learning	Used for adaptive V2G control in dynamic environments with uncertain prices, renewable output, user behavior, EV availability, and grid operating conditions.	Can learn control policies from interaction data and does not require a complete analytical model of the system. It is promising for real-time and data-driven scheduling.	Requires sufficient training data, careful reward-function design, and safety constraints. Interpretability, generalization, convergence, and constraint satisfaction remain major barriers.	Real-time charging control, AI-based aggregator platforms, adaptive PV charging stations, and renewable-rich distribution networks with high uncertainty.

4. Economic Incentives, User Participation and Battery Considerations

The economic feasibility and practical adoption of V2G depend on the interaction among revenue streams, cost factors, stakeholder interests, battery degradation, and user participation constraints. To provide an integrated view of these factors, Table 6 summarizes the main economic and user-centered mechanisms that should be considered in V2G deployment.

Table 6. Economic mechanisms, user-side concerns, and design implications for V2G deployment.

Mechanism or Factor	Main Value or Concern	Main Stakeholders	Design Implications for V2G Deployment
Energy arbitrage	EVs charge during low-price periods and discharge during high-price periods to obtain price-spread benefits.	EV owners, aggregators, retailers	Requires sufficient price differences, high round-trip efficiency, and degradation-aware scheduling to ensure positive net benefits.
Ancillary services	Aggregated EVs can provide frequency regulation, reserve capacity, voltage support, and fast-response flexibility.	Aggregators, system operators, EV fleets	Requires aggregation, accurate metering, reliable communication, and market access rules for small distributed resources.
Demand response and peak reduction	EV charging can be reduced or reversed during peak-load periods or grid-stress events.	Distribution operators, aggregators, charging operators	Requires clear baseline calculation, event notification, user opt-out options, and transparent compensation.
Renewable energy accommodation	EVs absorb surplus wind or photovoltaic generation and discharge during renewable shortfall or peak demand.	Renewable operators, grid operators, energy communities	Requires renewable forecasting, local congestion awareness, and incentives for charging during renewable-rich periods.
Battery degradation cost	Additional charge-discharge cycles may accelerate capacity fade and reduce battery lifetime.	EV owners, fleet operators, aggregators	Degradation cost should be included in scheduling objectives and user compensation mechanisms.
Bidirectional infrastructure cost	V2G requires bidirectional chargers, metering devices, communication systems, and platform operation.	Charging operators, aggregators, users, utilities	Cost-sharing models and long-term revenue certainty are needed to reduce investment risk.
User mobility requirement	Users need sufficient state of charge before departure and may resist excessive control of their vehicles.	Private EV users, fleet operators	V2G contracts should guarantee departure SOC, flexible participation, and simple opt-out mechanisms.
Revenue sharing and trust	Users may be unwilling to participate if compensation rules are unclear or perceived as unfair.	EV users, aggregators, charging service providers	Transparent settlement, simple contracts, and battery health protection can improve long-term participation.
Data privacy and cybersecurity	V2G operation requires data on SOC, location, charging behavior, and user preferences.	Users, aggregators, platform operators	Secure communication, privacy protection, and trusted data governance are necessary for scalable deployment.

4.1. V2G Revenue Sources and Pricing

The economic value of V2G mainly comes from the ability of EVs to shift charging demand, discharge electricity, and provide flexibility services to the power grid. The most direct revenue source is energy arbitrage, where EVs charge during low-price periods and discharge during high-price periods. This mechanism is usually enabled by time-of-use pricing, real-time pricing, or dynamic pricing schemes [83]. However, the profitability of energy arbitrage is strongly dependent on electricity price spreads, charging and discharging efficiency, battery degradation cost, and investment in bidirectional chargers [84].

Ancillary services represent another important revenue stream for V2G. Aggregated EVs can provide frequency regulation, reserve capacity, voltage support, congestion management, and other grid-support services due to their fast response capability. Compared to simple energy arbitrage, ancillary services can generate higher value because they compensate not only for energy delivery but also for flexibility, response speed, and availability [85]. Nevertheless, participation in ancillary service markets usually requires aggregation, accurate measurement, reliable communication, and compliance with market rules.

V2G can also participate in demand response programs. During peak-load periods or grid stress events, EVs can reduce charging power or discharge electricity to support the grid. In return, users or aggregators may receive demand response payments, capacity payments, or peak reduction incentives. For renewable-rich power systems, pricing mechanisms can further encourage EV charging during renewable surplus periods and discharging during renewable shortages. Such renewable-oriented incentives can improve renewable energy utilization while creating additional value for EV owners and aggregators.

Despite these potential revenue streams, V2G pricing should be evaluated from a net-benefit perspective. Gross revenue may be reduced by battery degradation, energy losses, communication and metering costs, transaction fees, and user inconvenience. Therefore, effective pricing mechanisms should not only reflect electricity market prices but also compensate users for battery aging and mobility constraints [86]. Simple and transparent

compensation rules are particularly important for private EV users, while fleet operators and aggregators may adopt more sophisticated market-based settlement mechanisms.

Recent techno-economic studies indicate that V2G profitability is highly context dependent. In [87], the authors explored the economic benefits and applicable conditions of different vehicle user groups that participate in V2G. In [88], the authors explored the carbon reduction and economic potential of the V2G mode of the EV. In [89], the authors investigated the costs and benefits of energy storage on the vehicle-side in the V2G mode. In some cases, V2G can improve renewable self-consumption and reduce energy procurement costs, while in other cases the net benefit may be weakened by low price spreads, uncertain market access, or insufficient compensation for battery usage.

Microgrid-level and vehicle-side studies further show that V2G economic performance is strongly affected by local system configuration. In remote or weak-grid areas, hybrid backup systems with V2G can reduce operating costs and improve energy resilience when coordinated with renewable generation and storage [90]. At the regional level, V2G benefits vary with home-parking and public-parking availability, electricity market conditions, and grid constraints [91]. From the vehicle-side perspective, the costs and profits of providing V2G services depend on electricity price spreads, battery degradation, compensation rules, and charging behavior. Therefore, V2G pricing mechanisms should be evaluated under realistic local tariff, battery cost, and user availability conditions.

Overall, V2G revenue models should combine multiple value streams, including energy arbitrage, ancillary services, demand response, capacity support, congestion management, and renewable energy accommodation. A well-designed pricing mechanism should align the interests of EV owners, aggregators, charging operators, and grid companies. Without sufficient and predictable economic incentives, technically feasible V2G scheduling strategies may fail to attract sustained user participation [77].

4.2. Battery Degradation Cost and Compensation

Battery degradation is one of the most critical barriers to V2G deployment because EV users may perceive bidirectional charging as a direct risk to battery lifetime and resale value. In V2G operation, additional charging and discharging cycles can contribute to capacity fade and internal resistance growth, especially when the battery is frequently operated under high depth of discharge, high charging or discharging power, elevated temperature, or unfavorable SOC range conditions. Therefore, the economic value of V2G should not be evaluated only by gross revenue but also by the degradation cost caused by additional battery usage [10,25].

Battery degradation in V2G systems is closely linked to scheduling decisions. Frequent shallow cycling may have limited aging impact, whereas deep discharge events or high-power cycling can increase degradation. As a result, battery-aware V2G scheduling should incorporate degradation-related constraints, such as SOC limits, depth-of-discharge limits, maximum charging and discharging power, and restrictions on unnecessary cycling. In optimization models, degradation costs can be included in the objective function together with electricity revenue, ancillary service income, and user compensation. This allows the scheduler to balance grid-service benefits against long-term battery health [92].

For economic assessment, battery degradation can be approximated using an energy-throughput-based cost expression:

$$C_i^{\text{deg}} = c_i^{\text{deg}} \sum_t (P_{i,t}^{\text{ch}} + P_{i,t}^{\text{dis}}) \Delta t, \quad (6)$$

where c_i^{deg} is the degradation cost coefficient per unit of battery energy throughput. This expression provides a simple way to incorporate battery aging into V2G revenue evaluation, scheduling objectives, and compensation design.

Compensation mechanisms are necessary to align system-level benefits with user-side costs. A fair V2G compensation scheme should cover not only the electricity delivered to the grid but also battery aging, energy losses, reduced mobility flexibility, and user inconvenience. Possible mechanisms include fixed participation payments, per-kWh discharge compensation, degradation-based reimbursement, performance-based rewards, and guaranteed minimum revenue contracts [86]. For private EV users, simple and transparent compensation rules may be more effective than complex market-based settlement, while fleet operators can adopt more detailed degradation models in operational optimization.

Battery health protection should also be embedded in V2G control and contract design. Practical V2G programs should guarantee departure SOC, allow users to set charging preferences, provide opt-out options, and clearly define responsibility for battery degradation among users, aggregators, charging operators, and manufacturers [93]. In this sense, degradation compensation is not only a technical cost-accounting problem but also a user-trust issue. Without transparent degradation assessment and fair compensation, users may be reluctant to provide schedulable battery capacity even if V2G is beneficial for the power system [94].

Recent degradation-oriented studies further show that battery aging should be treated as an operational constraint rather than as a post-processing cost. In [95], researchers investigated the battery degradation of electric vehicles that provide the reserve capacity for frequency regulation within transportation systems. In [96], the authors investigated battery aging patterns under various operating conditions and verified that rational V2G strategies can slow battery degradation and extend service life.

4.3. Business Models for Stakeholders

The commercial deployment of V2G depends on whether the value created by EV flexibility can be effectively allocated among different stakeholders [6]. The main participants include EV owners, aggregators, charging infrastructure operators, distribution system operators, electricity retailers, renewable energy operators, and fleet managers. Each stakeholder has different objectives: EV owners seek sufficient compensation and mobility protection; aggregators aim to monetize aggregated flexibility; grid operators require reliable peak reduction and ancillary services; and charging operators expect higher charger utilization and new service revenue [27].

Among these participants, the aggregator is usually the key intermediary in V2G business models. Individual EVs have limited capacity and uncertain availability, making it difficult for them to directly participate in electricity markets. Aggregators combine many EVs into a controllable virtual resource and participate in energy arbitrage, demand response, ancillary service markets, congestion management, and renewable energy balancing. The aggregator then shares part of the revenue with EV users according to predefined contracts, participation duration, available battery capacity, or delivered grid services [97].

Blockchain-based incentive systems have also been proposed to improve the transparency and credibility of EV participation in renewable energy consumption. By recording charging/discharging transactions and renewable-energy-related rewards on a distributed ledger, such systems can support traceable settlement, transparent incentive allocation, and user trust in V2G business models [98]. This is particularly useful when EVs are encouraged to charge during renewable surplus periods or provide flexibility services through aggregators. Nevertheless, blockchain-based incentive mechanisms still face challenges

related to scalability, transaction latency, privacy protection, and integration with existing market settlement rules.

Several business models can be developed for V2G deployment. In an aggregator-based model, private EV owners allow an aggregator to control part of their battery capacity within user-defined limits. In a fleet-based model, electric buses, taxis, logistics vehicles, or corporate fleets provide V2G services because their schedules and parking locations are more predictable. In a charging-station-based model, charging operators coordinate EVs, photovoltaic generation, stationary storage, and grid interaction to reduce electricity costs and improve renewable self-consumption. In a community-based model, EVs support local energy sharing, building energy management, and renewable energy utilization within residential or commercial communities [99].

Fleet-based and aggregator-based models are likely to be more practical in the early stage of V2G commercialization because they provide larger controllable capacity, lower coordination complexity, and clearer contractual relationships. Private EV participation has greater long-term potential, but it requires simple contracts, transparent revenue sharing, battery degradation compensation, data protection, and guaranteed mobility. Therefore, a successful V2G business model should not only maximize grid-side benefits but also provide predictable and understandable value to users.

Overall, V2G business models should align technical operation with economic incentives. If grid operators, aggregators, charging operators, and EV users do not share benefits fairly, the available V2G flexibility may remain theoretical rather than schedulable. Future business models should therefore combine multiple value streams, including energy arbitrage, demand response, ancillary services, renewable energy accommodation, and local grid support, while explicitly considering battery aging costs and user participation preferences [100].

4.4. User Concerns and Participation Behavior

User participation is a decisive factor for practical V2G deployment because EVs are primarily mobility assets rather than dedicated grid-storage devices. Even if V2G can provide system-level benefits, its available capacity depends on whether users are willing to plug in their vehicles, share battery flexibility, and accept controlled charging or discharging. Therefore, V2G participation should be understood not only as a technical scheduling problem but also as a behavioral decision influenced by perceived benefits, risks, trust, and convenience.

The main user concerns include range anxiety, battery degradation, loss of control, uncertain financial returns, data privacy, and contract complexity. Among these factors, guaranteed driving range and plug-in time are particularly important because they directly affect daily mobility flexibility. Recent stated-preference studies show that users do not evaluate V2G contracts only according to financial compensation; flexibility-related attributes, such as guaranteed range and required plug-in duration, may be more important for many users [101]. Similarly, user willingness studies indicate that financial incentives, grid-stability contribution, and environmental motivation can encourage participation, while loss of flexibility, battery degradation, and data concerns remain major barriers [102].

User participation also varies across vehicle types and usage patterns. Private EVs are numerous and widely distributed, but their availability is uncertain and strongly affected by individual travel behavior. In contrast, commercial fleets, buses, taxis, logistics vehicles, and shared mobility fleets usually have more predictable routes, parking periods, and charging locations, making them more suitable for early-stage V2G deployment. However, private EVs may provide substantial flexibility in the long term if aggregation platforms can offer reliable mobility guarantees and transparent compensation.

To improve user acceptance, V2G programs should include user-centered participation mechanisms. These include guaranteed departure SOC, flexible opt-out options, clear battery degradation compensation, transparent revenue sharing, simple contracts, and privacy protection. From a behavioral perspective, trust in aggregators and charging service providers is also essential. Users are more likely to participate when they understand how their vehicles will be controlled, how compensation is calculated, and how battery health and mobility needs are protected.

User-centered studies further suggest that participation in V2G cannot be explained by financial incentives alone. In [103], the authors explored the acceptance of V2G technology by users, calculated financial compensation and minimum guaranteed power demand, analyzed the influencing factors and their negative correlation, and proposed measures to reduce the relevant demands and concerns of users. In [104], the authors investigated a residential centralized photovoltaic system integrating V2H, photovoltaic power and green energy vehicles, which effectively reduced peak residential energy consumption.

Overall, user engagement determines whether V2G flexibility is actually schedulable. A technically optimal scheduling strategy may fail in practice if it ignores user preferences and perceived risks. Therefore, future V2G deployment should combine economic incentives with behavioral design, ensuring that users receive not only financial rewards but also mobility security, battery protection, and transparent control rights [31].

5. Standards, Challenges and Future Directions

The large-scale deployment of V2G systems requires not only advanced scheduling algorithms and viable business models but also reliable communication standards, interoperable charging infrastructure, appropriate market rules, and user-centered implementation strategies. Since V2G involves bidirectional energy exchange, real-time information transfer, user participation, and grid service provision, it is more complex than conventional unidirectional EV charging. This section summarizes key communication standards, identifies major deployment challenges, and discusses future development directions for practical and scalable V2G applications. In addition to introducing the functions of these standards, it further assesses their practical maturity, implementation limitations, and interoperability challenges across the vehicle, charger, aggregator, and grid-control layers. To better reflect real-world implementation conditions, this section also briefly discusses how regional regulatory environments, electricity-market access rules, technical requirements, cybersecurity obligations, metering and settlement arrangements, and consumer-protection frameworks influence the deployment of V2G technology.

5.1. V2G Communication and Key Standards

Communication standards are essential for ensuring interoperability among EVs, bidirectional chargers, aggregators, charging station management systems, and grid operators. In V2G operation, communication is required not only for basic charging control but also for authentication, authorization, charging schedule negotiation, metering, cybersecurity, payment settlement, and grid service coordination. Without standardized communication protocols, EVs and chargers from different manufacturers may not be able to exchange information reliably, which would limit the scalability of V2G services.

ISO 15118 [105] is one of the most important standards for vehicle-to-grid communication. It defines the communication interface between EVs and electric vehicle supply equipment and supports functions such as plug-and-charge, charging control, contract-based authentication, and bidirectional power transfer. For V2G applications, ISO 15118-20 is particularly important because it provides communication requirements for second-generation network and application layer functions, including bidirectional power transfer.

Therefore, ISO 15118 provides a technical basis for automated, secure, and interoperable EV–charger communication.

In addition to vehicle–charger communication, V2G deployment requires communication between charging stations and backend platforms. The Open Charge Point Protocol (OCPP) is widely used for communication between charging stations and charging station management systems. It enables remote monitoring, charging session management, smart charging, security functions, and integration with backend platforms. For aggregator-based V2G, OCPP can support the coordination of large numbers of chargers and provide the data infrastructure required for scheduling and settlement [106].

Demand response and grid-level coordination also require standardized interfaces. OpenADR is commonly used to automate demand response signals between utilities, aggregators, and flexible energy resources. In V2G applications, OpenADR can help grid operators or aggregators send demand response events, flexibility requests, and price-based control signals to charging networks. Therefore, ISO 15118, OCPP, and OpenADR can be viewed as complementary standards operating at different layers of the V2G communication architecture.

IEEE 2030.5 provides another important communication layer for grid-interactive distributed energy resources. Unlike ISO 15118, which focuses on EV–EVSE communication, and OCPP, which focuses on charging-station-to-backend communication, IEEE 2030.5 defines an application-layer protocol over TCP/IP for utility-facing energy management functions, including demand response, load control, time-of-use pricing, distributed generation, and electric vehicles. Therefore, IEEE 2030.5 can support the interaction between utilities, distributed energy resource management systems, aggregators, and flexible end-use resources, but it does not by itself define vehicle-level charging negotiation or charging-station transaction management. Table 7 presents the key standards and protocols related to V2G communication and interoperability. Table 8 further evaluates ISO 15118, OCPP, OpenADR, and IEEE 2030.5 in terms of practical maturity, key limitations, and interoperability implications for V2G systems.

Table 7. Key standards and protocols related to V2G communication and interoperability.

Standard or Protocol	Communication Layer	Main Function	Relevance to V2G
ISO 15118 [105]	EV–charger communication	Defines high-level communication between EVs and charging equipment, including authentication, charging negotiation, smart charging, and bidirectional power transfer.	Core standard for automated and interoperable V2G operation.
IEC 61851 [107]	Conductive charging system	Specifies general requirements for conductive EV charging systems, charging modes, and control functions.	Provides basic charging system requirements for safe EV–grid connection.
IEC 62196 [108]	Charging connectors and interfaces	Defines plugs, socket-outlets, vehicle connectors, and vehicle inlets for conductive charging.	Supports hardware interoperability between EVs and charging infrastructure.
OCPP	Charger–backend communication	Supports communication between charging stations and charging station management systems, including monitoring, session control, smart charging, and security functions.	Enables charging network management and aggregator-based coordination.
OpenADR	Utility–aggregator or demand response communication	Automates demand response and distributed energy resource signals between utilities, aggregators, and controllable resources.	Supports V2G participation in demand response and grid flexibility services.
IEEE 2030.5	DER and grid communication	Provides communication functions for distributed energy resources, energy management systems, and grid-interactive devices.	Can support DER coordination and grid-service communication for EV resources.

Although ISO 15118, OCPP, OpenADR, and IEEE 2030.5 are all relevant to V2G deployment, they operate at different layers and cannot be regarded as interchangeable standards. ISO 15118 mainly specifies the EV–EVSE communication interface, including

charging negotiation, authentication, smart charging, and bidirectional power-transfer-related messages. OCPP mainly supports communication between charging stations and charging station management systems, including charger monitoring, transaction management, smart charging profiles, device management, security functions, and backend integration. OpenADR operates at a higher demand-response and flexibility-event layer, where utilities, system operators, or aggregators send price, load-shifting, or grid-support signals to flexible resources. IEEE 2030.5 is more closely related to utility-facing smart-energy and distributed-energy-resource communication and can support functions such as demand response, load control, time-of-use pricing, distributed generation management, and electric-vehicle integration.

The main interoperability challenge is therefore not the absence of communication standards but the semantic and operational mapping among them. For example, a grid-level demand-response or DER-control request transmitted through OpenADR or IEEE 2030.5 must be translated into charger-level control commands through OCPP and then into vehicle-level charging or discharging schedules through ISO 15118. During this translation process, information on SOC, departure time, user preferences, battery limits, market prices, grid constraints, metering data, and settlement rules must remain consistent across different platforms. In practice, version mismatch, incomplete implementation of bidirectional functions, inconsistent data models, cybersecurity requirements, certificate management, and limited cross-protocol certification may restrict end-to-end V2G interoperability. Therefore, future V2G standardization should move beyond protocol-level compliance toward system-level interoperability testing that verifies whether EVs, chargers, aggregators, DER management systems, and grid operators can exchange actionable flexibility information in a secure, consistent, and verifiable manner.

Table 8. Practical maturity, limitations, and interoperability implications of major V2G-related communication standards

Standard or Protocol	Main Communication Layer	Practical Maturity	Main Limitation	Interoperability Implication for V2G
ISO 15118	EV–EVSE communication	Relatively mature for Plug & Charge, authentication, smart charging, and vehicle-side communication; bidirectional functions are strengthened in ISO 15118-20 [109].	Implementation of bidirectional charging, certificate management, and vehicle–charger compatibility remains uneven across manufacturers and charging platforms.	Vehicle-level constraints such as SOC, departure time, charging limits, and user preferences must be mapped to OCPP-based backend scheduling and aggregator optimization.
OCPP	Charging station–backend/CSMS communication	Widely adopted for charger management; OCPP 2.0.1 improves security and smart charging, while OCPP 2.1 adds stronger support for ISO 15118-20, bidirectional charging, and DER control. Mature for automated demand response and flexibility-event signaling; OpenADR 2.0a/2.0b and OpenADR 3.0 provide implementation profiles for OpenADR-enabled systems.	Many deployed chargers still use earlier versions, and OCPP 1.6 and OCPP 2.0.1 are not directly compatible. Bidirectional support also depends on the protocol version and vendor implementation.	Acts as the operational bridge between ISO 15118 vehicle-side negotiation and aggregator- or platform-level scheduling, metering, control, and settlement.
OpenADR	Utility/system-operator/aggregator demand-response layer		It does not define vehicle-level charging negotiation, charger transaction management, or battery-specific V2G operating constraints.	Grid-level event, price, or flexibility signals must be translated into OCPP-compatible charging or discharging schedules before they can be executed by EVSEs and EVs.
IEEE 2030.5	Utility-facing smart-energy/DER communication layer	Active standard for smart-energy profile application communication and relevant to DERs, demand response, load control, time-of-use pricing, distributed generation, and electric vehicles.	It is not EV-charging-specific and therefore requires integration with EVSE platforms, aggregators, and vehicle-side communication protocols for V2G use cases.	Can support utility-facing DER coordination, but V2G implementation requires mapping DER control signals to charger-level commands and vehicle-level constraints.

Although these standards provide an important foundation, interoperability remains a practical challenge. V2G systems must coordinate different communication layers, hardware interfaces, grid codes, cybersecurity requirements, and market platforms. Future V2G deployment will require more consistent implementation of standards, certification procedures, and cross-platform testing to ensure that EVs, chargers, aggregators, and grid operators can interact reliably at scale.

5.2. Regulatory and Regional Implementation Considerations

Beyond communication standards and technical interoperability, the practical deployment of V2G is strongly shaped by regional regulatory environments, electricity-market rules, tariff structures, aggregation mechanisms, metering and settlement requirements, cybersecurity obligations, and consumer-protection frameworks. These factors determine whether EV flexibility can move from technically feasible operation to market-recognized and compensated grid services. For example, V2G can create measurable system value by reducing the need for stationary storage and lowering system costs, but this value can only be realized when aggregated EV fleets are allowed to participate in flexibility, demand-response, or ancillary-service markets under clear operational and settlement rules [62]. Similarly, studies on low-carbon power-system transitions show that V2G can provide economic and emission-reduction benefits, but the realization of these benefits depends on coordination between power-system planning, electricity pricing, charging infrastructure deployment, and user-side participation mechanisms [110].

Regional differences are therefore important. In regions with mature wholesale electricity markets or ancillary-service markets, regulatory attention should focus on aggregator qualification, minimum bid size, baseline calculation, metering accuracy, and revenue allocation between aggregators and EV users. In regions where renewable curtailment and distribution-network congestion are more prominent, policy design may place greater emphasis on time-of-use pricing, renewable-oriented charging incentives, distribution-network constraints, and local flexibility markets. Recent clean-energy grid studies further indicate that optimized EV-grid coordination strategies, including time-of-use pricing, direct load control, and V2G, can reduce peak-valley load differences and improve renewable energy consumption, suggesting that tariff and demand-response design are important regulatory enablers for V2G-based renewable integration [38].

At the user side, regulatory and contractual arrangements also affect participation willingness. Practical V2G programs should clarify battery degradation responsibility, minimum departure SOC guarantees, opt-out rights, data privacy protection, cybersecurity requirements, and compensation transparency. Without such arrangements, EV owners may be reluctant to provide schedulable battery capacity even when V2G is technically capable of supporting the grid. Therefore, the regulatory environment should be understood as a deployment condition that connects technical standards, market access, user trust, and renewable-energy-oriented grid operation.

5.3. Critical Challenges for Deployment

Despite the technical potential of V2G, large-scale deployment still faces several critical challenges. These challenges can be grouped into technical, economic, user-related, and policy or regulatory dimensions [100].

The technical challenges remain significant. The operation of V2G requires accurate forecasting of EV availability, user travel behavior, renewable generation, electricity demand, and market prices. Forecasting errors may reduce scheduling performance and lead to insufficient vehicle SOC, underutilized renewable energy, or failure to deliver promised grid services [15]. In addition, high penetration of bidirectional charging may affect dis-

tribution network operation through voltage deviations, feeder congestion, transformer loading, and power quality issues. Therefore, V2G scheduling must be integrated with grid-aware constraints and real-time monitoring.

Communication and cybersecurity challenges become more important as V2G systems scale up [111]. V2G relies on frequent data exchange among vehicles, chargers, aggregators, and grid operators. This creates risks related to data privacy, authentication, unauthorized control, false data injection, and settlement manipulation. Since EV charging data may reveal user travel patterns and daily routines, privacy protection is also essential. Secure communication, encryption, identity management, and trusted data-sharing mechanisms are therefore necessary for large-scale V2G implementation. Recent privacy and authentication studies have further proposed secure charging authentication, privacy-preserving data aggregation, and anonymous key establishment schemes for V2G networks. In [112], the authors investigated the existing security and privacy vulnerabilities in charging authentication within V2G networks. In [113], the authors explored the security flaws of existing authentication schemes in V2G networks.

Economic uncertainty remains a major barrier. Although V2G can generate revenue from energy arbitrage, ancillary services, demand response, congestion management, and renewable energy accommodation, the actual net benefit may be reduced by battery degradation, charger investment, metering costs, transaction fees, and user inconvenience [114]. In some markets, the revenue from V2G may be insufficient or uncertain, especially when price spreads are small or market access rules are unclear [115]. Therefore, stable pricing mechanisms and fair compensation schemes are needed to make V2G economically attractive. User participation is still uncertain. EV owners may be concerned about range anxiety, battery degradation, loss of control, data privacy, and unclear compensation [116]. Even if a V2G program is beneficial from the system perspective, users may not participate if they perceive risks to mobility or battery lifetime. Fleet vehicles may be easier to schedule because their routes and parking patterns are more predictable, but private EVs require more flexible and user-friendly participation mechanisms [117]. Guaranteed departure SOC, opt-out options, transparent revenue sharing, and battery health protection are therefore essential.

Finally, policy and regulatory barriers may slow commercialization. Many electricity markets were not originally designed for small distributed resources such as EVs. Minimum capacity requirements, complex market registration procedures, unclear aggregator roles, and insufficient compensation for distribution-level services can limit V2G participation. In addition, battery warranty rules, metering standards, data ownership, and responsibility for degradation are not always clearly defined. These regulatory uncertainties make it difficult for users, aggregators, and charging operators to evaluate long-term risks and benefits.

5.4. Future Development Directions

The future direction should focus on translating V2G from technical feasibility to scalable implementation. Several directions are particularly important.

First, AI-based forecasting and scheduling should be further developed. Machine learning, deep learning, reinforcement learning, and model predictive control can improve the prediction of renewable generation, EV availability, charging demand, and electricity prices [118,119]. These methods can also support real-time or rolling-horizon scheduling with uncertainty. However, AI-based methods should be designed with interpretability, robustness, and safety constraints, especially when they are used for grid-support services.

Second, aggregator platforms should be strengthened. Aggregators are essential for combining many small EV batteries into a controllable flexibility resource. Future platforms should integrate EV behavior prediction, renewable forecasting, battery health

monitoring, grid constraint management, market bidding, and user compensation. A successful aggregator platform should not only optimize grid services but also protect user mobility and provide transparent economic benefits [120].

Third, fleet-scale V2G should be prioritized for early deployment. Electric buses, taxis, logistics vehicles, ride-hailing fleets, and corporate fleets usually have more predictable schedules and centralized parking locations than private EVs. This makes them suitable for controlled V2G demonstrations and commercial pilots. Fleet-scale studies can provide valuable evidence on battery degradation, revenue stability, operational reliability, user acceptance, and grid benefits.

Fourth, V2G should be integrated into low-carbon electricity markets. Current market designs often value energy and capacity, but may not fully compensate flexibility, renewable accommodation, congestion relief, or distribution-level support. Future market mechanisms should recognize the value of EV flexibility in renewable-rich power systems. Carbon-aware pricing, renewable surplus incentives, flexibility markets, and local congestion management mechanisms may improve the economic attractiveness of V2G.

Fifth, pilot-scale validation should be expanded. Many V2G studies remain based on simulation models, idealized user behavior, or simplified grid constraints. More field demonstrations are needed to evaluate real-world performance, including communication reliability, user participation, battery degradation, market settlement, interoperability, and cybersecurity. Pilot projects should compare private EVs, commercial fleets, charging stations, residential communities, and virtual power plant applications under different market and policy conditions.

In general, the future direction of V2G development should move toward integrated, user-centered, and market-compatible frameworks. Technical scheduling, economic incentives, communication standards, battery health protection, and user behavior should not be studied separately. Instead, they should be coordinated within practical deployment frameworks that reflect the operational requirements of renewable-rich power systems.

6. Conclusions

Vehicle-to-Grid (V2G) systems represent a promising pathway for linking electric mobility with renewable-rich power systems. As electric vehicles continue to expand from transportation assets into distributed energy resources, their aggregated battery capacity can provide flexible charging and discharging services to support grid operation. This review has examined V2G systems from the perspective of renewable energy integration, with particular emphasis on coordinated scheduling, economic feasibility, battery degradation, and user engagement. Rather than treating these aspects as isolated topics, the review highlights their strong interdependence in practical V2G deployment.

From a technical perspective, V2G can contribute to renewable energy accommodation by absorbing surplus solar or wind generation during periods of high renewable output and discharging electricity during peak demand or renewable shortfall. In this way, EV batteries can help reduce renewable curtailment, mitigate load fluctuations, support demand response, and provide ancillary services such as frequency regulation and voltage support. However, these benefits depend heavily on effective scheduling strategies. Price-based, load-based, renewable-forecast-driven, centralized, distributed, and aggregator-based scheduling approaches each offer different advantages in terms of cost reduction, grid support, scalability, privacy, and user autonomy. Future scheduling frameworks should further integrate renewable generation forecasting, mobility uncertainty, grid constraints, and battery health management.

Economic viability remains a decisive factor for large-scale V2G adoption. Although V2G can generate value through energy arbitrage, demand response, ancillary service

markets, congestion management, and renewable energy support, these revenues must be balanced against infrastructure costs, communication requirements, aggregator operation costs, battery degradation, and user inconvenience. In particular, battery aging should not be treated as a secondary issue, because additional charge–discharge cycles may influence both user acceptance and the long-term profitability of V2G services. Therefore, transparent compensation mechanisms, fair revenue-sharing models, and degradation-aware control strategies are essential for aligning the interests of EV owners, aggregators, charging operators, utilities, and market participants.

User engagement is equally important because EVs are primarily mobility assets rather than stationary storage devices. The availability of V2G resources depends on travel behavior, charging habits, state-of-charge requirements, risk perception, trust in aggregators, and willingness to participate. Private EV users may be sensitive to range anxiety, uncertain financial returns, battery lifetime concerns, and loss of control, while commercial fleets may offer more predictable V2G capacity but face strict operational constraints. Effective participation mechanisms should therefore guarantee mobility needs, provide clear compensation, allow flexible opt-out options, protect battery health, and reduce contractual complexity. Without sufficient user participation, even technically advanced scheduling algorithms and market designs may fail to deliver expected system-level benefits.

Several challenges still need to be addressed before V2G can be deployed at scale. These include the interoperability of bidirectional charging infrastructure, standardization of communication protocols, cybersecurity and data privacy, accurate modeling of battery degradation, scalable aggregator platforms, market access rules, and policy support for distributed flexibility resources. The future direction should pay greater attention to AI-based forecasting and scheduling, fleet-scale V2G operation, integration with photovoltaic and wind power systems, carbon-aware electricity markets, and pilot-scale demonstrations with real-world user behavior and grid constraints.

Overall, V2G should be understood not merely as a bidirectional charging technology but as a socio-technical system that connects vehicles, users, aggregators, electricity markets, and renewable energy resources. Its contribution to renewable energy integration depends on the coordinated development of technical scheduling methods, viable economic mechanisms, battery-conscious operation, and user-centered participation designs. By integrating these dimensions, V2G has the potential to become an important flexibility resource for future low-carbon, resilient, and user-oriented energy–transportation systems.

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