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COMMENTS

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How far are we from the large-scale adoption of V2G technology?

Abstract Vehicle-to-grid (V2G) technology enables electric vehicles (EVs) to discharge stored energy back into the grid, improving grid stability and renewable energy integration. Despite optimistic market forecasts projecting growth to $62 billion by 2033, V2G adoption remains predominantly at the pilot stage. This commentary reviews the current status of V2G technology, examining technical maturity, economic feasibility, stakeholder perspectives, and regulatory environments across regions. Demonstration projects in Denmark, the UK, Japan, and China have confirmed technical viability and economic promise, yet widespread commercial deployment faces significant challenges. Major barriers include immature business models, battery degradation concerns from frequent charge cycles, lack of standardized communication protocols, and insufficient consumer participation due to limited incentives and low public awareness. The study summarizes successful global pilots, identifies critical obstacles to large-scale implementation, and highlights strategic recommendations. Broad adoption requires coordinated efforts in standardizing technologies, developing clear incentives, supportive policies, and enhancing consumer engagement through targeted demonstrations and education.

Keywords V2G, electric vehicles, grid, renewable energy, cautiously optimistic

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1 Introduction

Vehicle-to-Grid (V2G) technology enables bidirectional energy exchange between electric vehicles and the power grid, effectively turning EVs into mobile energy storage units (Kempton and Tomić, 2005; Vollmuth et al., 2024). This concept has drawn significant attention for its potential to support grid stability and renewable energy integration (Noel et al., 2019). According to industry forecasts, the global V2G market is projected to grow from about $4.6 billion in 2024 to $62.0 billion by 2033, equivalent to a 33.4% compound annual growth rate (CAGR) (IMARC Group, 2024). This anticipated growth is fueled by the surging adoption of EVs, improvements in smart charging infrastructure, and the rising need for flexible grid services. However, in practice V2G remains in an early stage, with most implementations limited to pilot projects rather than mainstream commercial use (Aguilar Lopez et al., 2024).

At present, there are a considerable number of V2G projects globally, with over half being concentrated in Europe (V2G Hub, 2025). Many pilot programs across regions have demonstrated the technical feasibility and benefits of V2G on a limited scale (Aguilar Lopez et al., 2024). In Denmark, the Parker Project validated that a fleet of production EVs could provide services like frequency regulation to the grid and earn revenue, supporting a renewable-heavy power system (Nuvve, 2019). In the UK, trials such as Octopus Energy's Power-Loop, which enrolled 135 EV drivers in a home V2G bundle (UKRI, 2022), and the government-backed Project Sciurus (deploying over 300 domestic V2G chargers have been among the world's largest residential V2G demonstrations (Cenex, 2021). These projects confirmed that bidirectional charging can work at the household level to provide valuable grid services, while also collecting data on user behavior to inform future business models. Japan has also been a pioneer in V2G and vehicle-to-home (V2H) applications. The Japanese CHAdeMO fast-charging standard natively supports bidirectional charging, enabling EVs (e.g. the Nissan LEAF) to supply power back to homes. Japan already has thousands of V2H systems in use for emergency backup; indeed, over 10,000 bidirectional CHAdeMO chargers have been deployed worldwide Utilities such as TEPCO have additionally run V2G pilots to aggregate EV batteries for grid services (CHAdeMO, 2021a). Meanwhile, China is launching ambitious new V2G initiatives. In 2023, China's government selected nine cities (including Shanghai and Shenzhen) for its first large-scale V2G pilot program, encompassing 30 projects to test grid integration of EVs on a broad scale. These global efforts underscore V2G's versatility, showing it can stabilize power grids and provide backup power in practice (Howe, 2025). Despite these promising demonstrations, V2G has not yet achieved mainstream adoption. It largely remains in the pilot phase globally, with several barriers still hindering scale-up. A core challenge is the lack of a viable business model: for individual EV owners, revenue from grid services is typically modest and alone may not offset potential battery wear or other risks (CHAdeMO, 2021b). At the program level, additional barriers, such as high hardware costs, limited market access, and uncertain long-term remuneration, also constrain the development of a sustainable V2G business model. Without stronger incentives or simplified participation (e.g. through aggregators), most consumers are reluctant to enroll in V2G programs.

As a result, consumer participation remains low. Many drivers worry about battery degradation or find the complexity not worth a small payoff. In addition, technical and regulatory hurdles persist, such as interoperability issues and unclear compensation mechanisms for energy returned to the grid. Consequently, as of 2025 V2G is still largely confined to trials and demonstrations, with no large-scale commercial deployment yet realized. Continued innovation and policy support will be crucial to transition V2G from successful pilots to a mature, scalable component of the energy system in the coming years.

The main contributions of this study are to briefly summarize real-world stakeholder perspectives on V2G technology, including automotive manufacturers, energy companies, policymakers, consumers, and infrastructure operators, highlight critical adoption barriers such as immature business models, battery degradation, inadequate incentives, and standardization issues, and offer valuable recommendations and future outlook based on insights from leading experts.

2 Perceptions of different stakeholders on V2G technologies

2.1 Automotive manufacturers (OEMs)

The automotive industry's view of V2G technology has evolved from caution to active pursuit. Initially, limited by battery degradation concerns and unclear standards, few OEMs, such as Nissan, engaged in V2G. Recently, major automakers including GM, Ford, Volkswagen, BMW, Renault, and Tesla have embraced V2G, incorporating bidirectional charging into upcoming models and forming partnerships with utilities. Japan's Nissan and Mitsubishi integrate V2G into virtual power plants, while China's BYD actively expands capabilities, driven by strong governmental support. Challenges persist around technology standardization, battery warranty management, and revenue and liability models. Notably, studies have highlighted that V2G operations can accelerate battery degradation, with cyclic degradation contributing up to 20%–25% of total degradation over a decade, underscoring the need for economic compensation mechanisms (Sagaria et al., 2025).

2.2 Energy companies and grid operators

Grid operators generally support V2G for enhancing grid resilience, optimizing load management, and integrating renewables. V2G can supply fast balancing services (e.g., frequency response and renewable smoothing), but resource availability is variable and poorly coordinated charging can create secondary peaks after discharge events. Operators therefore need verified data from aggregators (refer to companies or platforms that enrolls EV owners or fleets, coordinates their charging and discharging, manages communications and telemetry, ensures compliance with grid requirements, and represents the group in energy service markets), dispatchable control (the ability to raise or lower power on command), clear service specifications, and settlement rules aligned with forecasting; under these conditions, managed V2G reduces net balancing needs and system costs (Department of Energy, 2025; IEA, 2025) European utilities lead with pilot projects, especially in the UK, where Octopus Energy incentivizes consumer participation. In the US, California's utilities explore V2G for peak management, supported by state-level policies. Japan incorporates V2G in virtual power plant projects, collaborating closely with automakers. Chinese utilities, such as State Grid, rapidly advance V2G pilots driven by governmental mandates for extensive EV-grid integration. However, unclear pricing mechanisms, complex regulations, and uncertain consumer engagement remain significant hurdles (Rao et al., 2025).

2.3 Government departments and policymakers

Policy support is crucial for V2G adoption, varying widely across regions. Europe supports V2G through pilot projects (Parker, WeDriveSolar) and targeted funding, despite limited formal regulations. The UK aims for a mature V2G market by the mid-2030s, while Germany explores regulatory adjustments. In the US, federal groundwork via FERC Orders 2222 and 755 enables EV participation in energy markets, with proactive states like California mandating future V2G capability (Schleeter, 2024). Japan promotes V2G through standards like CHAdeMO and localized subsidies but lacks large-scale mandates. China aggressively supports V2G, targeting standardization, extensive pilot projects, and EV-grid integration as national priorities by 2030.

2.4 Consumer and market acceptance

Consumer acceptance, critical for V2G commercialization, remains mixed. Concerns over economic returns, battery lifespan, and convenience restrict enthusiasm. Although financial incentives offer potential benefits, modest economic returns limit broader appeal. Real-world UK trials show customer payments of £0.30/kWh exported and up to approximately £725/year per household (Ofgem, 2021), while Project Sciurus reported £340–£513/year per home V2G charger and about £840/year potential bill savings under a V2G tariff for high plug-in users (Evbenata & Jakeman, 2023). Outside the UK, operational V2G aggregation in Denmark earned €1000–€1400 per vehicle-year for approximately 7000 plugged-in hours (Steward, 2017).

Battery degradation concerns, unsupported by most warranties, heighten skepticism. Range anxiety and concerns about vehicle control and data privacy further diminish consumer willingness. However, pilot projects, notably the UK's Sciurus initiative, have demonstrated significant improvements in consumer perceptions following firsthand experience, underscoring the importance of public education and pilot demonstrations (Cenex, 2021).

2.5 Charging infrastructure operators

Charging infrastructure operators maintain cautious optimism toward V2G, recognizing potential new revenue streams through ancillary grid services and price arbitrage. Successful projects like WeDriveSolar in the Netherlands validate strategic collaborations and profitable networks. However, substantial barriers include high costs for bidirectional chargers (approximately £3700 for hardware and installation), uncertain consumer participation rates, interoperability challenges, and unclear long-term investment returns. Operators thus favor small-scale pilot projects, cautiously awaiting clearer market frameworks and policy signals before committing to widespread deployment (Geng et al., 2024). At medium/low-voltage levels, bidirectional export can cause voltage rise, reverse power flow, and power-quality constraints, while uncoordinated charge–discharge cycles increase transformer thermal loading and shorten asset life; evidence from standards guides and studies shows that off-peak/managed scheduling, export caps, and local voltage control can mitigate these stresses (ENA, 2024; Nutkani et al., 2024).

2.6 Battery manufacturers and insurance companies

Battery manufacturers, which are often vertically integrated within EV manufacturers, generally view V2G with both technical interest and caution. On the opportunity side, V2G provides an extended value proposition for batteries, supporting new revenue streams and potential product differentiation through durability-optimized chemistries and management systems. However, these stakeholders also emphasize that unmanaged or high-rate cycling can accelerate capacity fade and increase warranty liabilities. Recent collaborative studies have demonstrated that with optimized operational envelopes, incremental degradation can be reduced to well below 1% per year (Sagaria et al., 2025). Insurers see V2G as both risk and opportunity. Concerns include uncertain long-term battery performance, equipment failure, and liability allocation. Opportunities lie in usage-based or condition-based policies that reward compliance with certified limits and verified telemetry. Effective integration will require clear contractual roles among EV owners, aggregators, manufacturers, and operators, plus reliable data sharing to assess risk and enable tailored insurance products (IEA, 2025).

2.7 Interactions among different stakeholders

As can be seen, the Fig. 1 illustrates interactions among stakeholders crucial to Vehicle-to-Grid (V2G) implementation. Government and policymakers play a central role, influencing manufacturers, grid operators, charging infrastructure operators, and consumers through regulations, incentives, and subsidies. They stimulate EV adoption and V2G development by setting policies that shape technological standards and market conditions. Automotive manufacturers respond to governmental directives and consumer demands by advancing vehicle capabilities and collaborating closely with battery manufacturers such as CATL, LG Energy Solution, Panasonic, and BYD. These battery companies address key V2G challenges like durability, cost efficiency, and compatibility, thereby enhancing overall technology integration. Grid operators and energy companies collaborate directly with manufacturers and charging infrastructure operators to optimize grid services, manage peak loads, and integrate renewable energy sources effectively. Charging infrastructure operators, incentivized by economic benefits, engage actively with consumers by providing convenient and reliable services, crucially influencing consumer acceptance. Consumers significantly impact the V2G ecosystem, guided by perceived economic benefits, battery reliability, and convenience. Insurance companies further reinforce consumer confidence through innovative coverage

Fig. 1 Interactions among different stakeholders.

models, including usage-based policies addressing battery health concerns. By mitigating perceived risks, insurers indirectly promote consumer participation and accelerate broader stakeholder investment in V2G. Collectively, these interactions create a dynamic ecosystem where governmental policy frameworks, technological advancements by battery and vehicle manufacturers, strategic engagement by energy companies, and supportive insurance solutions converge, facilitating the widespread commercial adoption of V2G technology.

3 Main concerns and challenges

Vehicle-to-Grid (V2G) technology faces interconnected barriers in technical, economic, regulatory, and social domains. Technologically, V2G remains in early stages, with limited compatibility between different vehicle models and charging infrastructures. Currently, standards such as ISO 15118-20, expected to be widely adopted by 2025, aim to enhance interoperability, yet significant compatibility issues persist. Complex real-time communication and coordination among vehicles, charging points, and grids present challenges including delays, reliability issues, and cybersecurity vulnerabilities. Battery degradation from frequent cycling further complicates adoption, despite ongoing research indicating mitigable impacts through optimized management and improved battery technology development (Aguilar Lopez et al., 2024; Sagaria et al., 2025).

Economically, the high cost of bidirectional chargers restricts broad consumer uptake. Bidirectional V2G equipment entails an additional hardware and installation cost of approximately £3700 compared with a standard smart (one-way) charger (Ofgem, 2021). For widespread adoption, charger costs must be reduced significantly to around £1000 per unit, a target not yet broadly achievable. Furthermore, unclear revenue mechanisms and distribution pose substantial obstacles. Many regions lack structured electricity pricing policies to fairly compensate consumers for grid contributions. Although aggregator business models, which describe the commercial arrangements by which aggregators capture value from V2G operations and share it with participants, and pool numerous EVs to engage effectively in energy markets, show potential to some extent, they require additional regulatory clarity and technological refinement. Grid infrastructure upgrades necessary to handle bidirectional flows represent another substantial economic challenge due to uncertain cost-sharing mechanisms between stakeholders.

Policy-wise, comprehensive regulatory frameworks remain incomplete, generating considerable stakeholder uncertainty. Clear legal and regulatory standards for safety, liability, grid access, and incentives are urgently

Table 1 Stakeholder attitudes and main concerns

Stakeholder	Attitude	Main concerns
Automotive Manufacturers	Generally positive, evolving from caution to proactive engagement; actively developing and planning V2G-enabled models (e.g., Nissan, GM, Ford, Tesla)	- Battery degradation and warranty uncertainty - Lack of unified standards - Unclear profitability and revenue-sharing models
Energy Companies and Grid Operators	Highly positive; perceive V2G as a tool for peak shaving, frequency control, and renewable energy integration; actively involved in pilot programs (UK, California, Japan)	Need for infrastructure upgrades, standardization of communication protocols, unclear economic returns and compensation mechanisms
Government Agencies and Policymakers	Generally supportive but varied; EU promotes via pilot projects; the UK and California leading with explicit legislation and incentives; Japan supports through targeted strategies; China implements top-down policies promoting rapid integration	Lack of harmonized international standards, complex regulations and tariff structures; uncertainty in compensation and incentives causing regional variations in adoption speed (FERC Order 2222 in the US, CHAdeMO standards in Japan)
Consumers and Public Acceptance	Mixed and generally cautious; acceptance increases significantly with actual usage experience; clear financial incentives improve willingness significantly (e.g., UK's Powerloop project)	Battery degradation fears, inconvenience concerns, range anxiety, concerns about loss of vehicle control, privacy and data security concerns, insufficient or unclear incentives
Charging Infrastructure Operators	Cautiously optimistic; see V2G as an opportunity to diversify business models and revenue streams (e.g., participation in ancillary service markets, peak demand management)	Significant upfront infrastructure costs, uncertainty in standardization, consumer acceptance, and unclear policy and regulatory framework

needed. While some jurisdictions, notably California and China, have actively promoted V2G via legislation and pilot projects, global regulatory support remains fragmented and inconsistent.

Social acceptance also significantly limits V2G deployment. Public awareness is minimal, with prevalent skepticism regarding economic viability, battery longevity, and vehicle autonomy. Addressing these concerns through public education, demonstration projects, and clearer financial incentives is essential for enhancing user acceptance and overcoming barriers to widespread V2G integration.

The perceptions and attitudes of the stakeholders and their main concerns are summarized in the Table 1.

4 Suggestions and future outlook

To facilitate V2G adoption, a multifaceted approach is necessary. First, standardizing technical frameworks, including bidirectional charging (ISO 15118, CCS protocols), cybersecurity (ISO 15118-20), and cross-border compatibility (GB/T, IEC 61851), will lower integration costs and build stakeholder confidence.

Technologically, enhancing battery durability through high-cycle-life materials (e.g., LFP, solid-state batteries) and optimized Battery Management Systems (BMS) is crucial. Accelerating affordable AC bidirectional chargers and innovations like silicon carbide semiconductors can significantly reduce infrastructure costs. Additionally, advanced materials (silicon anodes, sulfur cathodes) and AI-driven dispatch algorithms can further enhance V2G efficiency and profitability.

Diverse business models must ensure equitable stakeholder returns. Commercial fleets and public service vehicles, due to their predictable schedules, are ideal early adopters. Financial incentives (preferential electricity rates, participation subsidies) and straightforward remuneration mechanisms can motivate private users. Aggregator models enabling EVs to participate in energy markets should be encouraged, supported by regulatory clarity (e.g., US FERC initiatives).

Government policy support is essential, including clear legislative frameworks, updated grid interconnection codes, interim financial incentives, and refined pricing mechanisms. Setting long-term mandates (e.g., California' s 2030 V2G requirement) provides clear industry signals. Public education and transparency in user interfaces can significantly enhance consumer trust and participation.

Adopting phased implementation, initially focusing on regions and sectors best suited to V2G (e.g., commercial fleets, renewable-rich areas), will create successful benchmarks for broader adoption. As V2G transitions from pilots to mainstream, it promises transformative impacts on energy stability, transportation efficiency, and carbon neutrality, positioning EV owners as active energy participants in sustainable future ecosystems.

Competing Interests The authors declare that they have no competing interests.

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