A Study Of Vehicle To Grid Integration In Electric Vehicles Focusing On Opportunities Challenges And Future Directions

[1]Mohiyuddin T D, [2] Reshma Sultana ,
[1] Senior Grade Lecturer, Department of Electrical and Electronics Engineering, Government Polytechnic, Ballari, Karnataka, India.
[2] Senior Grade Lecturer, Department of Electrical and Electronics Engineering, Government Polytechnic, Ballari, Karnataka, India.

Abstract: The increasing adoption of electric vehicles (EVs) and the parallel growth of renewable energy sources have positioned Vehicle-to-Grid (V2G) technology as a critical enabler of sustainable energy transitions. V2G allows bidirectional power flow between EVs and the grid, offering services such as peak load management, frequency and voltage regulation, and improved integration of intermittent renewables. A comprehensive review of recent literature reveals significant opportunities, including reduced system costs, enhanced grid resilience, and new revenue streams for EV owners. However, widespread deployment faces multiple challenges. Technically, battery degradation, interoperability of charging standards, communication protocols, and grid stability under large-scale EV integration remain critical issues. From an institutional and policy perspective, barriers include non-harmonized standards, inadequate business models, regulatory uncertainty, and limited consumer awareness. While pilot projects demonstrate the feasibility of V2G, global implementation requires coordinated advances in battery technologies, charging infrastructure, smart grid systems, and supportive policy frameworks. This study synthesizes insights from state-of-the-art research to highlight both the potential and the bottlenecks of V2G adoption. It further identifies research gaps in socio-technical and institutional domains, underscoring the need for harmonized standards, stakeholder cooperation, and innovative market mechanisms. By bridging technical and policy perspectives, this review contributes to advancing V2G as a cornerstone of future low-carbon power and transport systems.

Index Terms - Electric vehicles (EVs), Vehicle-to-grid (V2G), Grid-to-vehicle (G2V), Bidirectional charging, Battery performance and degradation, Interoperability and standards (OCPP, ISO 15118, CHAdeMO), Renewable energy integration, Demand response and peak load management, Policy and regulation, Sustainable energy transition.

I. Introduction

The accelerating global adoption of electric vehicles (EVs) is reshaping both the transportation and energy sectors, driven by the dual imperatives of decarbonization and sustainable energy transitions. Unlike conventional internal combustion engine vehicles, EVs provide the advantage of high energy efficiency, low operating costs, and significant reductions in greenhouse gas emissions. Beyond their role as mobility solutions, EVs are increasingly recognized as mobile energy storage units with the potential to provide ancillary services to the power grid through vehicle-to-grid (V2G) technology. V2G enables bidirectional energy flow, allowing EVs to not only draw electricity from the grid but also discharge stored energy back into it, thereby offering services such as frequency regulation, peak load management, renewable energy integration, and enhanced grid resilience.Recent research and pilot projects highlight the transformative potential of V2G. Studies suggest that V2G can reduce system-level energy costs, improve the flexibility of renewable energy deployment, and generate economic benefits for EV owners and fleet operators. Furthermore, projections indicate that the aggregated storage capacity of EV fleets could become comparable to large-scale energy storage systems, positioning EVs as a critical asset in future smart grids. However, large-scale V2G deployment is still constrained by multiple challenges. On the technical side, battery degradation, interoperability of charging protocols, bidirectional charger availability, and grid stability under high EV penetration remain major hurdles. From an institutional perspective, a lack of harmonized standards, unclear business models, regulatory uncertainty, and limited consumer awareness continue to slow down commercialization.Given these opportunities and challenges, a comprehensive review of V2G integration is timely and necessary. This study synthesizes insights from recent literature to map the technical, economic, and institutional barriers to widespread V2G adoption, while also identifying key enablers and future research directions. By bridging perspectives from engineering, policy, and market domains, the paper aims to contribute to the understanding of how V2G can evolve from pilot-scale demonstrations to a mainstream solution for sustainable energy systems.

II. Background and Conceptual Framework

The growing urgency to decarbonize the transport sector and modernize electricity systems has positioned electric vehicles (EVs) as both a sustainable mobility solution and a critical element in energy transitions. EV adoption has expanded rapidly in recent years, supported by falling battery costs, stricter emission regulations, and consumer awareness of environmental impacts. According to international reports, the global stock of light-duty passenger EVs more than doubled between 2018 and 2020, and projections suggest that EV sales could account for nearly 50% of global car sales by 2030.

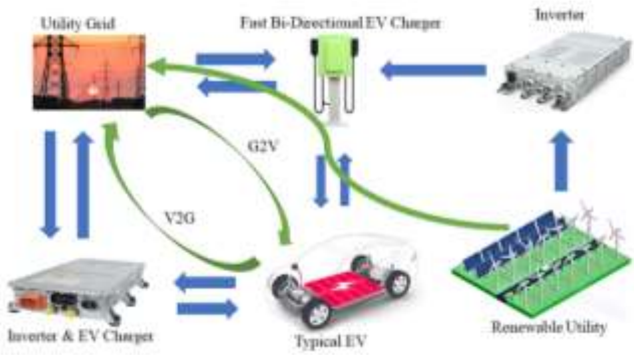

Fig 1: Block diagram of G2V and V2G power flows between electric vehicles, chargers, the grid, and renewable sources (adapted from [Source]).

In the context of vehicle-to-grid (V2G) systems, Figure 1 illustrates the bidirectional flow of electricity between the utility grid, renewable generation sources, and electric vehicles (EVs). In the grid-to-vehicle (G2V) mode, energy flows from the grid or renewable utility through a bidirectional charger to the EV battery for storage. Conversely, in the vehicle-to-grid (V2G) mode, the EV discharges stored energy back to the grid, enabling peak load management, frequency regulation, and renewable energy integration. The inverter and charger act as essential components to manage AC–DC conversion and maintain system stability. This diagram highlights the central role of EVs as both consumers and providers of electricity within smart grid ecosystems, thereby forming the conceptual foundation of V2G technology.

i) Evolution of Electric Vehicles

EV technologies are broadly categorized into Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs). BEVs operate solely on batteries, while HEVs and PHEVs combine combustion engines with electric propulsion, with PHEVs offering grid-charging capability. FCEVs differ in that they generate electricity through hydrogen fuel cells rather than relying on battery discharge. These variations influence the degree of integration with the grid, with BEVs and PHEVs being the most compatible for bidirectional energy exchange.

ii) Concept of Smart and Bidirectional Charging

Smart charging refers to controlled charging of EVs that responds to grid conditions, reducing peak demand and improving system stability. Bidirectional charging, or Vehicle-to-Grid (V2G), expands this concept by enabling EVs to discharge energy back into the grid. This transforms EVs from passive loads into active grid participants, capable of providing ancillary services such as voltage regulation, load balancing, harmonics mitigation, and renewable energy support. Broader concepts such as Vehicle-to-

Home (V2H), Vehicle-to-Building (V2B), and Vehicle-to-Everything (V2X) further extend the application of EVs as distributed energy resources.

iii) *Theoretical Foundations of Vehicle-to-Grid*

The V2G framework is built on the principle of bidirectional energy flow, where EV batteries function as distributed energy storage systems within the power grid. During low-demand periods, EVs can store excess electricity—often sourced from renewables—and discharge it back to the grid during peak demand, thereby flattening load curves. From a systems perspective, V2G supports peak shaving, frequency regulation, and reserve provision, which are essential for integrating variable renewable energy sources like solar and wind.

iv) *Global Development and Current Trends*

Governments and industries worldwide are recognizing the potential of V2G in achieving net-zero emission targets. Initiatives in regions such as Europe, Japan, and North America have demonstrated its feasibility, with projects using CHAdeMO and ISO 15118 standards enabling pilot-scale deployment. However, standardization remains fragmented, creating barriers for global scalability. At the same time, advancements in smart grid technologies, battery management systems, and communication protocols are providing a stronger foundation for wider adoption.

v) *Integration into Smart Grids and Renewable Systems*

The convergence of EVs with smart grids and renewable energy systems defines the conceptual framework of V2G. By acting as mobile storage units, EVs can complement distributed energy resources, enhance microgrid resilience, and enable local energy trading. Studies show that aggregated EV fleets could provide energy storage capacity comparable to large-scale stationary systems, underscoring their potential role in stabilizing future low-carbon power systems.

III. Technical Aspects of V2G Integration

The successful deployment of Vehicle-to-Grid (V2G) technologies depends largely on overcoming several technical challenges while maximizing operational benefits for both electric vehicles (EVs) and the power grid. The following subsections outline the key technical aspects that shape the feasibility, efficiency, and reliability of V2G systems.

i) *Power System Impacts*

EVs connected to the grid can provide crucial ancillary services, including frequency regulation, voltage stabilization, and reactive power support. Bidirectional charging enables peak shaving by discharging stored energy during high-demand periods and charging during off-peak hours. This load-shifting capability helps mitigate grid congestion and enhances the stability of renewable-dominated systems. However, large-scale uncoordinated charging and discharging can create risks such as voltage fluctuations, harmonics, and transformer overloading. Therefore, smart charging strategies, supported by advanced communication and control mechanisms, are essential to maintain power quality.

ii) *Battery Performance and Degradation*

Battery degradation remains one of the most critical technical barriers to V2G adoption. Frequent charge–discharge cycles accelerate capacity loss and reduce the overall lifespan of lithium-ion batteries. While some studies indicate that controlled V2G operations may have only marginal impacts, others highlight significant long-term risks for battery health. Advanced battery management systems (BMS) are being developed to optimize state of charge (SoC), depth of discharge (DoD), and thermal conditions, thereby minimizing degradation while ensuring reliable grid services.

iii) Charging Infrastructure and Bidirectional Chargers

V2G deployment requires a robust charging infrastructure equipped with bidirectional chargers. Currently, only a limited number of standards, such as CHAdeMO and ISO 15118, fully support V2G operations. The lack of harmonized global standards poses interoperability challenges for automakers and charging equipment providers. Furthermore, the widespread adoption of high-power fast chargers is constrained by their high installation costs and potential impacts on grid stability. Innovative solutions, such as inductive wireless charging and vehicle-to-home (V2H) setups, are emerging but remain in early stages of commercialization.

iv) Communication and Control Protocols

The integration of EVs into grid operations requires seamless two-way communication between vehicles, charging stations, and grid operators. Protocols such as the Open Charge Point Protocol (OCPP) and ISO 15118 enable authentication, billing, and dynamic load control. However, challenges remain in achieving cybersecurity, real-time data exchange, and cross-platform compatibility. Intelligent control algorithms, including model predictive control and decentralized energy management strategies, are being explored to optimize charging schedules and grid interactions.

v) Integration with Renewable Energy Systems

One of the most promising applications of V2G lies in its synergy with renewable energy sources (RES) such as solar and wind. EVs can absorb excess generation during periods of high renewable output and discharge stored energy during low-generation or peak-demand hours, effectively acting as distributed storage units. This integration enhances the reliability of microgrids, supports islanded operations, and reduces system-level costs. Pilot studies have shown that coordinated V2G and renewable systems can reduce charging costs by over 30% and lower energy supply system costs by more than 12%.

IV. Economic and Market Perspectives

While the technical feasibility of Vehicle-to-Grid (V2G) has been demonstrated in pilot projects, its large-scale deployment will ultimately depend on the development of sustainable business models and market structures. Economic viability is a key driver for adoption, as stakeholders—including EV owners, fleet operators, utilities, and aggregators—require clear financial incentives to participate in V2G programs.

i) Cost Savings and Revenue Streams

V2G can create direct and indirect economic benefits for EV owners and fleet operators. By enabling peak shaving and demand response, V2G allows participants to reduce electricity costs by charging during off-peak hours and discharging during peak demand periods. Studies have shown that smart and bidirectional charging strategies can reduce charging costs by more than 30% and lower system-wide energy supply costs by up to 12%. In addition, EV owners can generate revenue by providing ancillary services such as frequency regulation, reserve capacity, and voltage support. However, the actual profitability depends heavily on tariff structures, electricity market design, and battery degradation costs.

ii) Business Models and Stakeholders

Several business models have been proposed for V2G, often involving three primary stakeholders:

- EV owners and fleet operators, who provide battery capacity.
- Aggregators, who pool multiple EVs to deliver reliable grid services.
- Utilities and grid operators, who purchase services to enhance system stability.

Aggregator-based models are gaining attention as they enable scale, improve predictability, and reduce individual risks. Fleet-based V2G applications, such as school buses and delivery vehicles, are particularly attractive since they follow predictable usage patterns, allowing efficient scheduling of charging and discharging.

iii) Market Readiness and Regional Developments

The economic potential of V2G is being tested in different regions, with Europe and Japan leading early implementations. In Denmark, for example, fleet-based V2G projects have demonstrated the profitability of frequency regulation services, generating measurable revenue for participants. Japan has pioneered CHAdeMO-based V2G pilots, while Europe is advancing ISO 15118 standardization to facilitate broader adoption. In contrast, the United States has made progress in demand response-oriented V2G, particularly in school bus electrification projects. Despite these promising examples, global market readiness remains uneven, largely due to differences in electricity market design, tariff policies, and regulatory support.

iv) Barriers to Market Adoption

Several economic and market barriers hinder the scaling of V2G. The cost of bidirectional chargers remains significantly higher than unidirectional alternatives, limiting their affordability. Additionally, the absence of standardized compensation mechanisms for grid services reduces investor confidence. Battery degradation concerns also influence the cost–benefit analysis, as uncertain impacts on battery life may deter EV owners from participating. Finally, a lack of awareness among consumers and misalignment of incentives between stakeholders pose further challenges to commercialization

V. POLICY, REGULATORY, AND INSTITUTIONAL BARRIERS

Despite its significant technical potential, Vehicle-to-Grid (V2G) technology faces considerable institutional and regulatory challenges that hinder large-scale adoption. Unlike purely technical issues, these barriers arise from fragmented policy frameworks, inconsistent regulatory support, and misaligned institutional arrangements, all of which affect the ability of stakeholders to deploy V2G solutions effectively.

i) Fragmented Standards and Lack of Harmonization

One of the most pressing institutional barriers is the absence of harmonized international standards for bidirectional charging. While CHAdeMO supports V2G and ISO 15118 is progressing toward interoperability, competing standards and incomplete global adoption create uncertainty for original equipment manufacturers (OEMs) and charging infrastructure providers. The lack of standardization leads to higher development costs, delays in product rollouts, and limited consumer confidence in the technology.

ii) Regulatory Uncertainty and Market Design Limitations

Most electricity markets are not yet structured to accommodate distributed energy resources (DERs) such as EVs in providing ancillary services. Regulatory frameworks in many countries fail to define the conditions under which EVs can participate in demand response, frequency regulation, or capacity markets. Moreover, compensation mechanisms for V2G services remain unclear, reducing the economic incentives for EV owners and aggregators. Without transparent tariff structures, business models struggle to achieve profitability, and private investment is limited.

iii) Institutional Inertia and Stakeholder Misalignment

Institutional inertia within utilities, grid operators, and policymakers further slows the diffusion of V2G. Utilities often perceive EVs as a challenge to grid stability rather than as a resource, leading to cautious adoption of V2G-friendly regulations. Misalignment among stakeholders—including automakers, charging infrastructure providers, and regulators—creates additional friction, as each actor has different priorities and risk perceptions

iv) Consumer Awareness and Social Acceptance

Another institutional dimension is the limited awareness and acceptance of V2G among consumers. Concerns about battery degradation, privacy of data exchange, and uncertain financial benefits have discouraged wider participation. Furthermore, trust in utilities and aggregators to manage consumer assets for grid services remains low. These social barriers are tightly connected to policy design, as transparent communication, consumer protections, and visible financial benefits are essential for fostering public trust.

v) Policy Gaps and Limited Government Support

While some regions—such as Japan and parts of Europe—have developed supportive policies for V2G pilots, most countries still lack comprehensive policy frameworks to encourage mainstream adoption. Existing incentives are often fragmented, short-term, or limited to research and demonstration projects. Without long-term, stable policy commitments, industries hesitate to invest in large-scale V2G deployment.

VI. Opportunities and Future Prospects

While Vehicle-to-Grid (V2G) technology faces significant technical and institutional barriers, its opportunities for shaping the future of sustainable mobility and energy systems are substantial. If effectively deployed, V2G can become a cornerstone of decarbonized power systems and accelerate the global energy transition.

i) Enabling Renewable Energy Integration

One of the most promising opportunities for V2G lies in supporting the integration of renewable energy sources such as solar and wind. By acting as distributed energy storage units, EVs can store excess renewable generation during periods of oversupply and discharge electricity during demand peaks or renewable shortages. This flexibility reduces curtailment, stabilizes variable generation, and enhances the resilience of renewable-heavy grids. Studies indicate that V2G could increase renewable penetration by as much as 30% on a system level.

ii) Grid Flexibility and Stability

As EV adoption scales, aggregated fleets could provide significant grid services comparable to centralized storage plants. V2G-enabled EVs can offer demand response, voltage control, and peak shaving, reducing the need for costly infrastructure upgrades【24:sustainability-15-05782.pdf】. This flexibility is particularly valuable for future smart grids and microgrids, where localized energy balancing will be essential for system reliability.

iii) Economic and Business Opportunities

Beyond technical benefits, V2G offers new revenue streams and cost savings for multiple stakeholders. Fleet operators—such as school buses, taxis, and delivery services—stand to benefit most, given their predictable usage and large battery capacity. Aggregators and energy service providers can develop innovative business models to pool EV resources, while utilities can reduce peak demand and defer costly grid expansions. Furthermore, by stacking multiple services—such as frequency regulation, backup supply, and renewable integration—V2G can enhance its economic viability.

iv) Technological Synergies with AI, IoT, and Blockchain

The future of V2G is likely to be shaped by its convergence with digital technologies. Artificial intelligence (AI) and machine learning can optimize charging and discharging schedules based on grid conditions and user preferences. The Internet of Things (IoT) enables real-time communication between EVs, charging stations, and grid operators, ensuring seamless coordination. Blockchain-based platforms have also been proposed for secure, decentralized energy trading, enabling peer-to-peer (P2P) energy exchange between EV owners and consumers.

v) Pathways for Large-Scale Adoption

Scaling up V2G requires coordinated advances in technology, policy, and markets. Priorities include developing harmonized international standards (ISO 15118, CCS, CHAdeMO), reducing bidirectional charger costs, and ensuring supportive regulatory frameworks. Policy incentives, such as dynamic pricing, subsidies for V2G infrastructure, and inclusion of EVs in capacity markets, can accelerate adoption. Moreover, awareness campaigns and consumer education will be vital to improving social acceptance and participation.

VII. Recent Advances Addressing V2G Research Gaps

Recent research has begun to address many of the gaps previously identified in Vehicle-to-Grid (V2G) deployment. Studies show that battery degradation from V2G operations is minimal, and in some cases, optimized charging strategies may even extend battery life. International efforts are advancing standards, with ISO 15118-based "Plug and Charge" protocols and the Megawatt Charging System expected to enhance interoperability by 2025. Market deployment is also accelerating, with large-scale projects in Europe, Japan, and the United States, including school bus electrification and car-sharing fleets. Business models are gradually maturing, supported by pilots demonstrating revenue potential from frequency regulation and demand response. Consumer awareness is increasing, though battery warranty concerns remain a key adoption barrier. Together, these developments suggest that while challenges persist, significant progress has been made toward enabling large-scale V2G integration.

Table 1. Progress on Vehicle-to-Grid (V2G) Research Gaps Identified

Research Gap	Recent Progress / Findings
Battery degradation concerns	Recent studies show minimal or even positive impacts under optimized V2G strategies.
Standards & interoperability	ISO 15118 "Plug and Charge" and Megawatt Charging System (MCS) nearing adoption by 2025.
Limited V2G-capable vehicles	Rollout of V2G-ready fleets (Renault, Nissan) and U.S. school bus electrification projects.
Business models & deployments	Pilot programs demonstrate revenue streams from frequency regulation and demand response.
Consumer awareness & trust	Growing familiarity, though battery warranty and privacy concerns remain barriers.

VIII. Conclusion

This study reviewed the technical, policy, and institutional dimensions shaping the deployment of Vehicle-to-Grid (V2G) technology. While V2G offers clear opportunities for renewable energy integration, grid flexibility, and new business models, its widespread adoption is still constrained by fragmented standards, regulatory uncertainty, and consumer trust issues. Recent progress in international standardization, large-scale fleet demonstrations, and evidence of minimal battery degradation shows that many earlier concerns are being addressed. However, gaps remain in ensuring interoperability, developing profitable and scalable business models, and harmonizing policy frameworks across regions. Consumer engagement and transparent communication on warranties and benefits will also be essential for building trust in V2G. To accelerate adoption, coordinated action among policymakers, industry stakeholders, and researchers is required. Ultimately, V2G represents a transformative pathway for achieving sustainable, resilient, and decarbonized energy systems.

REFERENCES

[1] Kempton, W., and J. Tomić. 2005. Vehicle-to-Grid Power Fundamentals: Calculating Capacity and Net Revenue. *Journal of Power Sources*, 144(1): 268–279.

[2] Kempton, W., and J. Tomić. 2005. Vehicle-to-Grid Power Implementation: From Stabilizing the Grid to Supporting Large-Scale Renewable Energy. *Journal of Power Sources*, 144(1): 280–294.

[3] Kempton, W., and J. K. K. Udo. 2009. A Test of Vehicle-to-Grid for Energy Storage and Frequency Regulation in PJM System. *Journal of Power Sources*, 196(3): 1053–1062.

[4] Andersen, P. B., et al. 2012. Integration of Electric Vehicles in the Danish Power System. *Energy Policy*, 51: 242–251.

[5] Sovacool, B. K., et al. 2018. The Neglected Social Dimensions to a Vehicle-to-Grid Transition: A Critical and Systematic Review. *Environmental Research Letters*, 13(1): 013001.

[6] Noel, L., et al. 2019. Vehicle-to-Grid: A Sociotechnical Transition Beyond Electric Mobility. *Energy Research & Social Science*, 48: 66–75.

[7] Liu, H., et al. 2020. Optimal Scheduling of Vehicle-to-Grid Services Considering Battery Degradation Costs. *Applied Energy*, 262: 114523.

[8] Van der Kam, M., and R. van Sark. 2015. Smart Charging of Electric Vehicles with Renewable Energy Sources. *Energy*, 87: 385–396.

[9] Lopes, J. A. P., et al. 2011. Integration of Electric Vehicles in the Electric Power System. *Proceedings of the IEEE*, 99(1): 168–183.

[10] Ota, Y., et al. 2012. Autonomy and Stability of Collective Vehicle-to-Grid Systems in Power Grids. *IEEE Transactions on Smart Grid*, 3(1): 559–564.