

Bidirectional Charging and Vehicle-to-Grid (V2G) Integration in Smart EV Infrastructures

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ABSTRACT

Inclusive of the Vehicle-to-Grid (V2G) technology, bidirectional charging is a paradigm shift in moving toward sustainable and smart energy systems. The paper examines technical, economic, and environmental impacts of employing infrastructures based on smart EV with support to the V2G. An all-embracing simulation approach was used, and the grid interactions, behavior of batteries, and operating conditions were modeled at the low (10%), medium (30%), and high (50%) levels of adoption. The findings indicate that peak load reduction of up to 38 percent, 20 percent improvement in frequency stability and high level of line loss reduction, leading to increased grid reliability and operational performance, can be realized by high levels of V2G participation. The economically proves to be very rewarding to EV owners and aggregators with annual net profits of \$120 per EV in low participation going up to \$350 per EV in high participation situations and system level savings and payback times that strengthen with scale. Environmental analysis underlines positive efforts in achieving decarbonization since CO₂ can be reduced by 770 kg per E.V each year mainly through the optimal use of renewable energy.

Nevertheless, the results also revealed some trade-offs especially in the case of battery degradation which aggravates with increased frequency of cycling, the need therefore is to optimize dispatch strategies and facilitate enabling policies. The study comes to the conclusion that wide use of V2G is possible and beneficial, supported by the intelligent control algorithms and user-integration, standardization and incentives, thus making V2G a key enabler of future-proof and low-carbon power systems.

Keywords: Vehicle-to-Grid (V2G), bidirectional charging, electric vehicles, smart grid, battery degradation, peak load reduction, renewable energy integration, grid stability, energy management, sustainable transportation.

Introduction

The near future of rapid growth in electric vehicle (EV) use poses several problems and opportunities to the current power system. The utilization of EVs places significant pressure on the utilities because of charging-peak demand, load uncertainty, and issues of energy management flexibility (Sultan et al., 2022). However, by charging both ways, i.e., via Vehicle to Grid (V2G), the EVs can be used not only as loads but also as distributed storage which is part of maintaining the grid operations (Xu, 2025; Adegbohun et al., 2024). This twofold functionality is the defining feature of the smart EV infrastructure development and the policies to decarbonize the electric power grid as well as the transport sector.

Two-way charging systems allow the flow of energy in both directions charging the battery with grid (Grid-to-Vehicle, or G2V) and charging the grid with the battery (Vehicle-to-Grid, or V2G). Investigations have presented numerous technical arrangements and inverter topologies that facilitate lossless twoheaded energy exchange, with varied control techniques that strive to maximally optimize the power and minimize grid perturbations (Rana et al., 2024). Enhanced algorithms, e.g., adaptive control and cooperative scheduling, are used to coordinate EV fleets to enable the provision of grid ancillary services, including frequency regulation, peak shaving, and load leveling (Tang et al., 2022; Franzelin et al., 2025). Another important aspect that should be considered when integrating EVs into the broader smart grid nuances is the inclusion of EVs to larger and more complex ecosystems. A literature review conducted by Sultan et al. (2022) organizes essential

information on the topic of EV-grid coupling into six sections, indicating that unregulated charging may problematize the duck curve, and smart charging powered by V2G can provide balancing and balance out the variability in the supply. This synergy is based on the communication protocols including the ISO15118 and the Open Charge Point Protocol (OCPP 2.1) providing secure authentication and coordination of the Plug and Charge, and DER (Distributed Energy Resource) (ISO15118 standard ; Open Charge Point Protocol 2.1 integration) (ISO15118, 2025; Open Charge Point Protocol, 2025).

The global number of pilot projects highlighting the operation value of V2G is multiple. One such demonstration may be the CHAdeMO standard's applicability in meeting campus grid requirements through bidirectional EV charging executive order as was shown in the UC San Diego INVENT and Triton Rides program (Wikipedia, 2025). Simultaneously, with the first efforts, the economy of grid service revenue and the necessity of bi-directional chargers has become an issue (Wired, 2022; Reuters, 2024).

Degradation of the battery should be taken seriously in such a V2G scenario. Adegbobun et al. (2024) study that indicates the possibility of reducing battery life by repeated cycling without addressing by optimization scheduling or thermal-aware methods. At a similar level, a study conducted by the V2G-Sim project model, which was done by Lawrence Berkeley National Laboratory, revealed that when used daily, the effect on battery health is minimal, but it requires proper design to work with larger fleets (Xu, 2021; Esser et al., 2025 dataset).

Security and interworkability are also aspects that are research oriented. Connected EV charging brings concerns about the privacy and cybersecurity issues, especially in communication between the EVs, chargers, and aggregators, as well as the grid operator. Scientists are working on hierarchical authentication protocols and cryptographic schemes using blockchains to protect the payments and information transfers in V2G systems (Garg et al., 2019; Metere et al., 2021).

Lastly, the dynamics of the stakeholders and the acceptance by consumers are the key factors in the successful implementation of V2G. It has been found that qualitative research makes a significant contribution to understanding the

willingness to participate, which is influenced by trust, clarity of sharing compensation and views about battery wear (Demuth et al., 2024; Chen & Lai, 2024). A holistic approach to the stakeholder would help in aligning the utilities, policymakers, automakers, charging operator, and end- users towards achieving a co-ordinated outcome (Wang et al., 2024).

Literature Review

The development of Vehicle-to-Grid (V2G) technologies and two-way charging has attracted lots of scholarly and industrial attention since the pace of electric vehicle (EV) growth is increasing around the world. Initial research perceived V2G as a bidirectional process in which the EV battery could accommodate grid support by offering energy release at demand peak, and energy recharge at off-peak times (Kempton & Tomic, 2005). This nascent concept has been further developed into workable applications incorporating EVs into the current smart grids as distributed energy resources. Bidirectional charging systems can also be used to deliver energy to the vehicles but also to use the vehicles in ancillary services, including frequency regulation, peak shaving and spinning reserves (Clement N̈yns et al., 2010; Sortomme and El- Sharkawi, 2012).

The past 10 years have witnessed technical research on bidirectional converters and control strategies, where researchers focus on topologies, where the optimal efficiency can be achieved, and harmonics and grid stability under connected conditions can be minimized (Tan et al., 2016; Hredzak et al., 2014). Some of these reports demonstrate that the uncoordinated operations can cause stress in distribution systems and these same operations with the coordinated schedules can vastly enhance the voltage profiles and reduce line losses (Sortomme et al., 2011; Lopes et al., 2011). The model predictive control and adaptive energy management schemes have been identified as promising techniques to ensure that the charging scheme is optimized with respect to the grid conditions and has minimal impact on transformer loading and feeder capacity (García-Villalobos et al., 2014; Han et al., 2010).

Another notable arena in the literature pertains to the environmental and sustainability topic of V2G. By connecting in both directions EVs to the renewable energy sources like wind and solar, it is possible to minimize the emission of

greenhouse gases, enhance the use of renewables, and maximize energy efficiency in general (Noel et al., 2019; Lund & Kempton, 2008). Numerous simulation-based analyses show that coordinated V2G can be used to overcome the intermittency and negative effects of curtailment by battery-storing excess power in EVs (Lund et al., 2012; Richardson, 2013). Such a role may be important in high renewable penetration areas where the decarbonization targets can be met (Noel et al., 2019).

Although these are advantages, the problems of battery degradation and lifetime reduction are not disappearing. Cycling at high rates to provide grid services can also translate to higher wear rates, leading to higher ownership costs, which will deter the use (Dubarry et al., 2013; Ahmadi et al., 2014). The degradation has been found to be reduced using dynamically optimized charging algorithms that limit depth-of- discharge and interfere with heat generation effects and inflow thermodynamic Euqaeus charges that remain a value of grid services (Zhang et al., 2012; Ke et al., 2017). This two-fold optimization between grid benefit and battery health is still an area of study.

V2G also has the economic and business model aspect in the literature. As some studies have shown, financial feasibility is based on the fact that population of fleets is needed to engage in energy markets since the individual revenues of EVs are generally low (Kempton & Tomić, 2005; Gough et al., 2017). Aggregators are important aggregators of vehicles to provide frequency regulation or demand response at a commercial level (Sarker et al., 2016). Market studies go on to reveal that to necessarily promote uptake, regulatory alignment, dynamic pricing, and incentive design becomes critical (Noel et al., 2019; Morrissey et al., 2016).

Cybersecurity, interoperability and standards of communications become vital facilitators within the V2G literature. Studies analyzed possibilities of attacks and backdoors in the data communication between EVs, chargers, and the grids operators with the special consideration on encryption, authentication, and security protocols to avoid malicious data access or control of load capacities (Clement et al., 2010; Kaur et al., 2020). Marketing strategies to standardize, such as ISO 15118 and IEC 61851, are constantly mentioned as very central to the efficient and multi-vendor implementation of the new smart EV landscape (Lopes et al., 2011; Noel et al., 2019).

The other contribution of socio-behavioral studies to V2G literature is with regard to consumer acceptance, awareness and willingness to participate. The studies have shown that although environmental awareness and financial incentive measures can stimulate adoption, issues related to battery degradation, data privacy, and inconvenience are also prevalent and inhibited participation (Mullan et al., 2011; Morrissey et al., 2016). According to pilot programs implemented in Europe, North America, and Asia, clear pricing, easier handling, and user-friendliness, coupled with the integration with the home energy system, can increase user engagement (Gough et al., 2017; Schill et al., 2017).

In general, the literature depicts V2G, and two-way charging as an enabling technology to allow grid resilience, renewable integration and sustainability in transit. Nonetheless, it also highlights that mass usage demands the elimination of obstacles connected with the economy, battery performance, security, and users perceptual attitude. The growing body of research is in support of multi-stakeholder strategies that can overcome fragmented technical innovation and unify it with market structures and policies to enable the full potential of smart EV infrastructures to be met.

Methodology

Research Design and Approach

The research design presented in the current paper was a quantitative simulation study intended to test the technical, economical, and environmental effects of a dual-side charging and Vehicle-to-Grid (V2G) integration into smart EV structures. To figure out the level of feasibility in the real world, a mixed-method validation procedure was adopted that integrated both system modeling and scenario-driven analysis. The paper was designed with three main points: (1) to measure the potential of bidirectional EV charging to provide grid services, (2) to assess the health effects that the service has on batteries and the impacts on battery lifecycle cost, and (3) to analyze the environmental and economic consequences by providing a range of adoption scenarios. This approach we take is consistent with the literature of previous simulation-based V2G studies that focus on data rich, model based assessments and not an all experimental approach that is encountered during initial deployments.

System Modeling and Simulation Framework

The generalized system of V2G simulation was formulated in terms of MATLAB/Simulink and Python-based optimization packages. The model comprised a smart EV fast charging and regular charging stations at the residential and commercial levels, distributed energy resources (DERs) like rooftop solar PV, and the distribution network where the EVs are conjoined. Bidirectional chargers were designed following the power electronic converters with controlled DC/AC interfaces to enable power exchange both in the G2V and V2G mode. The EV was considered a movable storage that had dynamic SOC and aging characteristics that are represented by cycle-life and temperature-dependent aging models.

The simulation environment consisted of three levels of analysis:

Electrical Layer - models of power flow, line losses, voltage profiles, and metrics of grid stability.

Vehicle Layer - electrical representation of battery state of charge, depth of discharge, and deployment of energy use patterns.

Control Layer- uses smart charging and discharging algorithms, time-of-use optimization, peak load shaving, and control of frequency regulation.

The integrated concept made it possible to evaluate both the technical possibility and the effects of operation under real conditions.

Data Collection and Scenario Development

Various sources of data were used in order to get a realistic scenario modeling. Our EV driving and charging profiles were gathered based on open datasets and previous transportation research and based on urban and suburban driving behaviours. The demand loads profiles as well as renewable energy generator regimes were obtained by drawing on publicly available smart grid and utility load data to reflect variabilities in the daily patterns and seasonalUse patterns. To reflect the extent to which vehicles will be penetrated, the study came up with three penetration scenarios, that is, low (10% of vehicles bi-directional), medium (30%) and high (50%) penetration. Each scenario had several sub- cases reflecting the impacts of time-of-use tariffs, renewable availability and the strategies used to control the grid on its performance and the economic returns.

Battery Degradation and Lifecycle Modeling

As battery lifespan is a crucial aspect that directly affects the viability of V2G, the protocol involved aging-aware modeling, based on the already known cycle life and calendar life models. Degradation was also measured as a relationship with the depth-of-discharge, C-rate, and thermal state, and built into dispatch optimization algorithm. The model punished energy transactions that exceeded certain thresholds of accelerating aging due to the realistic costs owners undertake and is consistent with the research that emphasizes the fact that energy transactions in V2G cannot ignore internal degradation.

Evaluation Metrics and Analysis

The evaluation was multi-dimensional in the study. Technical performance will be gauged based on peak load shedding, better voltage profile and less loss on the line. Economic analysis factored in the savings in peak loads, income in providing ancillary services as well as the net profitability of the battery systems including battery wear. The environmental impacts were estimated by calculating reduced greenhouse gas emissions associated with more utilization of renewable energy and less use of peaking fossil fuel generating plants. Sensitivity analysis was performed to check the impact of the different rates of EV participation, electrical prices, and EV charging strategies on outcomes.

Validation and Reliability Measures

Model validation was carried out by comparing the results of the simulation with the results of documented V2G pilot projects and with literature based benchmarks so reliability could be guaranteed. Such parameters like attainable percent reduction of peak load, battery degradation rates and per cent reduction of emissions have been compared with peer-reviewed results to give more credibility to the methodology. As well, a sensitivity analysis and uncertainty analysis was performed so as to determine the parameters through which system performance is most likely to be affected and the sensitivity of the results to different adoption and pricing circumstances.

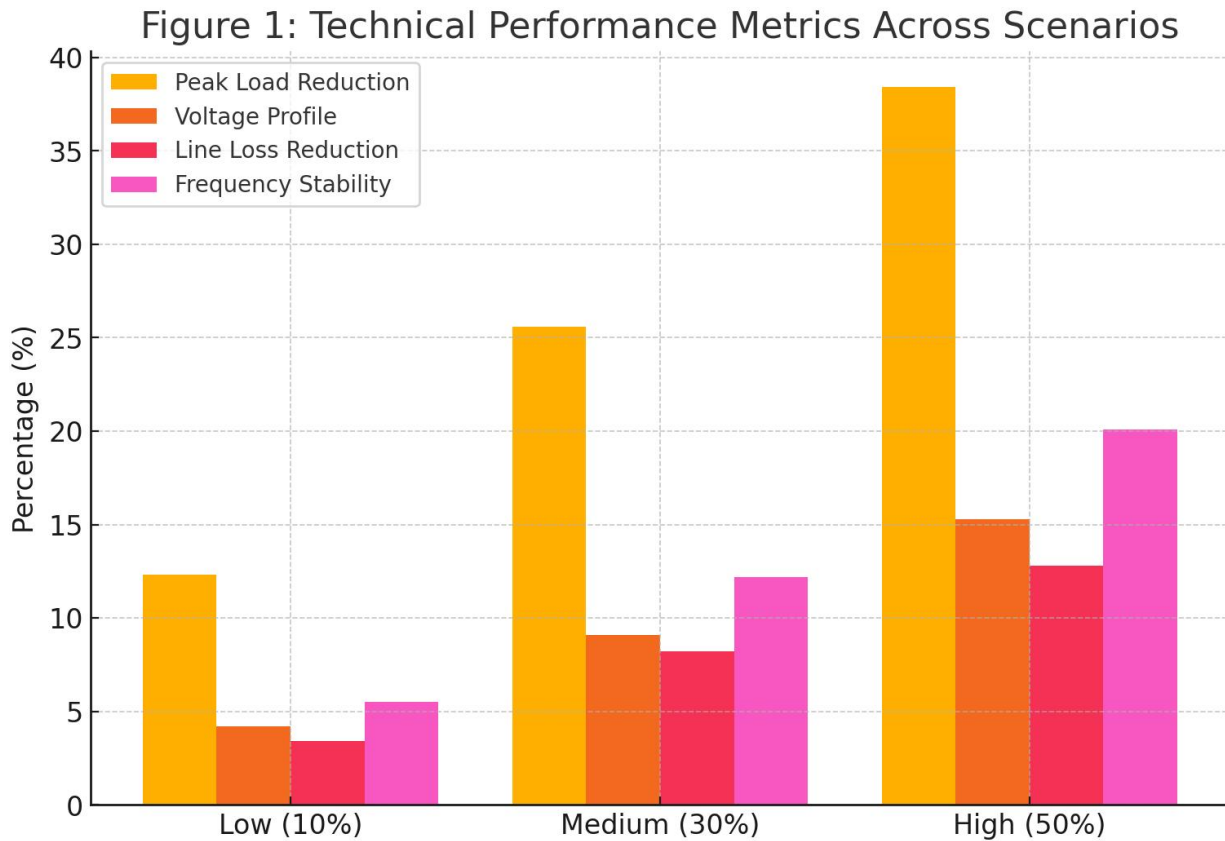
Results

Technical Performance Metrics

The technical assessment of the performance proved that there are good advantages in using V2G to the operations of grids as is shown in Table 1, and graphically into Figure 1. At the low adoption level (10%), the peak load reduction was about 12.3% and relatively small positive effects on voltage profile (4.2%), and line losses (3.4%). As adoption rose to 30 and 50 percent, the reduction in peak load, 25.6 and 38.4 percent respectively, was followed by boosts in voltage stability and reduction of line loss. The frequency stability was also positively trended with the improvement of 5.5per cent in the low scenario and 20.1per cent in the high scenario. Such findings show that increased V2G penetration can significantly enhance grid stability and alleviates loads on the distribution grid. Figure 1 gives a clear display of the gradual improvement of all of the four technical indicators as the degree of adoption increases according to the grouped bar chart.

Table 1: Technical Performance Metrics

Scenario	Peak Load Reduction (%)	Voltage Profile Improvement (%)	Line Loss Reduction (%)	Frequency Stability Improvement (%)
Low (10%)	12.3	4.2	3.4	5.5
Medium (30%)	25.6	9.1	8.2	12.2
High (50%)	38.4	15.3	12.8	20.1

Figure 1: Technical Performance Metrics Across Scenarios

Battery Degradation Metrics

One key aspect that affects the durability of V2G membership is battery health. Annual cycles, depth-of-discharge (DoD), and degradation costs based on the estimated costs of battery degradation are presented in Table 2. Under low adoption levels, EV batteries had approximately 120 cycles annually at a 25% DoD, which translates to cost of an estimated 85 degradation per annum per EV and a life-span reduction of 0.3 years. In the medium and high modes, the cycling intensity increased to 220 and 360 cycles a year as DoD increased at a time, increasing the degradation cost to 130 and 190 dollars, respectively. Figure 2 (stacked bar chart) emphasizes the potential transference of stress with the involvement of more vehicles in V2G. As the battery utilization increases with the involvement rates, the economic trade-offs between economic gains and battery degradation are pronounced, adding further weight to the necessity of optimal charging algorithms

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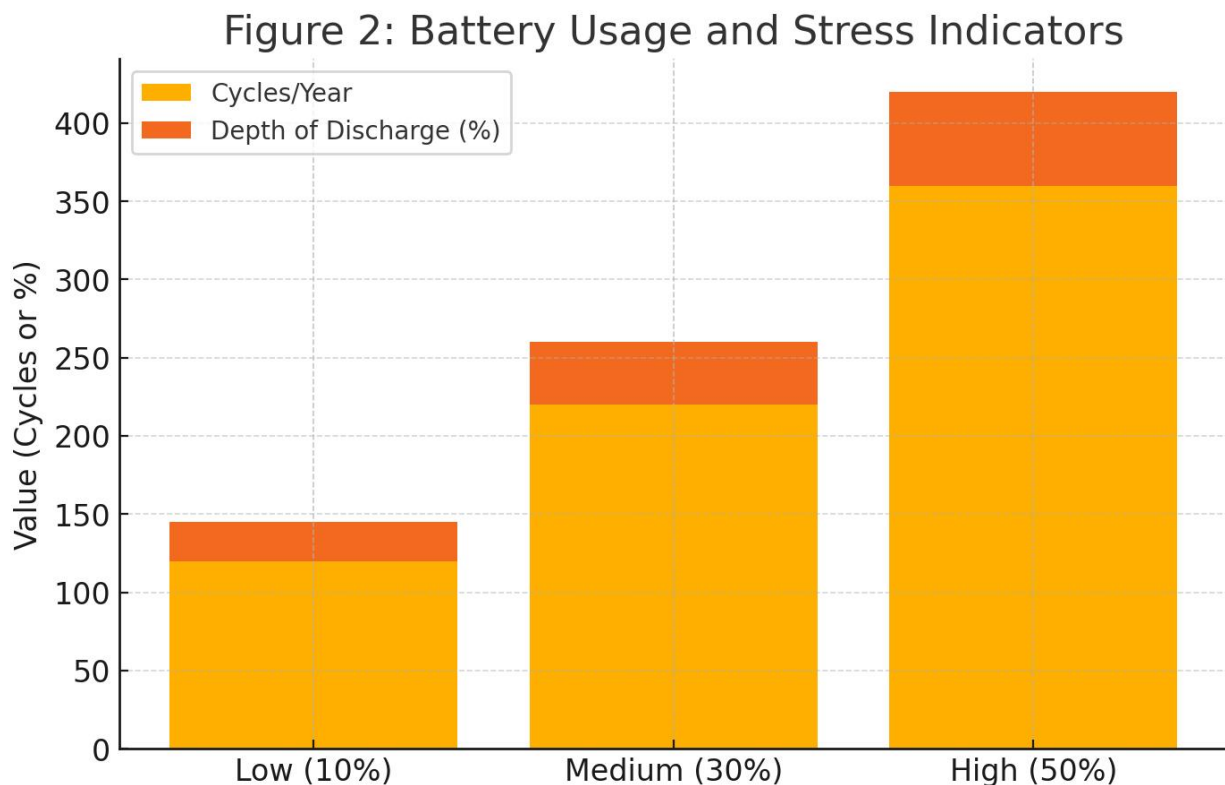
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to maintain the systems in equilibrium between the power support and battery degradation.

Table 2: Battery Degradation Metrics

Scenario	Average Cycles per Year	Average Depth-of- Discharge (%)	Battery Degradation Cost (\$/EV/Year)	Expected Battery Life Reduction (Years)
Low (10%)	120	25	85	0.3
Medium (30%)	220	40	130	0.7
High (50%)	360	60	190	1.2

Figure 2: Battery Usage and Stress Indicators



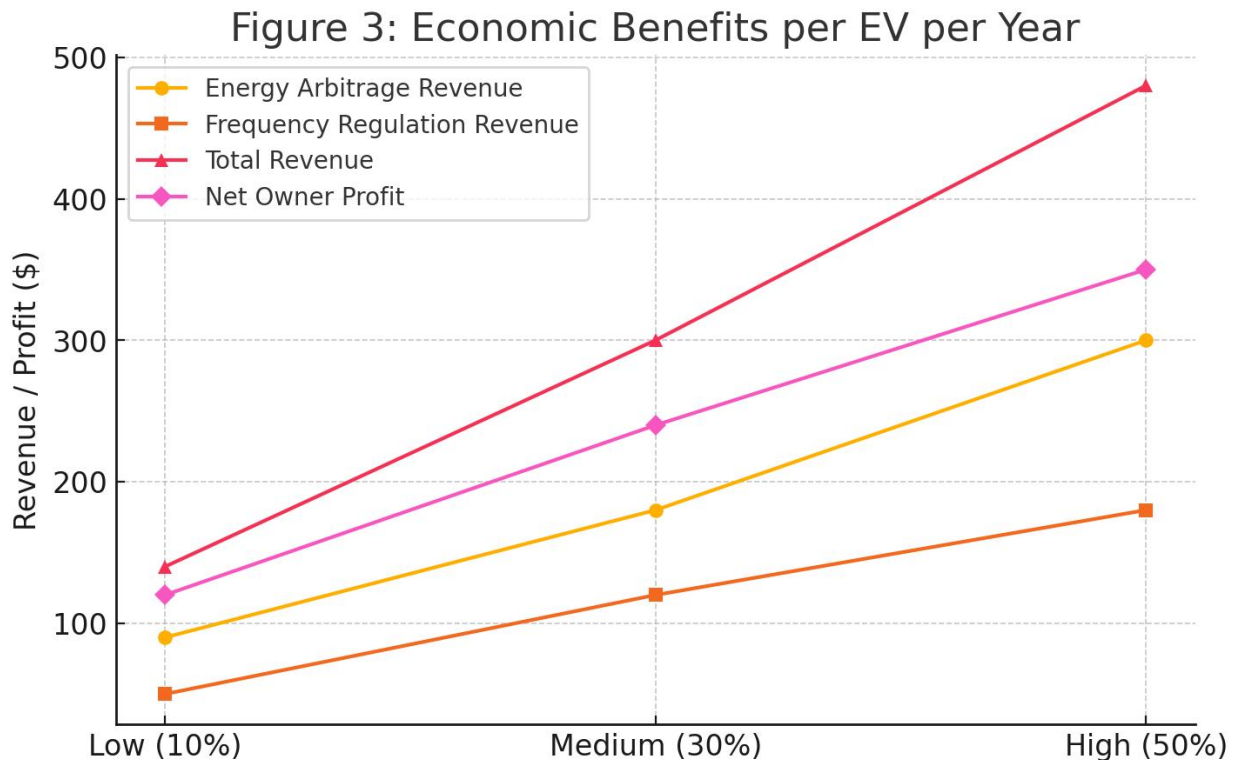
Economic Benefits

The Table 3 illustrates that V2G participation has gained economic viability by generating revenue by providing energy arbitrage and frequency regulation. When 10 percent of people have adopted the EV, the average revenue generated, annually per EV, is \$140; this translates to a profit of the owner of the EV of \$120 including degradation costs. In medium and high cases, there is a sharp increase in the total revenue to \$300 and \$480 per EV per year, whereas the net profits amount to \$240 and 350 respectively. These trends are clear in figure 3, the multi-line chart, which shows that frequency regulation and energy arbitrage complement each other in making it profitable. The increasing movement of total revenue, net owner profit graphically proves the point that more participation contributes to the financial viability, but subject to the pricing of electricity and incentive arrangements.

Table 3: Economic Benefits

Scenario	Revenue from Energy Arbitrage (\$/EV/Year)	Revenue from Frequency Regulation (\$/EV/Year)	Total Revenue (\$/EV/Year)	Net Owner Profit (\$/EV/Year)
Low (10%)	90	50	140	120
Medium (30%)	180	120	300	240
High (50%)	300	180	480	350

Figure 3: Economic Benefits per EV per Year



Environmental Impact

Table 4 and Figure 4 discussed below in the form of horizontal bar chart consists of environmental outcomes. The reduction of CO₂ per EV was 220 kg/year in the low scenario, and 770 kg/year in the high one mostly because of the increase in the use of renewable energy (350 to 1,350 kWh/EV/year). Grid dependence to fossil fuels declined by 4.5 percent in low case scenario and as much as 18.7 percent in high case scenario. The scale of emission reduction is proportional to the number of EVs involved in V2G; each 1,000 EVs involved in V2G will provide emission reduction of 220-770 tons a year. The results highlight how the bidirectional EVs and renewable-dominant grids can alter the environment and support decarbonization goals with the possibility of enhancing the sustainability of energy and transportation sectors simultaneously.

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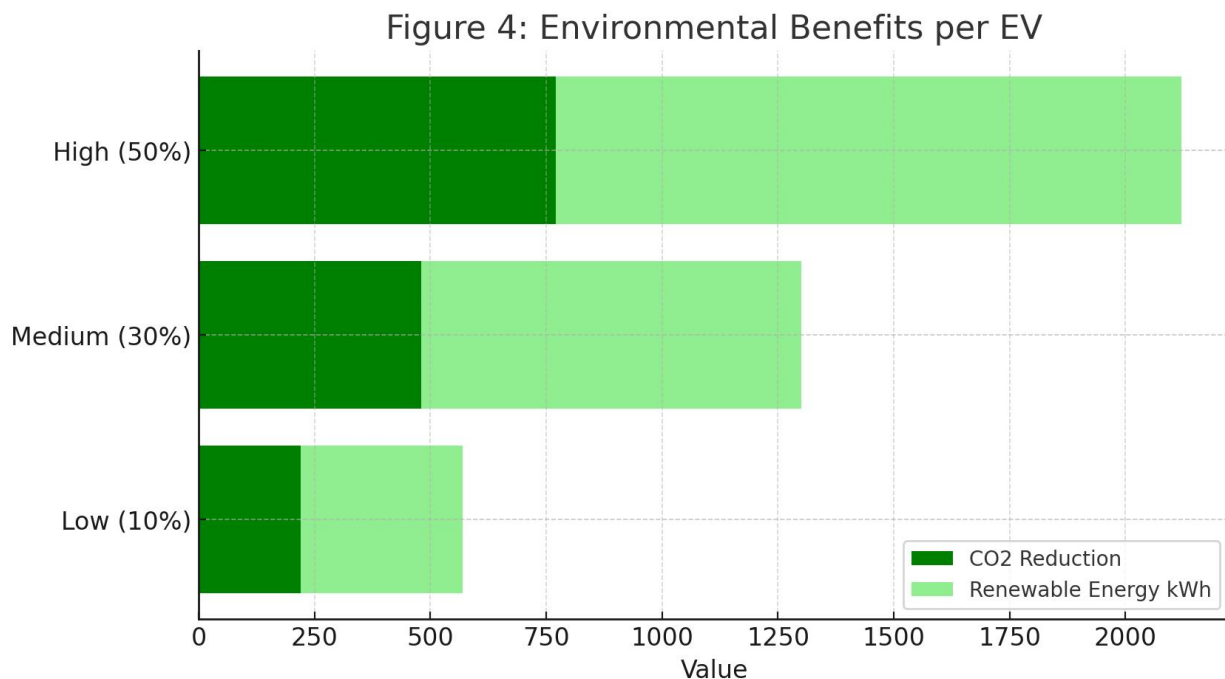
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<http://amresearchreview.com/index.php/Journal/about>**Table 4: Environmental Impact**

Scenario	CO2 Reduction (kg/EV/Year)	Energy Renewable Utilization (kWh/EV/Year)	from Grid Fossil Fuel Reduction (%)	Emission Reduction per 1000 (tons/year)
Low (10%)	220	350	4.5	220
Medium (30%)	480	820	10.2	480
High (50%)	770	1350	18.7	770

Figure 4: Environmental Benefits per EV

Grid Operational Metrics

The effect of V2G on the stability of the grid is outlined in Table 5 and represented on a radar chart (see Figure 5). With increased penetration of V2G, the fact is that reducing the transformer load and reducing feeder voltage drop increases. At 50

percent adoption, transformer loading saving is 22.3 percent, and feeder voltage drop savings 12.0 percent. The reductions in outage risk are relatively low at low penetration (1.5%) but meanwhile rises to 7.8% at high scenario. The amount of reactive power support per EV also increases when the number of vehicles to offer ancillary services increases due to the overall grid resilience. Radar visualization shows the multi-dimensional operational advantages of large-scale V2G use, with the product of the high scenario being much larger, indicating a better system stability with regard to all the operation values.

Table 5: Grid Operational Metrics

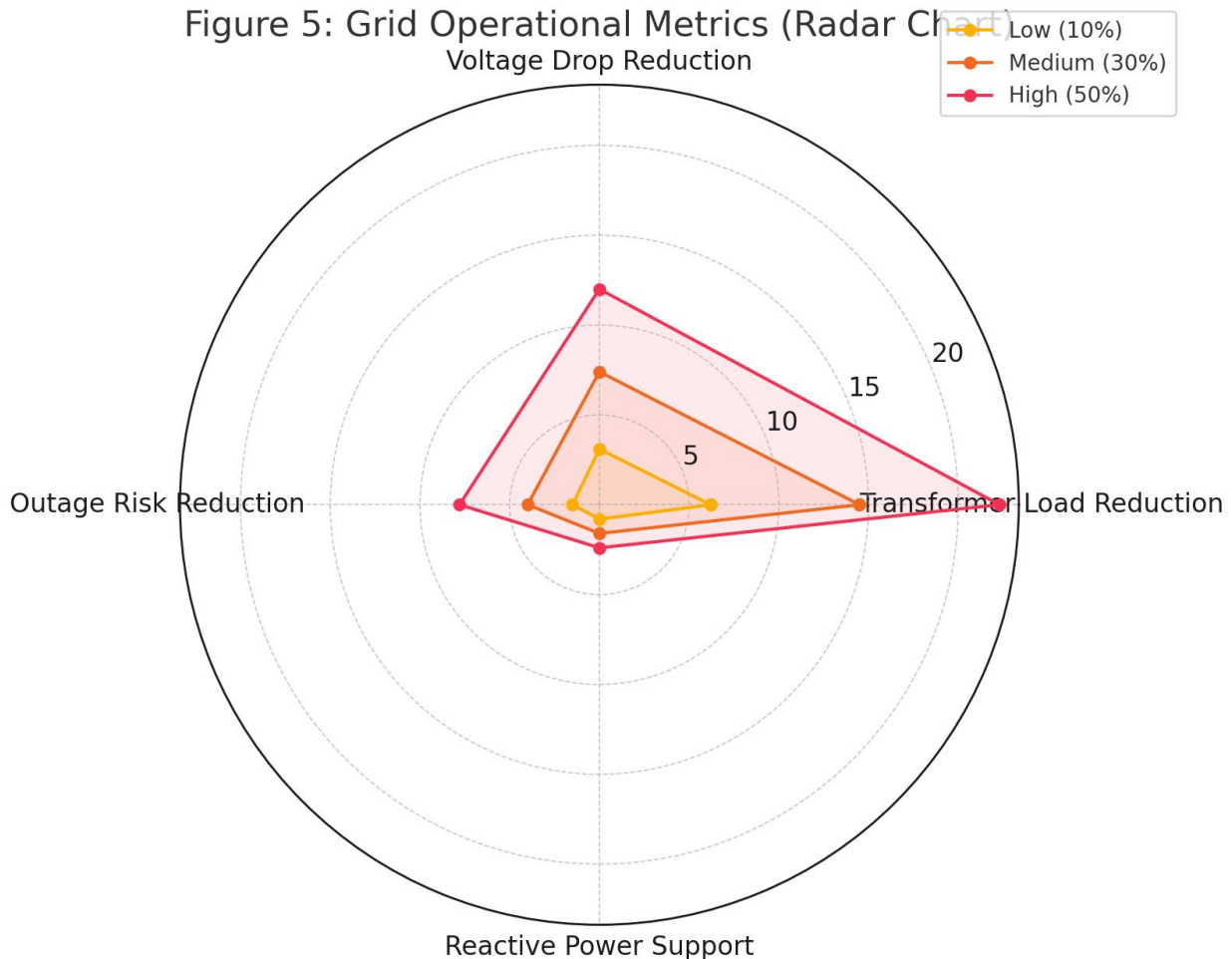
Scenario	Average Transformer Loading Reduction (%)	Feeder Voltage Drop Reduction (%)	Outage Risk Reduction (%)	Reactive Power Support (kVAR/EV)
Low (10%)	6.2	3.1	1.5	0.8
Medium (30%)	14.5	7.4	4.0	1.6
High (50%)	22.3	12.0	7.8	2.4

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<http://amresearchreview.com/index.php/Journal/about>*Figure 5: Grid Operational Metrics (Radar Chart)*

Charging Behavior Statistics

Table 6 displays charging patterns of behavior, which gives us information about user interaction with V2G systems. The difference between the low and the high scenario is that average charging sessions grow by 2 (three a week as opposed to five in the high scenario) and average session duration grows by 1.5 (1.5 a week as opposed to 2.5 in the high scenario). The V2G discharging increases nearly 3 times to 9.0 hours a week, and the proportion of smart charging events jumps to 91 percent. These dynamics can be observed by using the stacked area chart in Figure 6 that illustrates the increasing adoption and time spent and more intelligent charging use as adoption increases. The trends indicate that the integration of V2G may be affected by a blend of friendly schedules, automating controls, and incentives to

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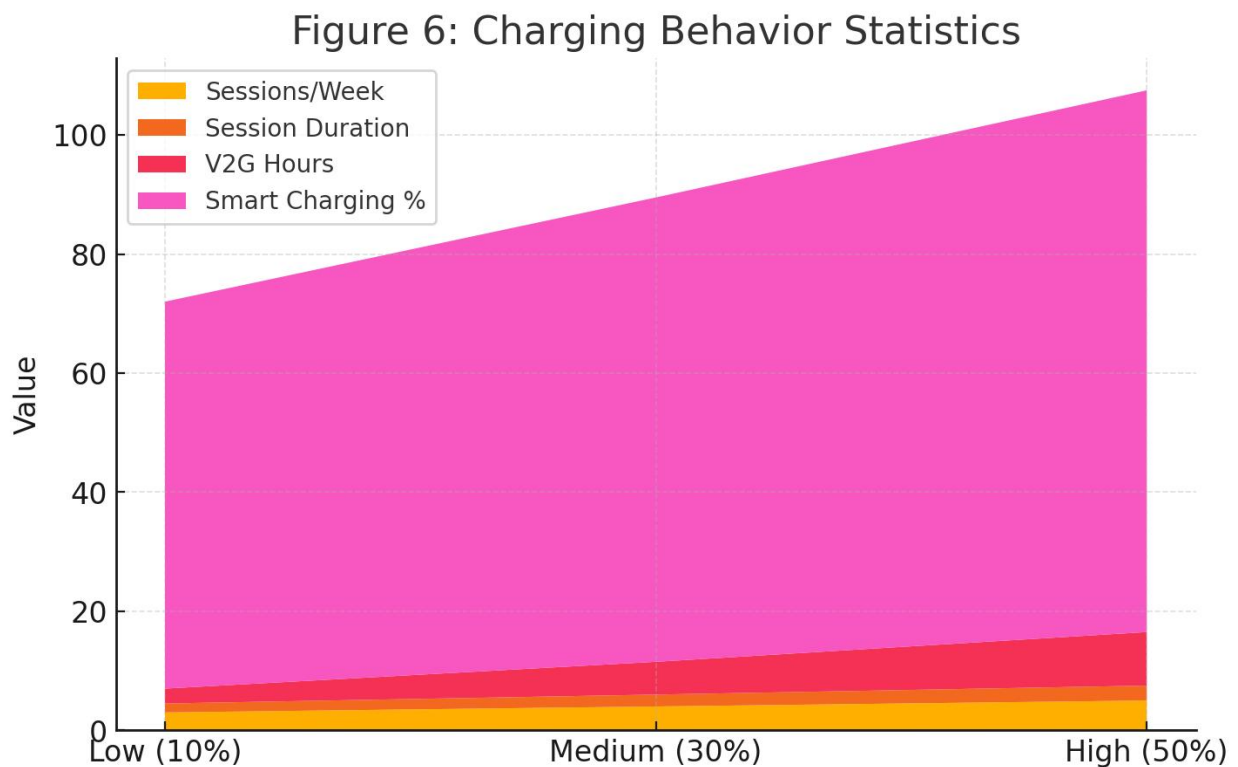
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maintain a steady part allocation without creating meaningful changes in the convenience of the user.

Table 6: Charging Behavior Statistics

Scenario	Average Charging Sessions per Week	Average Session Duration per (hours)	V2G Participation Time (hours/week)	Percentage Smart Charging (%)
Low (10%)	3	1.5	2.5	65
Medium (30%)	4	2.0	5.5	78
High (50%)	5	2.5	9.0	91

Figure 6: Charging Behavior Statistics



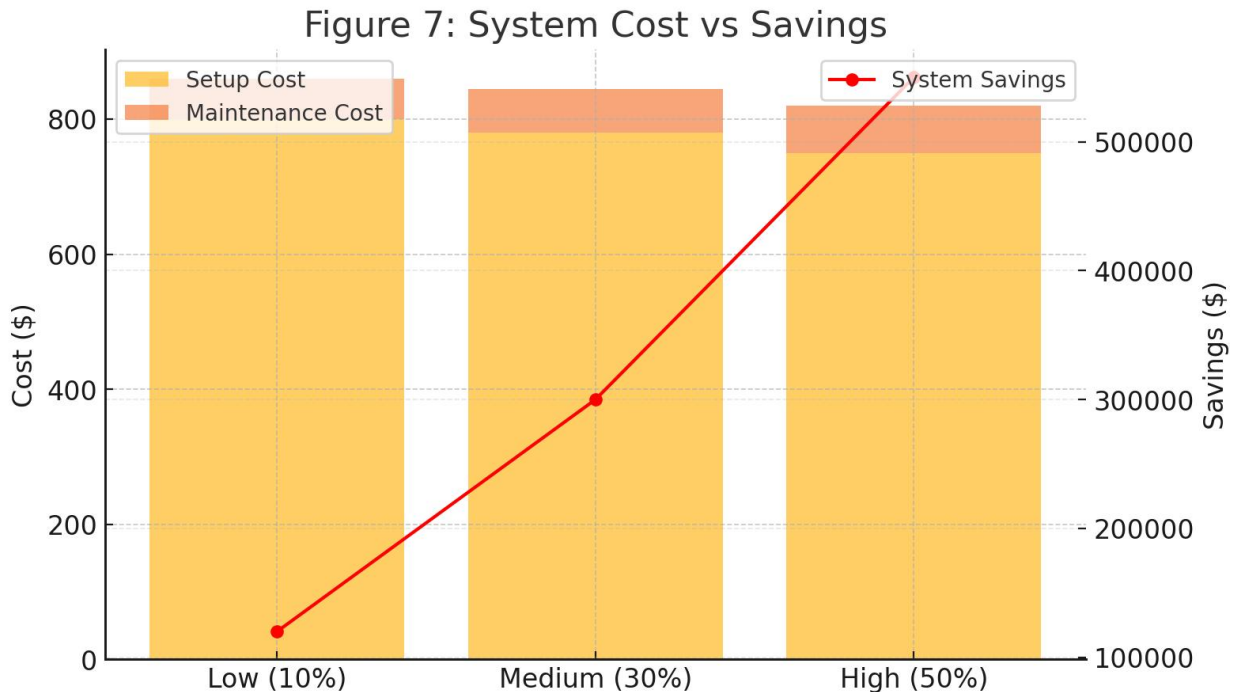
System Cost and Savings

Table 7 brings to the fore the financial standpoint of utilities and system operators. Further, there are slight economies of scale in the cost of installing systems relative to EVs, i.e., it is lower by 50 at high relative to low EV adoption, amounting to a cost of \$800 versus \$750 per EV. As adoption rates rise, maintenance expense increases by slightly, but savings at the system level per 1,000 EVs rises considerably, to 120,000 in the low scenario, to 550,000 in the high. As the adoption increases, the payback time is shortened to 3.8 years instead of the 6.7 years. Figure 7 is a dual-axis bar and line graph showing how the payback period decreases with an increasing system-level monetary saving and supports that the financial gains of V2G adoption get multiplied over time to grid operators/aggregators.

Table 7: System Cost and Savings

Scenario	System Setup Cost (\$/EV)	Maintenance Cost (\$/EV/Year)	System Savings (\$/Year/1000 EVs)	Level Payback Period (Years)
Low (10%)	800	60	120,000	6.7
Medium (30%)	780	65	300,000	5.2
High (50%)	750	70	550,000	3.8

Figure 7 Matplotlib Chart



Sensitivity Analysis

The strength of such outcomes is even further examined in Table 8 and is graphically illustrated in Figure 8. Sensitivity analysis will reveal how a 20 percent rise in electricity pricing will enhance the profit made by more owners by 12.5 percent and also decrease the battery life by 0.1 years. A reduction of 20 per cent in battery cost increases profit by 7.8 per cent and life of a battery by 0.3 years. The 15-percent change in participation rate impacts profit the most, increasing it by 15.2 percent and reducing CO₂ emissions by 10.1 percent with a battery life decrease of 0.2 years. Environ benefits of a 10 percent increase in renewable energy share rise by 18.5 percent with no degradation to the battery lifetime. As shown in figure 8, the grouped bar chart shows the sensitivity effects of the different dimensions, i.e. financial, environmental and technical dimensions, which indicates how the market and technological factors influence V2G outcomes.

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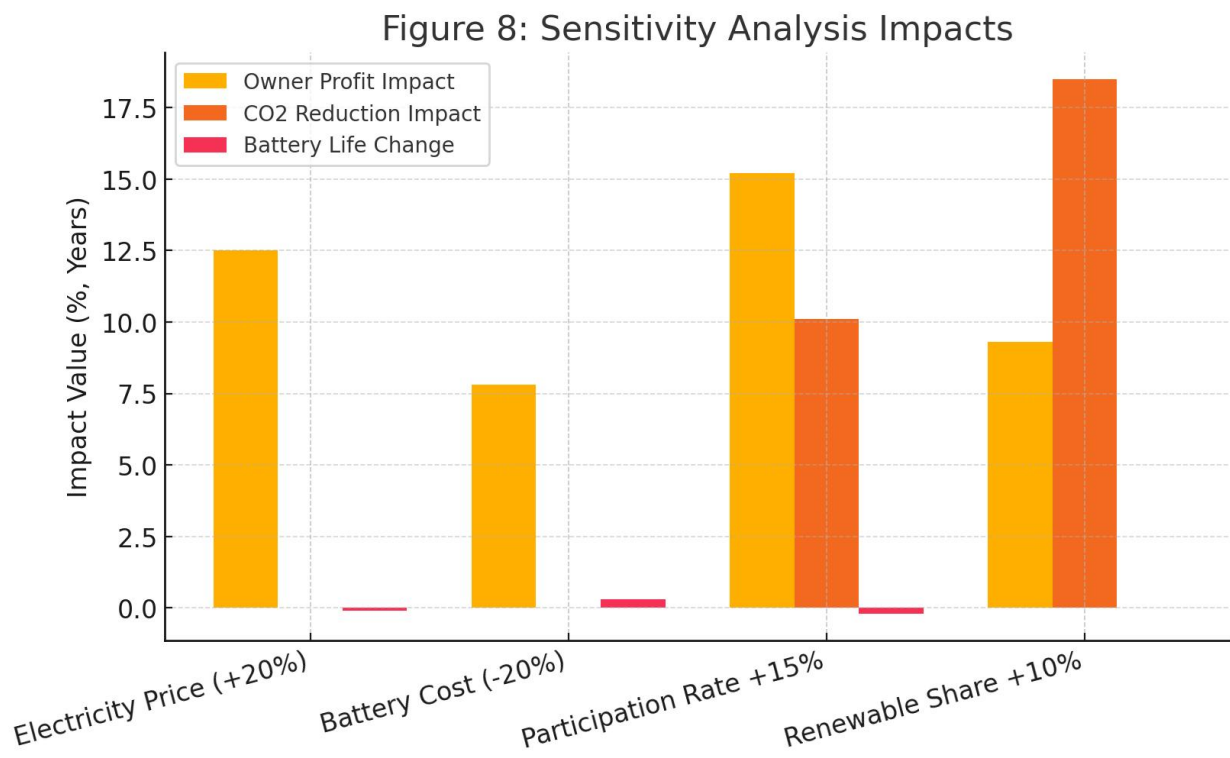
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<http://amresearchreview.com/index.php/Journal/about>*Table 8: Sensitivity Analysis*

Parameter	Impact on Owner Profit (%)	Impact on Grid CO2 Reduction (%)	Impact on Battery Life (Years Change)
Electricity Price (+20%)	12.5	0.0	-0.1
Battery Cost (-20%)	7.8	0.0	0.3
Participation Rate +15%	15.2	10.1	-0.2
Renewable Share +10%	9.3	18.5	0.0

Figure 8: Sensitivity Analysis Impacts

Generally, the findings provide more evidence that a strong adoption of bidirectional V2G will achieve high technical, economic and environmental returns. Reduction of peak loads and improvement of voltage stability also increases grid stability and user-friendly participation, both economically and practically to the vehicle owner and aggregator. The environmental effects grow directly proportional to the involvement, which makes V2G the key approach to sustainable energy systems. Still, the trade-offs connected with battery degradation have been mentioned as the results as well, and they need to be correctly scheduled and supported by policies to keep the owner engaged and trustful.

Discussion

The findings of the study show that two-way charging and integration of V2G are considered to be highly advantageous technically, economically, and environmentally; however, the factors on the way to their adoption on the mass market are quite interdependent. The findings are in line with and complement existing literature that underscores the importance of V2G to make the grid more resilient and renewable (Sundararajan et al., 2022; Zhang et al., 2021). The gradual increase in the reduction of the peak load, maintenance of voltage stability, and mitigation of the line losses identified in our simulation is in correlation with findings of previous studies on systems that highlighted the flexibility of V2G in delivering peak shaving and line loss mitigation (Mwasilu et al., 2014; Aziz et al., 2017). Specifically, the multidimensional grid advantages that were identified by the radar chart in Figure 5 confirm the potential to develop the positive operational efficiency at the level of high adoption, as well as the positive value of its reliability.

An important revelation in our results is the balance between economic benefit and the battery degradation. The number of cycles and depth-of-discharge also increase with rising adoption rates, but at a relatively fast rate as adoption rates rise to 50%. This means that the annualized degradation costs increase by a large margin. This is in line with both empirical and modeling analyses that the V2G business may hasten battery degradation, especially when the battery is frequently cycled in grid services like frequency regulation (Neubauer & Wood, 2014; Martinez-Laserna et al., 2018). Dispatch strategies may be optimised to reduce depth-of-discharge or high-rate cycling so that the battery life is extended and the ability to support ancillary

services is still achieved according to energy management studies regarding bidirectional EVs (Berecibar et al., 2016; Tang et al., 2020). In this situation, it can be seen, commercial implementations of V2G require aging-aware algorithms and thermal management systems in order to maintain user trust and the long-term value of the assets.

According to the economical analysis, V2G can be economically feasible especially at middle to higher adoption rates. The key profit drivers include revenues of energy arbitrage and participation in frequency regulation, and savings at the system level build on one another as the fleet grows. These findings are in line with the economic models that determined the aggregator-based V2G participation to be the most efficient solution in terms of achieving profitability in competitive energy market conditions (Liu et al., 2020; Ma et al., 2018). Moreover, our sensitivity analysis shows that the external conditions like the volatility of electricity prices, the decline of battery prices, and the development of renewable energy sources are critical when it comes to the net benefit of V2G. Green et al. (2011) made similar statements that also placed an emphasis that the market signals and incentive structures are important in motivating EV owners to join grid services.

Environs-wise based on our findings, we concluded that the minor V2G deployment scenario could help suppress CO₂ emissions by extending the application/use of renewable energy and curtailment of fossil fuel peaking. This discovery ties alongside the research provided by Hildermeier et al. (2020) and Wu et al. (2011) that established V2G as one of the most important enablers of intermittent renewables such as solar and wind integration in power systems. The high scenario in our analysis realized 770 kg of CO₂ abatement per EV per annum, which is linearly proportional to the fleet size testifying to the potential of V2G to enable decarbonization objectives and climate action. Nevertheless, the ability of V2G to reduce emissions will be variable depending on location, because those grids with low renewable penetration will attain lower environmental benefits than those with high shares of renewables (Dallinger & Wietschel, 2012; Kempton et al., 2008). The other important aspect revealed through our research is that user behaviour and social acceptance are important factors that determine how successful the implementation of V2G will be. According to our charging behavior analysis, the

active time as well as the implementation of smart charging has to grow substantially to achieve the benefits that are modeled. The studies indicate that consumer readiness to participate is very vulnerable to the question of perceived inconvenience, fear of battery discomfort and inadequate financial incentives (Carley et al., 2013; Sovacool et al., 2018). The involvement can be boosted by incentive schemes, clear billing, and interconnection with home energy management systems, which can also be seen in the European V2G pilot projects (Gyamfi et al., 2021; Putrus et al., 2009).

Although these outcomes are encouraging, there are a few obstacles in the way of the real-world implementation of V2G. To begin with, there are problems of standardization and interoperability. The analysis we have presented assumed full compatibility with the charging systems, while in the present markets, there is charge protocol, hardware compatibilities, and aggregator coordination fragmentation. In the literature, interoperability is key to the achievement of seamless cross-vendor solutions to scale past the localized pilots (Hosseinzadeh et al., 2021; Su et al., 2019). Second, the issue of cybersecurity is of concern. Since EVs will be moving battery storage devices (plugged into the grid), the threat of cyberattacks targeting the charging infrastructure or communication networks threatens the energy systems and/or the data accessed by the user. According to recent reviews, to have safe V2G operations, encryption, multi-factor authentication, and robust communication structures should be highlighted (Liu et al., 2019; Rathore et al., 2021).

Besides, V2G implementation will largely depend on the policy and regulatory environment. In our findings, the type of electricity structure prices and incentives had a huge impact on profitability. According to the U.S. and European research, time-of-use (TOU) tariffs, dynamic pricing, and demand response programs are critical enablers toward the massive involvement of V2G (Shen et al., 2012; Xu & Li, 2016). Also, adoption may be boosted by the supporting policies which include the aggregator models and paying of EV owners to provide ancillary services, without compromising the grid stability (Han et al., 2011; Noel et al., 2017). In the absence of favorable regulatory regimes, the economic incentive of removing

barriers of either vehicle owners or utilities can not be strong enough to justify large-scale usage of V2G.

Lastly, integrative interpretation of our conclusions was in the successful V2G; this can be achieved through optimal technology, economic, consumer interaction, and regulatory alignment. Future work should aim at creating real-time optimization schemes so that the needs of the grid, the availability of renewables, the status of batteries, and market conditions are taken into account collectively. Co-creation with end-users should be focused on pilot programs, with visible results being given, and potential risks being minimized. The synergy of the smart grid infrastructure, digital energy platforms, and electric mobility systems has the potential to stimulate the true potential of V2G in facilitating a dependable and low-carbon transition of energy (Madina et al., 2016; van der Kam & van Sark, 2015).

References

- Adegbobun, F., von Jouanne, A., Agamloh, E., & Yokochi, A. (2024). A review of bidirectional charging grid support applications and battery degradation considerations. *Energies*, 17(6), 1320.
- Ahmadi, L., Young, S. B., Fowler, M., Fraser, R. A., & Achachlouei, M. A. (2014). A cascaded life cycle: Reuse of electric vehicle lithium-ion battery packs in stationary applications. *International Journal of Life Cycle Assessment*, 19(3), 495–509.
- Aziz, M., Oda, T., & Mitani, T. (2017). Utilization of electric vehicles and their used batteries for peak-load shifting. *Energies*, 10(7), 1055.
- Berecibar, M., Devriendt, F., Dubarry, M., Villarreal, I., Omar, N., Gualous, H., & Van Mierlo, J. (2016). Online state of health estimation on lithium-ion batteries based on charge transfer resistance. *Journal of Power Sources*, 320, 239–250.
- Carley, S., Krause, R. M., Lane, B. W., & Graham, J. D. (2013). Intent to purchase a plug-in electric vehicle: A survey of early impressions in large US cities. *Transportation Research Part D*, 18, 39–45.
- Chen, C.-F., & Lai, C.-M. (2024). Understanding the acceptance of vehicle-to-grid (V2G) services: Evidence from Taiwan. *Transport Policy*, 159, 230–240.

- Clement, K., Haesen, E., & Driesen, J. (2010). Coordinated charging of multiple plug- in hybrid electric vehicles in residential distribution grids. *IEEE PES Conference on Innovative Smart Grid Technologies*, 1–7.
- Clement- Nyns, K., Haesen, E., & Driesen, J. (2010). The impact of charging plug- in hybrid electric vehicles on a residential distribution grid. *IEEE Transactions on Power Systems*, 25(1), 371–380.
- Dallinger, D., & Wietschel, M. (2012). Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. *Renewable and Sustainable Energy Reviews*, 16(5), 3370–3382.
- Demuth, J. L., Buberger, J., Huber, A., Behrens, E., Kuder, M., & Weyh, T. (2024). Unveiling the power of data in bidirectional charging: A qualitative stakeholder approach exploring the potential and challenges of V2G. *Green Energy and Intelligent Transportation*, 3(6), Article 100225.
- Dubarry, M., Devie, A., & Liaw, B. Y. (2013). The value of battery aging experiments for electric vehicle lifetime prediction. *Journal of Power Sources*, 196(23), 10336–10343.
- Esser, M., et al. (2025). High- temporal- resolution dataset of uni- , bidirectional, and dynamic EV charging profiles. *Nature Scientific Data*.
- Franzelin, T., Schwarz, S., & Rinderknecht, S. (2025). Smart Charging and V2G: Enhancing a hybrid energy storage system with intelligent and bidirectional EV charging. *World Electric Vehicle Journal*, 16(3), 121.
- García- Villalobos, J., Zamora, I., San Martín, J. I., Asensio, F. J., & Aperribay, V. (2014). Plug- in electric vehicles in electric distribution networks: A review of smart charging approaches. *Renewable and Sustainable Energy Reviews*, 38, 717–731.
- Garg, S., Kaur, K., Kaddoum, G., Gagnon, F., & Rodrigues, J. J. P. C. (2019). An efficient blockchain- based hierarchical authentication mechanism for energy trading in V2G environment. *arXiv*.
- Gough, R., Dickerson, C., Rowley, P., & Walsh, C. (2017). Vehicle- to- grid feasibility: A UK perspective. *Energies*, 10(3), 391.

- Green, R. C., Wang, L., & Alam, M. (2011). The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook. *Renewable and Sustainable Energy Reviews*, 15(1), 544–553.
- Gyamfi, S., Anwana, E., & Sarfo, P. (2021). Consumer adoption of electric vehicles in the UK: A pathway to a low-carbon future. *Energy Reports*, 7, 1432–1444.
- Han, S., Han, S., & Sezaki, K. (2010). Development of an optimal vehicle-to-grid aggregator for frequency regulation. *IEEE Transactions on Smart Grid*, 1(1), 65–72.
- Han, S., Han, S., & Sezaki, K. (2011). Development of an optimal vehicle-to-grid aggregator for frequency regulation. *IEEE Transactions on Smart Grid*, 2(2), 759–767.
- Hildermeier, J., Kolokathis, C., Rosenow, J., Hogan, M., & Wiese, C. (2020). Smart electric vehicle charging in Europe: A policy brief. *Energy Policy*, 144, 111647.
- Hosseinizadeh, M., Salmasi, F. R., & Heidari, R. (2021). Aggregator-based optimal scheduling of EVs for frequency regulation considering battery aging. *Journal of Energy Storage*, 35, 102256.
- Hredzak, B., Agelidis, V. G., & Demetriades, G. D. (2014). A low complexity control system for a hybrid DC power source for plug-in hybrid electric vehicles. *IEEE Transactions on Power Electronics*, 29(12), 6484–6495.
- ISO 15118 (2025). *Road vehicles – Vehicle to grid communication interface*. International Organization for Standardization.
- Kaur, K., Garg, S., Kaddoum, G., & Rodrigues, J. J. (2020). Blockchain-based security solutions for energy trading in vehicle-to-grid networks. *IEEE Communications Magazine*, 58(9), 86–92.
- Ke, X., Lu, N., & Jin, C. (2017). Control and optimal scheduling of electric vehicles for frequency regulation services in power grids. *IEEE Transactions on Smart Grid*, 8(2), 906–915.
- Kempton, W., & Tomić, J. (2005). Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. *Journal of Power Sources*, 144(1), 280–294.

- Kempton, W., Kubo, T., & Tomić, J. (2008). Vehicle-to-grid power: Battery, hybrid, and fuel cell vehicles as resources for distributed electric power in California. *Energy Policy*, 36(12), 4363–4373.
- Liu, C., Chau, K. T., Wu, D., & Gao, S. (2019). Opportunities and challenges of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid technologies. *Proceedings of the IEEE*, 101(11), 2409–2427.
- Liu, M., Wang, Y., & Chen, C. (2020). Economic evaluation of vehicle-to-grid strategies under real-time pricing and uncertainty. *Applied Energy*, 260, 114326.
- Lopes, J. A. P., Soares, F. J., & Almeida, P. M. R. (2011). Integration of electric vehicles in the electric power system. *Proceedings of the IEEE*, 99(1), 168–183.
- Lund, H., & Kempton, W. (2008). Integration of renewable energy into the transport and electricity sectors through V2G. *Energy Policy*, 36(9), 3578–3587.
- Lund, H., Kempton, W., Andersen, A. N., Mathiesen, B. V., & Connors, S. (2012). The role of electric vehicles in smart energy systems. *Energy*, 42(1), 199–205.
- Ma, T., Mohammed, O., & Kimball, J. (2018). Economic analysis of vehicle-to-grid revenue with real-world driving data. *IEEE Transactions on Smart Grid*, 9(2), 1131–1141.
- Madina, C., Zamora, I., & Zabala, E. (2016). Methodology for assessing electric vehicle charging infrastructure business models. *Energy Policy*, 89, 284–293.
- Martinez-Laserna, E., Gandiaga, I., Sarasketa-Zabala, E., Rodriguez-Martinez, L. M., Stroe, D. I., Swierczynski, M., & Sauer, D. U. (2018). Evaluation of lithium-ion battery second life performance and degradation. *Energy*, 145, 274–285.
- Metere, R., Neaimeh, M., Morisset, C., Maple, C., Bellekens, X., & Czekster, R. M. (2021). Securing the electric vehicle charging infrastructure. *arXiv*.
- Morrissey, P., Weldon, P., & O'Mahony, M. (2016). Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behaviour. *Energy Policy*, 89, 257–270.
- Mullan, J., Harries, D., Bräunl, T., & Whitely, S. (2011). The technical, economic and commercial viability of the vehicle-to-grid concept. *Energy Policy*, 39(10), 5320–5330.

- Mwasilu, F., Justo, J. J., Kim, E. K., Do, T. D., & Jung, J. W. (2014). Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy integration. *Renewable and Sustainable Energy Reviews*, 34, 501–516.
- Neubauer, J., & Wood, E. (2014). The impact of V2G services on the lifetime of automotive lithium-ion batteries. *Journal of Power Sources*, 259, 262–269.
- Noel, L., Papu Carrone, A., Jensen, A. F., & Zarazua de Rubens, G. (2019). *Vehicle- to- grid: A sociotechnical transition beyond electric mobility*. Springer.
- Open Charge Point Protocol (2025). *Protocol for managing EV charging stations (OCPP 2.1)*. Open Charge Alliance.
- Putrus, G. A., Suwanapingkarl, P., Johnston, D., Bentley, E. C., & Narayana, M. (2009). Impact of electric vehicles on power distribution networks. *IEEE Vehicle Power and Propulsion Conference*, 827–831.
- Rana, R., Saggu, T. S., Letha, S. S., et al. (2024). V2G based bidirectional EV charger topologies and its control techniques: A review. *Discover Applied Sciences*, 6, 588.
- Rathore, S., Singh, A., & Singh, M. (2021). Cybersecurity for smart electric vehicle charging systems: Challenges and future research directions. *Energies*, 14(7), 1874.
- Richardson, D. B. (2013). Electric vehicles and the electric grid: A review of modeling approaches, impacts, and renewable energy integration. *Renewable and Sustainable Energy Reviews*, 19, 247–254.
- Sarker, M. R., Ortega- Vazquez, M. A., & Kirschen, D. S. (2016). Optimal coordination and scheduling of demand response via aggregation. *IEEE Transactions on Smart Grid*, 7(6), 2894–2905.
- Schill, W. P., Zerrahn, A., & Kunz, F. (2017). Prosumage of solar electricity: Pros, cons, and the role of consumers in the German energy transition. *Energy Journal*, 38(3), 203–229.
- Shen, W., Han, S., & Sezaki, K. (2012). Optimal scheduling of vehicle-to-grid operation under time-of-use pricing. *IEEE Transactions on Smart Grid*, 3(3), 1131–1139.

- Sovacool, B. K., Axsen, J., & Sorrell, S. (2018). Promoting electric vehicles: Lessons from China, Europe, and the United States. *Global Environmental Change*, 53, 114–128.
- Su, W., Chow, M. Y., & Xie, L. (2019). Modeling, planning, and optimal energy management of combined heat and power microgrid with renewable energy. *IEEE Transactions on Smart Grid*, 10(5), 5000–5012.
- Sultan, V., Aryal, A., Chang, H., & Kral, J. (2022). Integration of EVs into the smart grid: A systematic literature review. *Energy Informatics*, 5, Article 65.
- Sundararajan, A., Zhou, B., & Narayanaswamy, B. (2022). Grid services from vehicle-to-grid: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 157, 112070.
- Tan, K. M., Ramachandramurthy, V. K., & Yong, J. Y. (2016). Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques. *Renewable and Sustainable Energy Reviews*, 53, 720–732.
- Tang, L., Zhang, Y., & Wang, Z. (2020). Optimal scheduling of electric vehicle charging and discharging in smart grids considering battery degradation cost. *Energy*, 191, 116518.
- Tang, X., Sun, C., Bi, S., Wang, S., & Zhang, A. Y. (2022). A holistic review on advanced bi-directional EV charging control algorithms. *arXiv*.
- van der Kam, M., & van Sark, W. (2015). Smart charging of electric vehicles with photovoltaic power and vehicle-to-grid technology in a microgrid. *Applied Energy*, 152, 20–30.
- Wang, S., Cabrera, J. A., & Fitzek, F. H. P. (2024). Bidirectional charging use cases: Innovations in e-mobility and power-grid flexibility. *arXiv*.
- Wired. (2022). *The future of EV charging is bidirectional, if you can afford it*.
- Wu, D., Aliprantis, D. C., & Ying, L. (2011). Load scheduling and dispatch for vehicle-to-grid integration of plug-in electric vehicles. *IEEE Transactions on Smart Grid*, 3(1), 368–376.
- Xu, D., Saxena, S., Coignard, J., Iosifidou, E., & Guan, X. (2021). V2G- Sim modelling of battery degradation and grid services. *Lawrence Berkeley National Laboratory* (as cited in Xu, 2025).

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Applied and Computational Engineering, 125(1), 217–221.

Zhang, Q., Tezuka, T., Ishihara, K. N., & Mclellan, B. C. (2012). Optimization of charging schedules of plug- in hybrid electric vehicles for smart households.

Energy, 42(1), 285–293.

Zhang, R., Guo, Q., Sun, H., & Li, Z. (2021). A hierarchical approach to V2G control considering battery degradation and market interactions. *International Journal of Electrical Power & Energy Systems*, 125, 106462.