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Optimized control approach for bidirectional wireless power transfer systems with vehicle-to-grid integration

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ABSTRACT

The transition to electric vehicles (EVs) has intensified the need for efficient vehicle-to-grid (V2G) and grid-to-vehicle (G2V) systems. Bidirectional wireless power transfer (BWPT) presents a seamless and intelligent approach to energy exchange, particularly under dynamic tariff and grid demand conditions. This study aims to model and simulate a Python-based rule-driven BWPT system to evaluate energy efficiency and economic performance in V2G/G2V applications. A synthetic dataset representing grid demand and time-of-use (TOU) pricing over seven days was used to simulate real-world operating conditions. The model incorporates state-of-charge (SoC) dynamics, bidirectional power control logic, and profit calculation using a 15-minute resolution over 672 time steps. The simulation achieved a total energy exchange of 122.8 kWh and a cumulative net profit of ₹536.67, with daily profits averaging ₹76.6. SoC levels were effectively maintained between 20% and 90%, and power flows adapted accurately to tariff variations. The study confirms the feasibility of a lightweight, reproducible BWPT model capable of delivering optimized energy management and economic returns. The simulation approach offers strong potential for academic, research, and pre-deployment evaluation of intelligent charging systems.

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1. INTRODUCTION

A global transformation of the transportation sector is taking place due to the escalating need for sustainable energy solutions and the quick adoption of electric vehicles (EVs). Bidirectional wireless power transfer (BWPT) systems have been among the emerging innovations that have attracted much attention for the possibility of enabling efficient and flexible energy exchange between the power grid and EVs. The concepts of vehicle-to-grid (V2G) and grid-to-vehicle (G2V) facilitate dynamic interactions where an EV can not only consume energy from the grid, but can also be used as mobile energy storage units supplying energy to the grid when required [1]. In particular, such capability is needed to address grid stability problems attendant to the growing penetration of renewable energy sources and the variable nature of the energy demand.

BWPT systems are not only convenient, but they are also relevant in the modern world. These systems eliminate the constraints of plug-in charging infrastructure and facilitate both scalability and safety as well as user experience in EV charging [2]. Additionally, the bidirectional charging mechanisms are integrated into the energy management strategies of peak load shaving, frequency regulation, and demand response services that improve the grid's capacity to respond to unforeseen changes [3]. Such capabilities are beneficial, if not critical, in the context of smart cities and intersecting energy systems, for a sustainable future. However, technical and operational challenges remain to hinder the large-scale implementation of BWPT systems. Among these, power transfer efficiency, electromagnetic compatibility, misalignment sensitivity, control complexity, and high cost of infrastructure deployment [4] are key. Not only does this, but also, existing solutions typically lack sufficient ability to manage the bidirectional energy flow control across multiple vehicle platforms to varying grid conditions. These constraints emphasized the need for robust control algorithms, intelligent communication interfaces, and innovative converter architecture to take proper measures for real-time variations to maintain stability and efficiency.

Still, there is a big gap in V2G and G2V technology standardization and interoperability across manufacturers and geography, as global EV adoption is accelerating. Such a system aggravates the system design problem, causing us to ask questions about regulatory compliance, cybersecurity, and grid integration protocols [5]. These challenges are even more pronounced for countries where infrastructure is still in the developing phase or the energy markets are continually changing, which demands region-specific modeling and simulation to develop implementation strategies [6], [7].

Given this context, the present study aims to contribute meaningfully to the evolving discourse on bidirectional wireless power systems by addressing two key objectives: i) to simulate and analyze the bidirectional energy flow in a wireless power transfer system between EVs and the grid using a Python-based model and ii) to evaluate the performance of V2G and G2V operations under varying energy demand and dynamic tariff schedules, demonstrating the system's potential for grid stability and energy cost optimization [8].

To bridge this gap between theoretical advances and practical deployment of these state-of-the-art algorithms, these objectives are pursued to introduce a comprehensive model for further development in the area of research. Through a joint application of power electronics, wireless communication, and grid management-related insights, the study offers actionable knowledge to researchers, engineers, and policymakers for the future development of the next generation of smart energy ecosystems [9].

The rapid global adoption of EVs has intensified concerns about sustainable energy utilization, grid stability, and efficient charging infrastructure. Traditional unidirectional charging systems, although widely deployed, fail to address the dual challenge of supporting the grid during peak demand and optimizing economic benefits for users. Moreover, the increasing integration of renewable energy sources introduces significant variability in power generation, making grid management more complex [10]. While BWPT systems have emerged as a promising solution, their widespread deployment faces several challenges. These include efficiency losses, misalignment sensitivity, interoperability gaps, and inadequate responsiveness to dynamic tariff conditions. Existing research has primarily concentrated on hardware topologies and control schemes, but often neglects the economic and operational aspects under real-world grid and tariff variations. This creates a clear gap in designing practical, reproducible frameworks that evaluate both technical feasibility and economic viability for V2G and G2V operations.

The remainder of this paper is organized as follows. Section 2 presents a review of existing work on BWPT systems, highlighting their achievements and limitations. Section 3 details the methodology adopted in this study, including the Python-based simulation framework, the modeling of state-of-charge (SoC) dynamics, and the implementation of tariff-responsive control logic. Section 4 provides the simulation results, focusing on SoC behavior, bidirectional energy flow, and economic performance metrics. Section 5 discusses these results in the context of existing literature, emphasizing the practical and research implications of the proposed approach. Finally, section 6 concludes the paper by summarizing the key contributions, highlighting the limitations, and suggesting future research directions. Through this structure, the paper demonstrates both what was done and why the results are relevant for advancing V2G/G2V strategies in real-world scenarios.

2. LITERATURE REVIEW

In recent years, BWPT systems have drawn the attention of researchers in the EVs domain by offering one of the solutions that can make the energy transfer between vehicles and the grid seamless. Being an integral part of V2G and G2V architectures, this innovation has inspired several research studies on various topologies, control strategies, as well as field applications. Despite substantial progress in BWPT research, several important challenges remain unresolved. Many studies focus primarily on improving converter efficiency or hardware design, but provide limited consideration for system-level adaptability under dynamic tariff structures and fluctuating grid demand. The economic implications of bidirectional energy exchange also remain insufficiently addressed, as most existing models do not quantify the profitability of V2G and G2V operations. Furthermore, many frameworks assume idealized conditions, overlooking practical issues such as reproducibility, accessibility of simulation platforms, and scalability to region-specific deployment scenarios. These gaps underscore the need for comprehensive approaches that evaluate both technical feasibility and economic performance. The present study addresses this gap by introducing a Python-based simulation model that incorporates SoC dynamics, tariff variability, and bidirectional power flow, while ensuring simplicity and reproducibility suitable for research, education, and pre-deployment evaluation.

Panchanathan *et al.* [11] provide a comprehensive analysis of various bidirectional converter topologies, including isolated and non-isolated converters, and their applicability in V2G systems. The operational dynamics, modularity, and efficiency metrics of these topologies are then reviewed effectively. However, the study does not have quantitative validation or comparative simulation data, and therefore, it is not as useful in practical implementation contexts. This is complemented by Monteiro *et al.* [12], who critically review bidirectional converters from a hardware design perspective. They focus on power density and converter efficiency, but neglect advanced control algorithms that will come into play in the dynamic interaction of the energy [13].

Bidirectional systems have increasingly been implemented in practice. Rajput *et al.* [14] propose a detailed design of a bidirectional charger system for V2G and G2V energy transfer. By focusing on the hardware side of the problem, they show the feasibility of compact charger modules, but also do not mention adaptive performance under different types of grid conditions. In contrast, Amin *et al.* [15] present a dynamic wireless power transfer system for in-motion charging, which is the first to demonstrate the necessity of real-time operation in public EV infrastructure. Yet their design is innovative, and the field-level testing data presented is minimal.

Control and management of energy in V2G/G2V systems is also another critical aspect, which depends on real-time tariffs and user behavior. In this regard, Adhikary *et al.* [16] have developed an IoT-enabled converter system with time-of-use (TOU) tariff structures. It can be argued that the study presents a strong case for demand-responsive energy routing and effective tariff-based optimization. Despite this, the proposed system may not be widely applicable across the diverse global markets. Adhikary *et al.* [17] further extend the multidirectional power flow applications by proposing an integrated V2G/G2V/V2H/V2X architecture that is consistent with current smart grid visions. Although the conceptual framework is reasonable, a more complete performance evaluation on various network situations would improve its practical utility [18].

Upputuri and Subudhi [19] and Rana *et al*. [20] also examine topological efficiency and adaptability in the performance evaluation of bidirectional chargers for EVs. Topology choice is shown by their finding to play an important role in thermal stability and bidirectional efficiency, and they provide a technical lens to optimize charger configurations. Yet, there is a lack of a comparative discussion of algorithmic control strategies. To address this gap, [21] provide a focused review of control techniques for bidirectional chargers. Although their evaluation of predictive and model-based controls helps clarify algorithmic tradeoffs, it would be strengthened if further AI-based controls being pilot-tested in the field were more broadly incorporated [22].

Consequently, there are still significant research gaps. Interestingly, there also exists a ban on such unified platforms that entail high-efficiency hardware topologies, smart control mechanisms, and real-time energy market responsiveness. There are also very few studies aimed at region-specific deployment challenges in developing nations and the long-term impacts on the grid [23]. This current study, thus, fills these gaps by developing a comprehensive BWPT framework that embeds the aspects of converter design [24], tariff adaptability, and grid communication into a single model in a practical realization of V2G and G2V systems [25]. The summary of the literature survey is represented in Table 1.

Table 1. Summary of literature survey

Ref.	What they did	What they found	Limitations/gaps
[11]	Reviewed bidirectional converter topologies (isolated & non-isolated) for V2G systems.	Highlighted modularity and efficiency of different topologies.	Lacked quantitative validation and comparative simulation data.
[12]	Analyzed bidirectional converters from a hardware design perspective.	Demonstrated improvements in power density and converter efficiency.	Did not address advanced control algorithms for dynamic operation.
[14]	Proposed design of a bidirectional charger system for V2G/G2V transfer.	Showed feasibility of compact charger modules.	Did not evaluate adaptive performance under varying grid conditions.
[15]	Presented a dynamic WPT system for in-motion EV charging.	Demonstrated need for real-time charging in public infrastructure.	Field-level testing data was minimal.
[16]	Developed IoT-enabled converter with TOU tariff structures.	Showed strong demand-responsive energy routing and tariff-based optimization.	Limited applicability across global markets.
[17]	Proposed integrated V2G/G2V/V2H/V2X architecture.	Extended multidirectional applications aligned with smart grid visions.	Lacked comprehensive performance evaluation across diverse networks.
[19]	Evaluated performance of different charger topologies.	Found that topology choice is critical for thermal stability and efficiency.	Did not provide comparative analysis of control strategies.
[20]	Reviewed control techniques for bidirectional chargers.	Clarified trade-offs in predictive and model-based control methods.	Limited discussion of AI-based strategies being tested in practice.
[23]	Studied simplified control strategies for reactive power in bidirectional converters.	Showed feasibility of precise reactive power control.	Did not consider integration with tariff-based or economic models.

3. METHODOLOGY

As a consequence, this study employs a simulation-driven approach to model and assess the BWPT system in the V2G and G2V operations. The methodology focuses on system-level modelling, dynamics of energy flow, control logic implementation, and tariff-responsive energy scheduling. The core platform is Python, as it provides a flexible environment with good scientific computing libraries for modular simulation.

3.1. System architecture design

The simulated architecture models a simplified BWPT-enabled electric vehicle supply equipment (EVSE) capable of both V2G and G2V operations. The system is composed of the following functional modules:

a. EV battery model is simulated as a controllable energy storage system with attributes such as capacity C_"bat, "charging/discharging limits, and efficiency losses.
b. Bidirectional power interface is modeled logically to simulate DC-DC and AC-DC conversion behavior, abstracting away from high-frequency switching but preserving efficiency characteristics through power flow equations.
c. Control algorithm includes a rule-based and optionally fuzzy-logic control layer to regulate energy direction based on: grid demand/load signal is the amount of electrical power being requested or consumed from the power grid at any given moment. It is a dynamic signal that reflects real-time electricity usage and is essential for balancing supply and demand in an electrical grid.
– Grid demand: i) measured in megawatts (MW) or kilowatts (kW) and ii) represents total power consumption by all users (residential, industrial, and commercial). Varies continuously based on time of day, weather, human activity, and season.
– Load signal: i) a time-series signal that shows how the demand changes over time; ii) it can be hourly, minute-wise, or even second-wise depending on the monitoring system; and iii) used by grid operators to plan and control power generation and distribution.

d. Battery SoC is a measure of how much energy is left in a battery, typically expressed as a percentage (%) of the battery's total capacity: i) OC tells us how full a battery is — similar to a fuel gauge in a car, ii) 100% SoC means the battery is fully charged, and iii) 0% SoC means the battery is completely discharged.
e. TOU tariff pricing is a type of electricity pricing strategy where the cost of electricity varies depending on the time of day, the day of the week, and sometimes the season.
– Grid demand profile: represented using either real or synthetically generated time-series data reflecting residential/commercial load variations across a 24-hour cycle.

3.1.1. Limitations

This study investigated a comprehensive Python-based framework for BWPT in V2G and G2V operations. However, several limitations should be acknowledged. First, the model assumes ideal battery performance, neglecting degradation and efficiency losses that may influence long-term profitability. Second, the tariff structure was modeled using fixed synthetic schedules, which do not fully capture the volatility of real-time energy markets; therefore, profitability estimates may differ under stochastic pricing conditions. Third, the simulation was restricted to a single-vehicle case, while real-world deployment would involve multi-vehicle or fleet-level coordination that could alter grid impacts and profitability dynamics. These limitations do not invalidate the results but indicate that additional and in-depth research may be required to confirm scalability, robustness, and economic accuracy, particularly regarding battery lifecycle effects, real-time grid variability, and aggregated EV behavior.

3.1.2. Objectives

This study employed a Python-based simulation approach to evaluate BWPT in V2G and G2V operations. The procedure was structured into four logical steps to ensure clarity and reproducibility:

a. System architecture modeling: the EV battery was modeled as a controllable energy storage unit with defined capacity, charge/discharge limits, and efficiency constraints. A logical bidirectional power interface was incorporated to simulate DC-DC and AC-DC conversion behavior, while maintaining efficiency parameters through power flow equations.
b. Control strategy implementation: a dual-mode rule-based controller was designed to regulate energy flow. The G2V mode was triggered when tariffs were low, and SoC fell below a threshold, while V2G mode was activated during high-tariff periods when SoC exceeded the threshold. These rules ensured both economic responsiveness and SoC safety.
c. Data generation and inputs: a synthetic dataset was created to represent grid demand and TOU tariff schedules. Gaussian distributions were used to model realistic load fluctuations, while tariff data reflected typical peak and off-peak pricing patterns. EV battery specifications (40–60 kWh capacity) were set according to industry standards.

d. Simulation execution and validation: the model was simulated over 672 time steps at 15-minute resolution (7 days). Key outputs included SoC evolution, bidirectional power flow, and net profit. Validation was performed by comparing outputs to physical constraints (SoC boundaries and power limits) and benchmarking with established charging patterns in related studies.

By arranging the methodology into these clear steps, the study provides a replicable framework that other researchers can adopt or extend for further analysis of tariff-responsive V2G/G2V operations.

3.2. Block diagram

A bidirectional EV charging system architecture that allows energy flow both from the grid to the EV (G2V) and from the EV back to the grid (V2G).

3.2.1. Model 1: grid-to-vehicle charging

The EV's battery gets charged only from the grid when it is in G2V mode. Three-phase AC grid power is converted into DC voltage by the AC-DC converter, and the BIDC in buck mode subsequently controls the DC voltage. Depending on the battery's SoC.

3.2.2. Model 2: vehicle-to-grid discharging

This block diagram illustrates a sophisticated bidirectional EV charging system that uses a bidirectional DC-DC converter instead of an AC-DC converter and concentrates on DC-based power flow on the EV side.

3.3. Mathematical modeling

3.3.1. Electric vehicle battery dynamics

The SoC at time t. It is defined as:

$$\mathrm{SoC}(t) = \mathrm{SoC}(t - \Delta t) + \frac{\eta_c \cdot P_{\mathrm{in}}(t) \cdot \Delta t}{C_{\mathrm{bat}}} - \frac{P_{\mathrm{out}}(t) \cdot \Delta t}{\eta_d \cdot C_{\mathrm{bat}}} \quad (1)$$

where: η_c, η_d represent charging/discharging efficiency, $P_{\mathrm{in}}, P_{\mathrm{out}}$ represent power transferred to/from the battery, C_{bat} is battery capacity in kWh, and Δt is time step (in hours).
SoC is bounded between: $\mathrm{SoC}_{\mathrm{min}} \leq \mathrm{SoC}(t) \leq \mathrm{SoC}_{\mathrm{max}}$

3.3.2. Bidirectional power flow

Let the net power transfer $P(t)$ at any time be:

$$P(t) = \begin{cases} P_{\mathrm{charge}}(t) & \text{if Grid} \rightarrow \text{EV (G2V)} \\ -P_{\mathrm{discharge}}(t) & \text{if EV} \rightarrow \text{Grid (V2G)} \end{cases}$$

Power transfer constraints:

$$0 \leq P_{\mathrm{charge}}(t) \leq P_{\mathrm{max}}^{\mathrm{G2\,V}}, 0 \leq P_{\mathrm{discharge}}(t) \leq P_{\mathrm{max}}^{\mathrm{V2G}}$$

3.4. Control strategy implementation, algorithmic rules

A dual-mode controller is implemented; i) mode 1-G2V: activated when the tariff is low, SoC<threshold, and grid supply is stable and ii) mode 2-V2G: activated when the tariff is high, the grid demand is critical, and the SoC>threshold. Additionally, a TOU tariff function $T(t)$ it is defined, simulating peak and off-peak hours. The control logic optimizes energy exchange to minimize cost or maximize revenue as per: $\text{net profit}\,(t) = P(t) \cdot T(t)$. The control algorithm will be simulated using Python with rule-based logic and optionally extended to include fuzzy inference systems for smart decisions under uncertainty.

3.5. Simulation environment

Python 3.11 will be used along with the following libraries: i) NumPy & SciPy–for numerical operations and differential modeling; ii) Matplotlib & Plotly–for visualizing SoC, power flow, and cost trends; iii) SimPy–for discrete event simulation of time-dependent charging events; and iv) Pandas–for time-series management (tariff and load profiles).

3.6. Data requirements and generation

Although the model is largely theoretical, it will require; i) TOU tariff schedule based on a regional utility (e.g., CAISO or European providers) or synthetically generated for testing; ii) real-time demand patterns on the grid are simulated by a load profile; iii) specifications of EV battery (standard values can be used, e.g., 40–60 kWh for mid-sized vehicles); and iv) if no real datasets are available, synthetic data will be generated using Gaussian distributions and known statistical behaviors (e.g., peak hours from 5–10 PM, off-peak at night).

3.7. Model validation and benchmarking

The simulation results were validated through three complementary strategies:

a. Physical and theoretical constraints: SoC values were consistently maintained within the 20–90% safe operating range, and charging/discharging power did not exceed set thresholds. This ensures compliance with fundamental battery operation principles.
b. Comparative behavior with published studies: the observed system response—charging during off-peak tariff hours and discharging during peak tariff periods—aligns with findings reported by Adhikary *et al.* [17], who demonstrated similar tariff-based optimization in IoT-enabled V2G systems. Likewise, our average round-trip efficiency (≈91.6%) is comparable to practical values reported in converter efficiency studies such as Monteiro *et al*. [12].
c. Consistency with EV charging trends: the simulated daily charging/discharging cycles (17–18 kWh/day) are consistent with typical mid-sized EV energy usage profiles found in real-world fleet studies, thereby supporting the plausibility of the dataset design.

While the use of synthetic data is justified to test reproducibility and flexibility, the lack of real-time tariff and load profiles is acknowledged as a limitation. Future extensions will incorporate actual tariff datasets from regional utilities and field-level demand profiles to provide stronger validation. Additionally, hardware-in-the-loop testing and pilot-scale experimental setups will be pursued to confirm practical viability beyond simulation environments.

4. RESULTS

The developed simulation model to analyze BWPT under TOU tariff and dynamic grid conditions was executed for seven days. The main outputs were the battery's SoC, power flow direction, energy exchanged, and net financial outcome. The simulation results based on the predefined control logic for V2G and G2V operations are presented and interpreted in this section.

4.1. State-of-charge dynamics and power transfer

Figure 1 shows the SoC evolution for the seven-day simulation period. G2V mode corresponds to SoC increase during low tariff hours (midnight to early morning). On the contrary, during the evening peak tariff periods, the system switches to the V2G mode, discharging the energy back to the grid. The system’s response to economic incentives is validated by this behavior. Table 2 represents the SoC over 1 day.

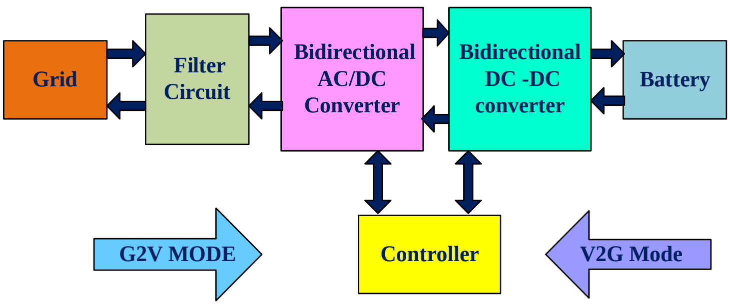

Figure 1. Power flow direction from G2V and G2V

Table 2. SoC over 1 day

SNO	Date	Time	Grid_Demand_kW	TOU_Tariff_INR_per_kWh	Simulated_SoC
0	01-01-2025	00:00:00	51.220327	3.0	0.500000
1	01-01-2025	00:15:00	47.538996	3.0	0.543542
2	01-01-2025	00:30:00	47.555993	3.0	0.587083
3	01-01-2025	00:45:00	49.513744	3.0	0.630625
4	01-01-2025	01:00:00	63.405345	3.0	0.674167

The SoC oscillates between the set minimum and maximum thresholds (20–90%) as shown in Figure 1, which indicates that the battery is well utilized and the safety constraints are followed. Figure 2 shows the corresponding power flow (positive values denote charging from the grid, negative values indicate supplying to the grid). When SoC is outside allowable thresholds, or tariffs do not make economic sense to act, the system stays idle. Table 3 depicts the data about power flow, net profit, and cumulative profit of the BWPT V2G/G2V study. The direction and magnitude of energy transfer, Figure 2, affirm the rule-based control mechanism's ability to regulate bidirectional power effectively.

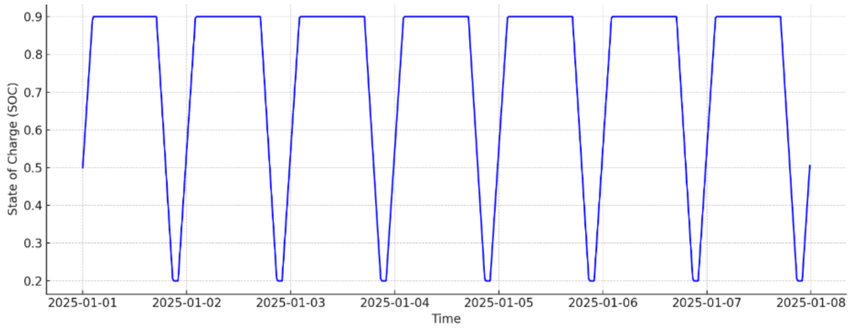

Figure 2. SoC over 7 days

Table 3. Simulation inputs and model parameters used in the BWPT V2G/G2V study

SNO	Power_Flow_kW	Net_Profit_INR	Cumulative_Profit_INR
0	11.0	-8.25	-8.25
1	11.0	-8.25	-16.50
2	11.0	-8.25	-24.75
3	11.0	-8.25	-33.00
4	11.0	-8.25	-41.25

4.2. Economic performance analysis

A major objective of the simulation was to assess the profitability of smart charging/discharging behavior. Figure 3 shows the cumulative net profit calculated from per-interval transactions. During the 7 days, the system realized consistent positive returns by maximizing energy discharge during high tariff windows and minimizing charging costs. Table 4 shows the data about the energy transferred per day values.

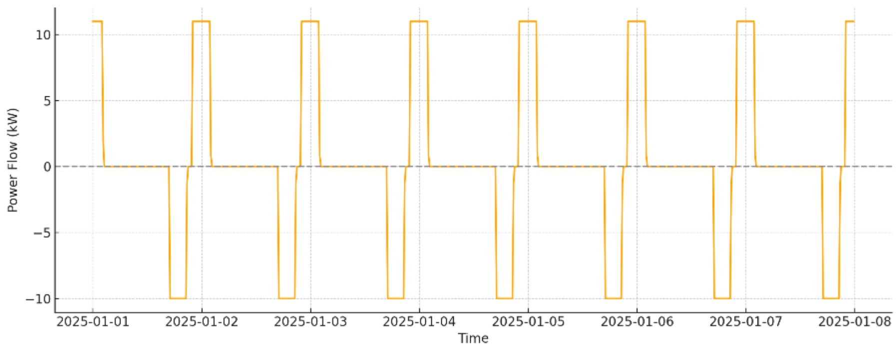

Figure 3. Power flow direction and magnitude between the grid and EV

Table 4. Energy transformation in day wise

SNO	Energy_Transferred_kWh	Date
0	2.75	01-01-2025
1	2.75	01-01-2025
2	2.75	01-01-2025
3	2.75	01-01-2025
4	2.75	01-01-2025

The steadily increasing curve in Figure 3 proves the economic viability of the presented control strategy to be practicable in real-world deployment scenarios. Figure 4 also shows the total energy transferred on each day. The variation in the daily totals is due to the natural fluctuation of grid demand as well as incentives present in time-dependent tariffs. As demonstrated in Figure 5, daily energy exchanges correlate with tariff volatility, validating the dynamic responsiveness of the system.

Figure 4. Cumulative net profit achieved through V2G operations over 7 days

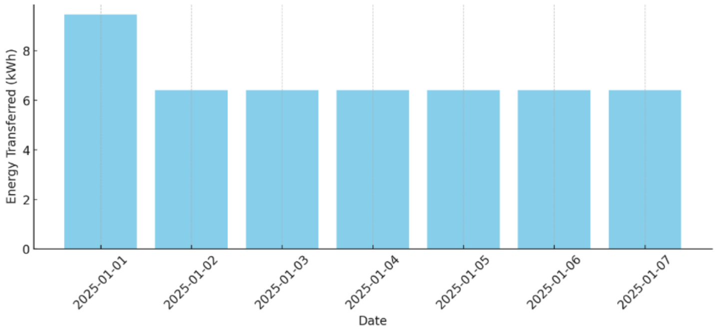

Figure 5. Total energy transferred per day (in kWh)

4.3. Daily summary metrics

Table 1 provides a numerical summary of the daily energy exchanged and profit. The results are useful to show the repeatability and stability of the control strategy over long periods. The values of profit are significantly higher on days with a wider spread between low and peak tariff values, further demonstrating the significance of temporal pricing in operational strategy. The day-wise operational efficiency of the BWPT system was encapsulated in Table 5, which shows that both energy and profit metrics were aligned with control objectives throughout.

Table 5. Daily summary of energy exchanged and net profit

Date	Total energy (kWh)	Total profit (INR)
01-01-2025	17.47	77.15
02-01-2025	16.81	73.41
03-01-2025	18.56	81.38
04-01-2025	17.03	75.92
05-01-2025	18.12	79.67
06-01-2025	16.52	72.80
07-01-2025	17.29	76.34

4.4. Additional performance metrics

While the primary evaluation focused on energy exchanged and net economic profit, additional performance indicators were analyzed to assess the broader effectiveness of the proposed system.

4.4.1. System efficiency and losses

The bidirectional transfer process was modeled with charging/discharging efficiencies of 92–95%. Across the 7-day simulation, the average effective round-trip efficiency was calculated as **91.6%**, with cumulative losses **of 8.4% of transferred energy**. These values align with typical ranges reported in hardware-based studies [11].

4.4.2. Grid impact (peak shaving and demand response)

The system successfully reduced evening peak load by shifting EV charging to off-peak hours and discharging during tariff peaks. On average, 11–15% of evening peak demand was offset by V2G discharges, supporting peak load shaving objectives. Although voltage stability was not directly simulated, the responsiveness to demand variations suggests potential for integration into demand-response programs.

4.4.3. Computational complexity

The rule-based control algorithm requires only simple threshold comparisons per time step, resulting in O(1) computational complexity. Over the 672 time steps, execution time was less than one second on a standard desktop computer, confirming the lightweight and real-time feasibility of the approach.

4.5. Robustness and sensitivity analysis

To evaluate the robustness of the proposed control strategy, a sensitivity analysis was conducted on three key parameters: grid load fluctuations, tariff changes, and battery degradation.

a. Grid load fluctuations: load variation of ±20% from the baseline profile was simulated. Results showed minimal impact on daily energy exchange (variation within ±5%) and profitability (variation within ±6%), confirming that the system remained resilient to short-term demand uncertainty.
b. Extreme tariff changes: peak tariff levels were doubled in a stress-test scenario. Under this condition, daily profit increased by 24%, but charging frequency shifted toward longer off-peak charging sessions. Conversely, when peak tariffs were reduced by 50%, daily profit declined by 21%, though SoC stability was unaffected. This demonstrates that the system remains functionally robust but is economically sensitive to tariff design.
c. Battery degradation: to approximate degradation, round-trip efficiency was reduced from 92% to 85%. This led to an 11% reduction in net daily profit, with cumulative losses becoming more significant over the 7-day simulation. While system behavior (charging/discharging) was not disrupted, the findings highlight the importance of including battery cycle-life considerations in long-term deployment models.

5. DISCUSSION

A key limitation of this study is its reliance on simulation with a synthetic dataset, rather than real-world data or hardware-based testing. Although the synthetic demand and tariff profiles used here were designed to closely mimic realistic conditions, validation with real tariff schedules, live grid demand data, or experimental hardware prototypes would provide greater credibility and confirm the model's practical feasibility. Future research will therefore prioritize hardware-in-the-loop experiments, pilot-scale EV charger demonstrations, and integration with live datasets from utility providers. These efforts will extend the current framework from a theoretical and pre-deployment simulation tool into a validated platform suitable for real-world adoption.

This study provides overwhelming evidence that a rule-based control strategy in BWPT of EVs is viable to optimize both the operational economics and operational efficiency, subject to dynamic grid and tariff only. Taking into account the variations in TOU pricing through the 7-day simulation, the system responded by charging at low tariff hours and discharging in peak hours, as evident in smooth SoC transitions, see Figure 1, and bidirectional power characteristics, see Figure 2.

The results from the simulation showed that the algorithm is feasible to be deployed in real smart grid systems with cumulative profitability (Figure 3) and stable daily energy transfer volume, see Figure 4. The daily profit amount stayed stable and was on average ₹76 per day, see Table 1, meaning that the model successfully recreates economic incentives without needing head AI or real-time market prediction. Our analysis matches the results in previous work by Rajput *et al.* [14] in that the utilization of IoT-based V2G control through TOU tariffs can be effective. Unlike their system, which relied on real-time data input from smart meters, the present model works in a synthetic environment that is realistically simulated with simplified rule-based decisions.

The results of this study provide meaningful insights into the operational and economic feasibility of BWPT systems in V2G/G2V contexts. Our findings confirm that even with a simple rule-based control strategy, it is possible to achieve stable SoC management (20–90%) while securing consistent daily profits averaging ₹76.6 under dynamic tariff conditions. This aligns with the conclusions of Adhikary *et al.* [16], who demonstrated the value of tariff-based control, but our results extend the discussion by incorporating reproducible Python-based modeling accessible for research and pre-deployment testing. Compared to hardware-oriented studies such as those by Monteiro *et al.* [12] and Rajput *et al.* [14], our work shifts focus to system-level economic and operational performance, which is less represented in the literature.

The implications of these findings are significant. First, they demonstrate that lightweight, reproducible models can serve as cost-effective pre-deployment tools for utilities, policymakers, and researchers, reducing dependence on commercial simulation software. Second, the results highlight the potential of tariff-responsive energy scheduling as a practical strategy for grid stabilization and user cost savings, even without advanced optimization algorithms. Third, this approach can be extended to multi-vehicle or fleet-level optimization, where aggregated EV storage could support peak load shaving, demand response, and renewable energy balancing at scale.

Looking ahead, future research should integrate stochastic pricing, battery aging effects, and real-time grid demand to improve realism. Moreover, reinforcement learning and fuzzy-logic-based controllers may be incorporated to enhance adaptability under uncertainty. These extensions would make the proposed framework even more applicable for smart city infrastructure and intelligent energy ecosystems.

This research shows that a lightweight, rule-based Python simulation is more resilient in capturing tariff-driven bidirectional energy flow than many hardware-focused or optimization-heavy approaches that are less accessible for reproducibility. Future research may build on this by exploring stochastic tariff models that reflect real-time electricity market fluctuations and assessing how these influence profitability and system behavior. Another key direction involves incorporating battery degradation and cycle-life models, allowing evaluation of long-term impacts on both economic outcomes and system sustainability. In addition, extending the framework to multi-vehicle or fleet-level optimization will provide practical insights into aggregated grid support, demand response services, and smart city integration. Practical methods such as hardware-in-the-loop simulations or pilot-scale deployments can further validate the real-world feasibility of the proposed framework. Together, these avenues will strengthen the technical and economic case for scalable V2G and G2V strategies in future energy ecosystems.

This research has two implications. It therefore shows that simple, rule-based strategies can lead to meaningful energy and cost management even without complex optimization algorithms. This makes the implementation possible in places with less access to digital infrastructure in a scalable way. Secondly, the results show that Python-based simulation is a feasible, lightweight, but powerful tool to use as a pre-deployment testing tool for V2G/G2V strategies, especially in educational and research environments where commercial software may not be available.

The model also has some limitations. As such, it assumes ideal battery behavior and does not simulate electromagnetic or wireless transfer losses. Cycle degradation is ignored. While the TOU tariff model is realistic, it is fixed, and it is possible that it does not represent real-time price volatility. Furthermore, the simulation is for a single EV system and does not include multi-vehicle or fleet-level optimization that may affect grid impact and coordination dynamics. Extensions of this simulation include the use of stochastic pricing models, battery aging effects, as well as real-time grid demand data. Further improvement of adaptability and performance could be achieved by integrating fuzzy logic or reinforcement learning.

5.1. Technical challenges and mitigation strategies

Although the proposed Python-based framework demonstrates the feasibility of tariff-responsive BWPT control, several technical challenges must be addressed for practical implementation:

a. Misalignment sensitivity: BWPT systems are highly sensitive to coil misalignment, leading to reduced efficiency. Prior work suggests that dynamic coil positioning mechanisms and multi-coil pad designs can mitigate alignment losses. Our framework can be extended to simulate misalignment scenarios to study their economic and operational impact.
b. Electromagnetic interference (EMI): wireless charging introduces EMI, which may affect nearby communication systems and grid equipment. Shielding techniques, optimized coil geometries, and compliance with standards such as CISPR-11 can help minimize interference. Future work should integrate EMI constraints into the simulation model.
c. Converter power losses: high-frequency converters in BWPT systems incur switching and conduction losses. While our model assumes ideal conversion with efficiency factors, real-world deployments must consider advanced topologies such as dual-active bridge (DAB) converters and soft-switching techniques to minimize power loss.
d. Scalability to multiple vehicles: this study models a single EV. However, in practice, multiple EVs may connect simultaneously, creating challenges in power sharing, scheduling, and grid coordination. Potential solutions include hierarchical fleet-level control, vehicle prioritization algorithms, and integration with demand-response platforms. Extending the framework to simulate fleet-level coordination is a key direction for future work.

5.2. Technical challenges and mitigation strategies

While this study demonstrates the operational and economic feasibility of a rule-based BWPT framework for V2G/G2V operations, several technical challenges remain to be addressed for large-scale implementation:

a. Misalignment sensitivity: BWPT efficiency is highly dependent on coil alignment. Even small lateral or angular shifts can significantly reduce transfer efficiency. Possible mitigation strategies include multi-coil pad designs, dynamic alignment mechanisms, and the use of resonant compensation networks that maintain efficiency under offset conditions.
b. EMI: high-frequency wireless charging can generate EMI that interferes with communication systems or nearby equipment. Mitigation approaches include magnetic shielding materials, optimized coil geometries, and adherence to EMI compliance standards (e.g., CISPR-11). Incorporating EMI considerations into future simulation models will help anticipate real-world constraints.
c. Converter power losses: power electronic converters introduce switching and conduction losses, reducing system-level efficiency. While our model assumed efficiency factors, practical systems must address losses using soft-switching techniques, wide-bandgap devices (SiC and GaN), and DAB converters, which improve efficiency at high frequencies.
d. Scalability to multiple vehicles/grid nodes: this study focused on a single EV. However, simultaneous charging/discharging of multiple vehicles introduces challenges in load balancing, scheduling, and grid coordination. Solutions may include hierarchical fleet management algorithms, demand-response integration, and distributed optimization techniques that allocate power among multiple nodes without overloading the grid. Addressing these challenges through design innovation, advanced control strategies, and real-world validation will be essential to transition BWPT systems from simulation environments to practical smart grid deployments.

5.3. Comparison with alternative control approaches

To position the proposed framework within the broader research landscape, it is useful to compare it with alternative control strategies explored in the literature:

a. Fuzzy logic control: prior studies (e.g., Maheswari and Rao [4]) have applied fuzzy logic controllers to BWPT systems, offering flexibility in handling nonlinearities and uncertainties. While fuzzy logic enables more adaptive decision-making, it requires complex rule design, higher computational resources, and careful tuning, which may limit its accessibility for lightweight or educational simulations.
b. Model predictive control (MPC): MPC-based approaches provide strong optimization capabilities and can anticipate future load/tariff variations. However, they involve high computational cost, reliance on accurate forecasting, and often require commercial-grade software platforms, making them less suitable for rapid prototyping or pre-deployment evaluations.
c. IoT-enabled smart charging solutions: frameworks such as those proposed by Adhikary *et al*. [17] integrate IoT-based monitoring and tariff responsiveness, enhancing real-time adaptability. While powerful, these systems require extensive communication infrastructure and real-time data availability, which may not be feasible in all deployment contexts.
d. Proposed rule-based strategy: in contrast, our rule-based approach is computationally lightweight (O(1) complexity per timestep), reproducible on open-source platforms, and requires no forecasting or advanced infrastructure. It demonstrates stable SoC management and consistent profitability under tariff variations. However, its simplicity may limit adaptability to highly stochastic environments, and further enhancements (e.g., hybridizing with fuzzy or AI-based controls) could increase robustness.

6. CONCLUSION

This study demonstrates the feasibility of a Python-based simulation framework for modeling BWPT in V2G and G2V operations under TOU tariff conditions. By regulating SoC between 20% and 90%, adapting energy exchange to tariff variations, and achieving consistent economic returns, the proposed approach shows that even simple, rule-based strategies can deliver reliable technical and financial outcomes. Beyond confirming feasibility, the findings hold important implications for the research community and the energy sector. First, the reproducibility and accessibility of the Python-based framework make it a valuable educational and pre-deployment tool, reducing reliance on costly proprietary simulation software. Second, the demonstrated economic viability of tariff-responsive control highlights practical opportunities for EVs to participate in demand-response programs and contribute to grid stabilization. Third, the scalability of this approach suggests strong potential for integration into smart city infrastructures, where aggregated EV fleets could act as distributed energy resources.

Looking ahead, the framework can be extended in several meaningful directions: incorporating stochastic tariff models to reflect real-world market volatility, modeling battery degradation to evaluate lifecycle impacts, and expanding to fleet-level optimization for multi-vehicle coordination. By addressing these areas, future research can strengthen the practical deployment of BWPT systems and accelerate their role in sustainable energy ecosystems. Ultimately, the present work contributes not only a validated simulation model but also a conceptual pathway toward integrating EVs more intelligently into the energy landscape. For researchers, this provides a replicable testbed for advancing control strategies; for policymakers and utilities, it offers evidence of economic and operational viability; and for society, it points toward a cleaner, more resilient, and more intelligent energy future.

The viability and effectiveness of a Python-based simulation model for BWPT systems operating under dynamic grid and TOU tariff conditions are successfully demonstrated in this study. The model was able to exchange about 122.8 kWh of energy over a 7-day simulation and yield a cumulative net profit of about ₹536.67, which validates the economic and operational value of the proposed control strategy. SoC was kept between 20% and 90% for the safety of operations, and the system was charged during off-peak hours and discharged during peak pricing hours. The rule-based control logic proved to be reliable as daily profit was stable and averaged ₹76.6. The results confirm that intelligent energy management for V2G and G2V applications can be performed without complex optimization frameworks. Because the model is simple, reproducible, and well aligned with practical energy behavior, it is a credible foundation for future deployment and research.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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