

Integrating EVs, PV, and ESS in Commercial Parking Lots: A Cooperative Nash Game for Transactive Energy

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ABSTRACT

Electric vehicles (EVs) are widely recognized as a key solution for reducing emissions in the transportation sector. Their growing adoption, combined with flexible charging schedules, presents a valuable opportunity to enhance grid operations. Unlike traditional approaches, a transactive energy (TE) model provides a more balanced framework, creating mutual benefits for both the grid and EV owners while ensuring that owners retain autonomy to decide how and when their vehicles are charged. In this work, we present a comprehensive TE management framework designed to optimize energy exchange among EVs, photovoltaic (PV) systems, battery energy storage systems (BESS), and the utility grid, addressing the limitations of conventional centralized energy markets. A novel EV parking lot model is proposed, enabling peer-to-peer (P2P) transactions powered exclusively by renewables and the grid, supporting both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operations to enhance energy utilization. The proposed model enables peer-to-peer (P2P) electricity transactions within a decentralized architecture. To capture the strategic behavior of self-interested energy agents, a game-theoretic approach based on Nash equilibrium is formulated, enabling coordinated decision-making under competitive conditions. The model is implemented using a non-linear programming formulation in GAMS and tested over a 24-hour operational cycle. Comparative analysis between a baseline scenario and the Nash-based model reveals significant improvements in energy utilization, cost-effectiveness, and overall system reliability. The results demonstrate that the proposed cooperative game-theoretic framework not only enhances economic performance but also promotes grid stability and equitable resource allocation, positioning it as a viable solution for future decentralized energy systems.

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1. INTRODUCTION

To address the challenge of climate change by reducing greenhouse gas emissions, there has been a substantial increase in the adoption of EVs, accompanied by a rapid expansion of EV charging infrastructure [1]. According to the International Energy Agency, the global number of public EV charging stations worldwide is expected to surpass 15 million by 2030—an impressive rise from around 4 million in 2023—highlighting the strong global push toward cleaner and more sustainable mobility solutions [2]. Among various charging approaches, slow charging in parking lots is increasingly recognized for its dual benefits of optimizing energy trading and extending battery lifespan compared to fast charging, which can accelerate battery degradation due to higher heat generation [3]. EVs can consume, store, and supply electricity to the grid via vehicle-to-grid (V2G) services, which support grid stability and load balancing [4]. V2G service participates effectively in accounting for user preferences such as charging duration and target battery level.

The rising EV adoption strains the grid, prompting the integration of renewable energy and battery energy storage systems (BESS) in EV charging infrastructures. Solar-powered EV lots combined with BESS are emerging as sustainable microgrid solutions [5]. On the other hand, as energy systems progress toward higher levels of intelligence, flexibility, and sustainability, traditional control and management approaches are no longer enough. The widespread integration of distributed energy resources (DERs) into the electricity grid introduces additional layers of complexity and operational challenges. Consequently, passive and uncoordinated DER operation can create significant issues for the network. These circumstances necessitate more advanced coordination mechanisms to ensure stability and efficiency [6].

Transactive energy (TE) and peer-to-peer (P2P) trading have emerged as promising paradigms to address these challenges. TE leverages distributed information architectures to optimize energy dispatch and system coordination at the local level, while also enhancing power quality and market participation [7]. The multifaceted advantages of P2P energy trading can be categorized into demand-side, societal, and grid-level dimensions, offering significant benefits to all stakeholders. On the demand side, prosumers are empowered to participate in a genuinely decentralized energy trading ecosystem, eliminating the need for intermediaries. At the societal level, local P2P trading fosters the integration of renewable energy by incentivizing prosumers to invest in DERs, ensuring their energy consumption aligns with sustainable practices. On the grid level, P2P trading equips system operators with enhanced flexibility to mitigate network congestion, addressing the challenges posed by uncoordinated DER operations among prosumers and the inherent intermittency of renewable energy sources [8].

This research paper presents a comprehensive TEM framework designed to facilitate efficient energy exchange among EVs, PV systems, BESS, and the utility grid. The model explores the operational dynamics and economic behavior of all participating entities. The key contributions of this research include:

- A novel model is proposed for an EV parking lot that supports P2P energy transactions while sourcing power exclusively from renewable energy and the grid. The system supports both grid-to-vehicle (G2V) and V2G, improving overall energy utilization.
- The study outlines a decentralized trading mechanism that reflects the diverse roles, constraints, and decision-making capabilities of energy agents—such as EVs, PV arrays, storage units, and grid components—enabling coordinated and adaptive energy sharing.
- The study investigates the impact of applying a cooperative Nash game theory approach and comparing two scenarios—one where energy agents operate independently without game-theoretic coordination, and another where a Nash equilibrium guides their strategies. This comparison highlights the benefits of strategic cooperation in ensuring mutual gain and market efficiency.
- A detailed case study is conducted on a smart PV-based EV parking lot integrated with ESS and EVs. The results confirm the feasibility and effectiveness of the proposed framework and demonstrate the value added by incorporating Nash-based coordination in enhancing system reliability and economic performance.

2. LITERATURE REVIEW

Several studies in the literature have also proposed innovative approaches to improve system efficiency, consumer engagement, and economic feasibility in modern energy markets. A study [9] introduces a novel approach that empowers consumers to actively participate in the electricity markets. This strategy focuses on minimizing energy expenses for users while optimizing consumption behaviors and effectively managing stored energy resources. Moreover, [10] evaluates the economic feasibility of using BESS for daily energy storage profit using RES. Additionally, the study highlights that while BESS can store surplus energy generated from PV systems, the operational costs escalate during certain periods, especially in specific seasons. Despite this limitation, the results show improvements in system dependability and a reduction in power interruptions. In the context of EVs, the study conducted by [11] investigates a charging station that combines flywheel storage with PV generation. The study focuses on enhancing distributed energy performance by optimizing the system's size and operational costs. It includes a comprehensive cost analysis covering investment, maintenance, degradation, replacement, and residual value.

Reference [12] emphasizes the importance of distributed energy storage in P2P TE markets, emphasizing its contribution to lowering costs and enhancing market adaptability, while establishing a foundation for future explorations into decentralized energy frameworks. The study in [13] offers an extensive analysis of P2P TE markets, addressing optimization complexity, cooperative strategies, and the role of machine learning and blockchain. Meanwhile, [14] introduces a detailed optimization framework for sizing renewable energy technologies—such as PV panels, wind turbines, and fuel cells—while accounting for their role in electricity markets. Although it incorporates a transactive trading layer and prioritizes system reliability, it does not adopt a Nash-based method for optimizing individual player costs. A risk-sensitive approach to day-ahead bidding for microgrids was introduced in [15], addressing both economic dispatch and decentralized

energy trading challenges within TE markets. The interaction between the microgrid controller and participating prosumers was modeled using a hierarchical Stackelberg game framework.

In [16], a coordinated framework integrating aggregators and network operators was introduced to enhance intra-regional energy coordination and inter-regional P2P multi-energy exchanges. The model aimed to improve local energy dispatch within regions, enable cross-regional energy exchange, and strengthen the operation of both unbalanced three-phase distribution systems and district heating infrastructure. Reference [17] proposes a stochastic dual-phase model for optimizing microgrid energy flows, integrating solar generation, hydrogen energy storage, and V2G operations. However, the absence of a TE framework and the lack of game-theoretic methods, such as Nash equilibrium, limit its strategic coordination capabilities. This study [18] developed a multi-timescale mechanism for trading reactive power ancillary services to enable P2P transactions in distribution networks. While these efforts emphasize the impact of P2P trading on energy scheduling strategies, they fall short of providing a detailed examination of direct bilateral transactions between individual participants in TE markets.

3. SYSTEM DESCRIPTION

The proposed decentralized TE management framework introduces a modern energy trading model that transforms traditional energy systems by enabling a more open, autonomous, and prosumer-driven energy marketplace. This model allows direct P2P electricity transactions between prosumers, fostering dynamic pricing, greater autonomy, and more equitable tariff structures.

Figure 1 illustrates the contrast between conventional and TE frameworks: in the conventional framework, the utility acts as the sole coordinator and intermediary. Microgrids and individual prosumers do not trade energy directly with one another. Instead, all energy transactions—whether buying or selling—must go through the utility. The utility sets prices, controls dispatch, and monopolizes the flow of energy and data. Conversely, the transactive system empowers microgrids to autonomously buy and sell energy among themselves, fostering P2P interactions that reduce dependency on the utility, promote local energy self-sufficiency, and enable real-time adjustments to fluctuating renewable generation, thereby decentralizing decision-making and enhancing market responsiveness. To further illustrate this fundamental shift in energy management, Table 1 provides a comparison between the conventional centralized model and the proposed transactive (decentralized) model, highlighting key differences in structure, control, pricing, and participant roles.

Table 1. Centralized vs. TE system characteristics.

	Conventional Centralized Model	Proposed Decentralized Model
Energy exchange structure	Energy transactions are handled exclusively by the utility; end users cannot trade energy directly.	Participants exchange energy directly via P2P mechanisms.
Control structure	Centralized, utility-driven decision making.	Distributed, agent-based decision making.
Pricing structure	Utility sets fixed or time-of-use tariffs; limited negotiation.	Dynamic pricing determined by local supply/demand; prices can be negotiated or set by market-clearing.
Role of EVs and DERs	EVs and DERs function as simple, passive consumers or one-way generators.	EVs and DERs actively participate as prosumers, capable of both buying and selling energy.
Grid reliance	High reliance on the main grid.	Reduced reliance due to local balancing.
Power flow	One-way power flow from the grid to consumers is typical.	Bidirectional power flows with V2G and local transactions.

Figure 2 illustrates the proposed architecture for a decentralized TE system, specifically tailored for commercial buildings equipped with parking infrastructure. The system comprises three key prosumers: the utility grid, a PV system coupled with a BESS, and EVs. Each component interacts through bidirectional power flows managed via AC/DC and DC/DC converters.

The utility grid supplies electricity to EVs and can also receive surplus energy from both the PV system and EVs via V2G transactions. Meanwhile, the PV system and its associated BESS act as a local energy generator and storage unit, supplying power to both the grid and the EVs as needed. EVs, in turn, operate as dynamic energy entities capable of buying electricity from the grid and selling stored energy back.

This setup is particularly suited for daytime applications, where EVs are typically parked from 9:00 a.m. to 5:00 p.m.—the standard hours of operation in commercial settings. To manage complex interactions among these entities, an aggregator is introduced. The aggregator plays a central role in coordinating energy exchanges, optimizing charging and discharging decisions for EVs based on factors such as the state of charge (SoC), parking duration, electricity prices, and grid conditions.

To further enhance decision-making among multiple self-interested prosumers, we integrate a Nash equilibrium-based game-theoretic model. This approach accounts for the strategic interactions among players, where each aims to optimize their own utility while considering the actions of others. To demonstrate the effectiveness of this framework, we conduct a comparative analysis between two cases: a baseline scenario without Nash coordination, and an optimized scenario incorporating Nash equilibrium strategies. The results highlight the advantages of adopting game theory in terms of cost efficiency, energy utilization, and overall system performance.

Table 2 summarizes the characteristics of the EV model used in this study [19], providing the technical foundation for formulating energy exchange strategies in the proposed architecture.

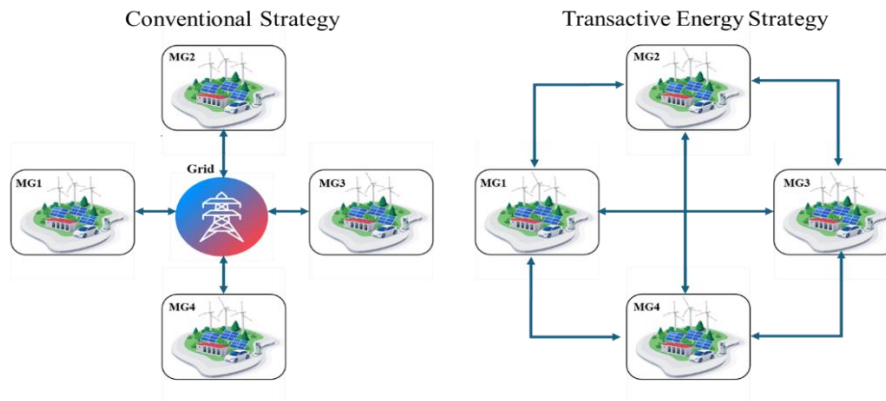


Figure 1. Conventional VS TE Strategy

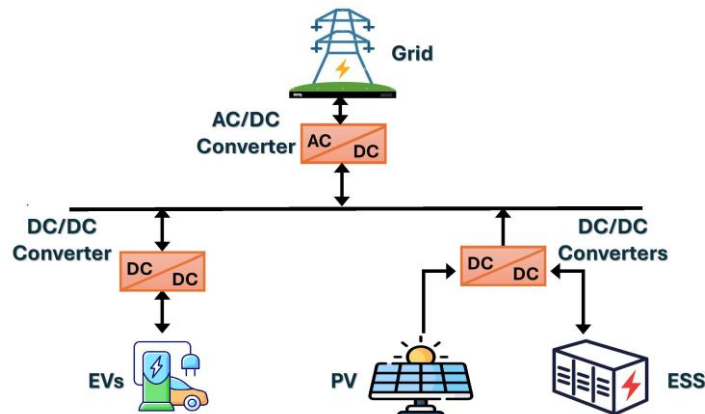


Figure 2. TE Proposed Framework

Table 2. EV PARAMETERS

	Battery capacity [kWh]	Max charging power [KW]
Mitsubishi Outlander	13.8	3.7
Hyundai Ioniq	38.3	7.2
Tesla Model 3	55	7.4
Toyota Prius	8.8	3.3
Nissan Leaf	40	3.6

4. MATHEMATICAL MODEL DESCRIPTION

The optimization model presented herein is designed to minimize a composite cost function that balances the economic interests of multiple stakeholders within a TE framework, namely the grid utility, PV, and EVs. By adopting a multiplicative cost structure, the model aligns with the principles of Nash equilibrium, ensuring equitable resource allocation.

4.1. Objective Function

The primary goal of the model is to minimize the overall cost function C , expressed as the product of normalized costs for the grid utility (C_g^{norm}), PV systems (C_{pv}^{norm}), and EV (C_{ev}^{norm})

$$\text{Min}(C) = C_g^{norm} \times C_{pv}^{norm} \times C_{ev}^{norm} \quad (1)$$

where each normalized cost is computed as

$$C_{norm} = \frac{C - C_{min}}{C_{max} - C_{min}} \quad (2)$$

where C_{min} and C_{max} represent the predefined minimum and maximum costs for each stakeholder, respectively.

4.2. Grid Utility Cost

The grid utility cost C_g is a pivotal element of the model, comprising two components: C_{g1} and C_{g2} , which address financial transactions during on-peak and off-peak periods, respectively:

$$\text{Min}(C_g) = C_{g1} + C_{g2} \quad (3)$$

4.2.1. On-Peak Period Cost (C_{g1}): The on-peak period cost, denoted as $C_{g1}(i,t,p)$, is formulated to maximize the grid's procurement of energy from distributed resources during peak demand intervals, specifically from $t_1=7:00$ to $t_2=11:00$ and $t_3=17:00$ to $t_4=19:00$. This cost component is mathematically expressed as:

$$C_{g1} = - \sum_{p=1}^P \sum_{t=1}^T \sum_{i=1}^N [(P_{i,t,p}^{v2g} + P_{t,p}^{pv2g} + P_{t,p}^{bs2g}) \times C_{Fit}], \text{ for } t_1 \leq t < t_2 \text{ and } t_3 \leq t < t_4 \quad (4)$$

where $P_{i,t,p}^{v2g}$, $P_{t,p}^{pv2g}$, and $P_{t,p}^{bs2g}$ denote the power supplied to the grid from EV i , PV systems, and battery storage, respectively, during time t in scenario p . In addition, t_1 and t_3 denote the expected start times of peak demand, while t_2 and t_4 indicate the expected end times of peak demand.

4.2.2. Off-Peak Period Cost (C_{g2}): The off-peak hour cost captures the grid's financial interactions across all time periods:

$$C_{g2} = \sum_{p=1}^P \sum_{t=1}^T \sum_{i=1}^N [((P_{i,t,p}^{v2g} \times \lambda_{ev}) + (P_{t,p}^{pv2g} + P_{t,p}^{bs2g}) \times \lambda_{pv}) - (P_{i,t,p}^{g2v} \times \lambda_g)]. \quad 0 \leq t < 6, 11 \leq t < 17 \text{ and } 19 \leq t < 24 \quad (5)$$

where $P_{i,t,p}^{g2v}$ represents the power supplied from the grid to EV i at time t in scenario p . This equation accounts for the grid's expenditures in purchasing energy from EVs, PV systems, and battery storage at tariffs $\lambda_{ev}(t)$ and $\lambda_{pv}(t)$, offset by revenue from selling energy to EVs at $\lambda_g(t)$.

4.3. PV System Cost

The cost of PV systems includes generation, storage, and sale of energy:

$$\text{Min}(C_{pv}) = \sum_{p=1}^P \sum_{t=1}^T \sum_{i=1}^N [(P_{i,t,p}^{pv2ev} + P_{t,p}^{pv2g}) \times C_{pv} + (P_{t,p}^{bs2g} + P_{i,t,p}^{bs2ev}) \times C_{bs} - (P_{i,t,p}^{pv2ev} + P_{t,p}^{pv2g} + P_{t,p}^{bs2g} + P_{i,t,p}^{bs2ev}) \times \lambda_{pv}] \quad (6)$$

where $P_{i,t,p}^{pv2ev}$ and $P_{t,p}^{pv2g}$ are PV power to EVs and the grid, $P_{t,p}^{bs2g}$ and $P_{i,t,p}^{bs2ev}$ are battery power to the grid and EVs, C_{pv} is the levelized cost of energy of PV, and C_{bs} represents the levelized cost of storage for the BESS [20].

4.4. EV Cost

The EV cost C_{ev} is minimized as:

$$Min(C_{ev}) = \sum_{p=1}^P \sum_{t=1}^T \sum_{i=1}^N [P_{i,t,p}^{g2v} \times \lambda_g + P_{i,t,p}^{v2g} \times C_{deg} + (P_{i,t,p}^{pv2ev} + P_{i,t,p}^{bs2ev}) \times \lambda_{pv} - (P_{i,t,p}^{v2g}) \times \lambda_{ev}]. \quad (7)$$

where C_{deg} is the degradation cost from V2G.

4.5. Variable Costs

The model incorporates time-dependent tariffs— $\lambda_g(t)$, $\lambda_{pv}(t)$, and $\lambda_{ev}(t)$ —representing the pricing mechanisms for grid energy, PV energy, and EV energy exchanges, respectively. These tariffs are assumed within a 20% variation from the standard TOU and FIT rates, ensuring flexibility while maintaining price stability:

$$TOU(t) \leq \lambda_g(t) \leq 1.2 \times TOU(t) \quad (8)$$

$$FIT(t) \leq \lambda_{pv}(t), \lambda_{ev}(t) \leq 1.2 \times FIT(t) \quad (9)$$

for each time period t . These bounds allow the model to adapt to market dynamics while mitigating excessive price volatility.

4.6. System Constraints

The constraints of the proposed scheme are defined as follows:

- A. To safeguard the batteries and ensure optimal performance, explicit boundaries are established to define the charging and discharging power limits for each EV and BESS

$$P_{i,t,p}^{g2v} + P_{i,t,p}^{pv2ev} \leq P_{i,t}^{Max\ ch} \quad (10)$$

$$P_{i,t,p}^{g2v} + P_{i,t,p}^{pv2ev} \leq P_{i,t}^{Max\ ch} \quad (11)$$

$$P_{t,p}^{pv2bs} \leq P_t^{Max\ ch} \quad (12)$$

$$P_{t,p}^{bs2g} + P_{i,t,p}^{bs2ev} \leq P_t^{Max\ dsch}. \quad (13)$$

- B. Equations (14) and (15) introduce specific limitations that govern the charging behavior of the EV. Equation (14) shows that the EV can only engage in either charging or discharging at any given time, but not both simultaneously. Additionally, equation (15) imposes a constraint that restricts the charging process of the EV to utilize only one power source at a time as follows:

$$(P_{i,t,p}^{g2v} + P_{i,t,p}^{pv2ev} + P_{i,t,p}^{bs2ev}) * P_{i,t,p}^{v2g} = 0 \quad (14)$$

$$P_{i,t,p}^{g2v} * (P_{i,t,p}^{pv2ev} + P_{i,t,p}^{bs2ev}) = 0. \quad (15)$$

- C. During the charging and discharging process of EVs and BESS, there is a certain amount of power loss due to system inefficiencies. As a result, the charging and discharging operations are not 100% efficient, and instead, have an efficiency rate of 90% as determined by reference [23]. The equations representing the power of the EV and BESS are as follows:

$$P_{i,t,p}^{EV} = \eta_{ch} \times (P_{i,t,p}^{g2v} + P_{i,t,p}^{pv2ev} + P_{i,t,p}^{bs2ev}) - \frac{P_{i,t,p}^{v2g}}{\eta_{dsch} \times \eta_{inv}} \quad (16)$$

$$P_{t,p}^{BS} = \eta_{ch} \times P_{t,p}^{pv2bs} - \frac{\sum_{i=1}^N P_{i,t,p}^{bs2ev}}{\eta_{dsch} \times \eta_{inv}} - \frac{P_{t,p}^{bs2g}}{\eta_{dsch}}. \quad (17)$$

- D. The State of Charge (SoC) of EVs and BESS can be calculated using equations (16) and (17). The EVs arrive with varying SoC levels. To ensure that EVs have the desired level of charge, it is necessary for EV owners to determine the departure SoC based on their preferences. As for BESS, it is assumed to have an initial SoC of 50%:

$$SOC_{i,t,p}^{EV} = \begin{cases} 0 & t < T_{i,p}^{Arrv} \\ SOC_{i,p}^{Arrv} & t = T_{i,p}^{Arrv} \\ SOC_{i,t-1,p}^{EV} + \frac{P_{i,t,p}^{EV}}{BC_t^{EV}} \times \Delta t & T_{i,p}^{Arrv} < t < T_{i,p}^{Dept} \\ SOC_{i,p}^{dept} & t > T_{i,p}^{Dept} \end{cases} \quad (18)$$

$$SOC_{t,p}^{BS} = SOC_{t-1,p}^{BS} + \frac{P_{t,p}^{BS}}{BC_t^{BS}} \times \Delta t. \quad (19)$$

- E. Equations (20) and (21) define a vital constraint that guarantees optimal battery performance and extends its lifespan by preventing deep discharges and overcharges:

$$SOC_{Min}^{ev} \leq SOC_{i,t,p}^{ev} \leq SOC_{Max}^{ev} \quad (20)$$

$$SOC_{Min}^{bs} \leq SOC_{i,t,p}^{bs} \leq SOC_{Max}^{bs}. \quad (21)$$

- F. When EVs are neither arriving at nor departing from the charging station, there is no power gained or drawn from the EVs:

$$\begin{cases} P_{i,t,p}^{v2g} = 0 \\ P_{i,t,p}^{g2v} = 0 \\ P_{i,t,p}^{pv2ev} = 0 \\ P_{i,t,p}^{bs2ev} = 0. \end{cases} \quad t < T_{i,p}^{Arrv} \quad or \quad t > T_{i,p}^{Dept} \quad (22)$$

- G. To ensure the PV system does not exceed its rated capacity, specific boundaries are established to limit its power generation. With a converter and inverter efficiency of 98% [19] :

$$\frac{\sum_{i=1}^N P_{i,t,p}^{pv2ev}}{\eta_{dc-dc}} + \frac{P_{t,p}^{pv2g}}{\eta_{dc-dc} \times \eta_{inv}} + \frac{P_{t,p}^{pv2bs}}{\eta_{dc-dc} \times \eta_{inv}} \leq P_t^{pv} \leq P_{pv}^{Max}. \quad (23)$$

5. NUMERICAL DEMONSTRATION

This section provides a numerical demonstration to validate the efficacy of the proposed solution methodology and to investigate the roles of the utility grid, EVs, BESS, and PV systems within a TE framework. The analysis employs a non-linear Programming (NLP) mathematical model, implemented via the General Algebraic Modeling System (GAMS), with all simulations executed over a 24-hour operational horizon using an hourly time step. To assess the feasibility of the proposed system, a comparative analysis is conducted, incorporating a transactive management framework. The framework is designed to foster cooperation among stakeholders using a Nash equilibrium-based optimization strategy, which ensures a "win-win" scenario for all participants by simultaneously minimizing the costs of each stakeholder. Various configurations are examined, including scenarios with and without Nash equilibrium, to demonstrate how the latter optimally refines the model. The analysis compares the proposed Nash-based model against a base case consisting of three independent scenarios, each of which optimizes cost for a single stakeholder without considering the impact on the others:

- Scenario 1: The system minimizes grid utility costs exclusively, with no consideration for the interests of PV or EV stakeholders.
- Scenario 2: The optimization focuses solely on minimizing PV-related costs, disregarding grid and EV benefits.
- Scenario 3: The model prioritizes minimizing EV operational costs, excluding grid and PV interests.

In contrast, the proposed case introduces a collaborative optimization framework based on Nash equilibrium, which concurrently considers the economic interests of all stakeholders to achieve an optimal and equitable distribution of benefits.

The investigation centers on an EV parking lot equipped with a 60 kWp PV system and three AC Tesla Powerwall units, each with a rated capacity of 14 kW. The BESS is assumed to have a usage cost of 0.314 c\$/kW, representing the levelized cost of storage [20]. The PV generation profile is based on real data obtained from PJM [21]. The parking lot is assumed to host 25 EVs participating in the transactive system.

The feed-in tariff (FIT) employed is 0.0713 c\$/kWh [22]. Time-of-use (TOU) pricing is stratified into off-peak (0.074 c\$/kWh), mid-peak (0.102 c\$/kWh), and on-peak (0.151 c\$/kWh) periods [24]. Additionally, the battery degradation cost is set at 0.056 c\$/kWh, and the levelized cost of energy (LCOE) for the PV system is 0.065 c\$/kWh [23].

5.1. Base Case

In the baseline case, the analysis is structured around three distinct scenarios—Scenarios 1, 2, and 3—each designed to optimize the cost minimization objectives for the grid, PV systems, and EVs, respectively. The analysis incorporates observations from Figure 3, which depicts the power supplied from the grid to EVs (G2V Power) across different scenarios. It is observed that EVs procure a portion of their energy from the grid in Scenario 1, whereas no grid purchases are observed in Scenarios 2 and 3. This behavior is attributable to the strategic sourcing of all energy requirements from PV systems in Scenarios 2 and 3, driven by the objective to minimize PV costs in Scenario 2 and EV costs in Scenario 3, respectively. This preference is facilitated by the lower selling price of PV-generated energy compared to grid tariffs.

Figure 4 illustrates the magnitude of power sold from EVs to the grid, highlighting the substantial and effective contribution of EVs to the V2G process through significant power sales. Figure 5 depicts the power transferred from the PV system to charge the BESS, with a notable observation that in Scenario 2, the PV system allocates a negligible amount of power to the BESS, attributable to its strategy of directing all generated power to EVs and the grid to optimize cost efficiency. Figure 6 and Figure 7 present the power sourced by EVs from PV systems and BESS, revealing that in Scenario 2, EVs predominantly procure nearly all their energy directly from the PV system, reflecting a cost-minimization approach. Figure 8 and Figure 9 delineate the power acquired by the grid from PV systems and BESS, with a key finding in Scenario 1 that the grid purchases energy from these sources during on-peak hours, driven by constraints on maximum power availability.

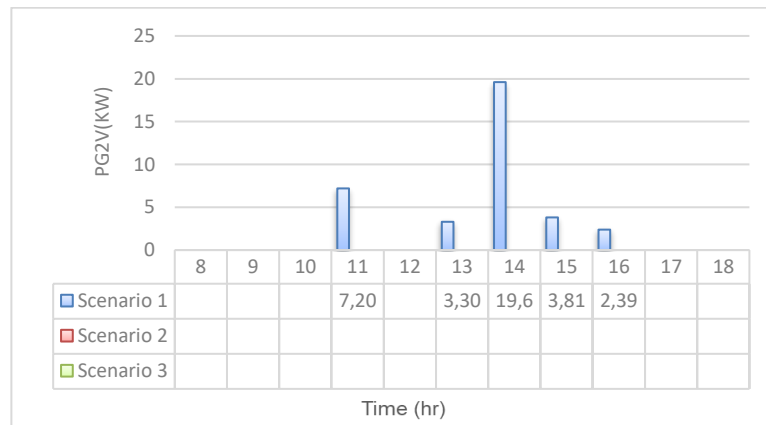


Figure 3. G2V Power in the baseline case

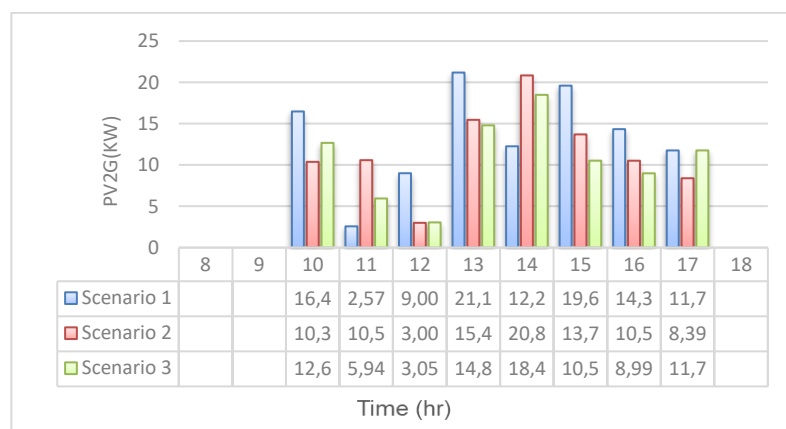


Figure 4. V2G Power in the baseline case

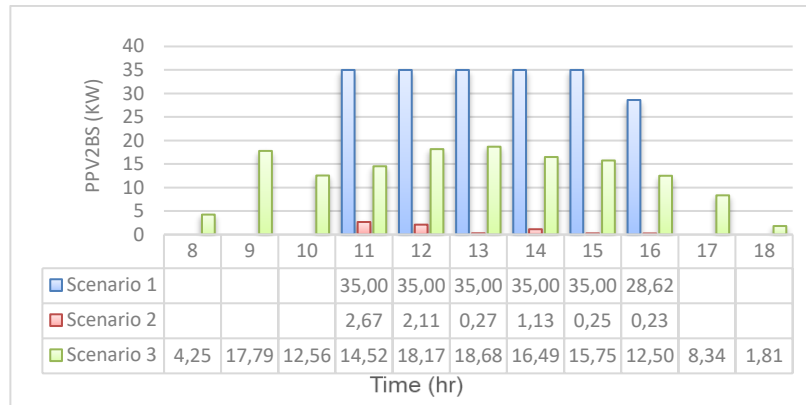


Figure 5. PV2BS Power in the baseline case

Figure 10, 74Figure 11, and Figure 12 present the variable costs associated with the grid, EV fleet, and PV system, respectively, under the three base-case scenarios. These graphs underscore the drawbacks of single-objective optimization when each stakeholder—grid, PV, or EV—operates solely in pursuit of its own benefit. As depicted in Figure 8, when the optimization is centered on minimizing the grid cost (Scenario 1), the grid purchases electricity at low-cost periods without regard for the revenue loss this may impose on the PV system and EV users. In Figure 10, Scenario 3 yields the highest EV cost, highlighting how minimizing EV costs alone can result in unfavorable outcomes for the other players. Similarly, Figure 11 reveals that Scenario 2, which focuses on minimizing PV costs, leads to the highest overall cost for the PV system due to a lack of coordination and shared objective alignment. These findings demonstrate that independent optimization for each player can inadvertently cause economic harm to others. This reinforces the necessity of a cooperative, multi-agent framework—such as the proposed Nash-based TE model—to enable balanced decision-making and ensure a win-win situation where all stakeholders benefit equitably.

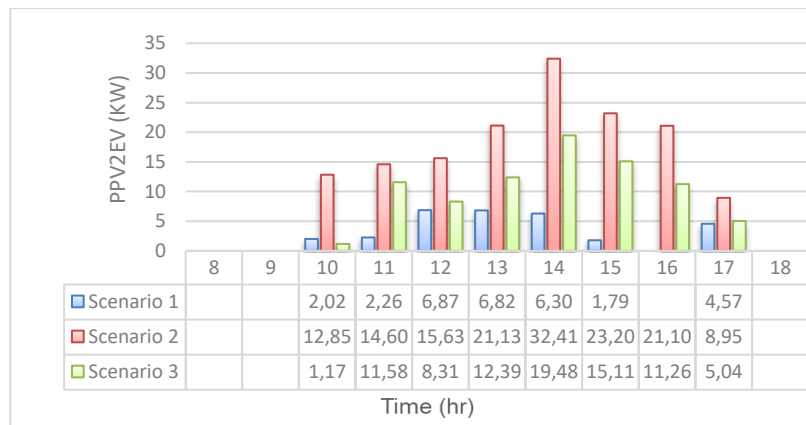


Figure 6. PV2EV Power in the baseline case

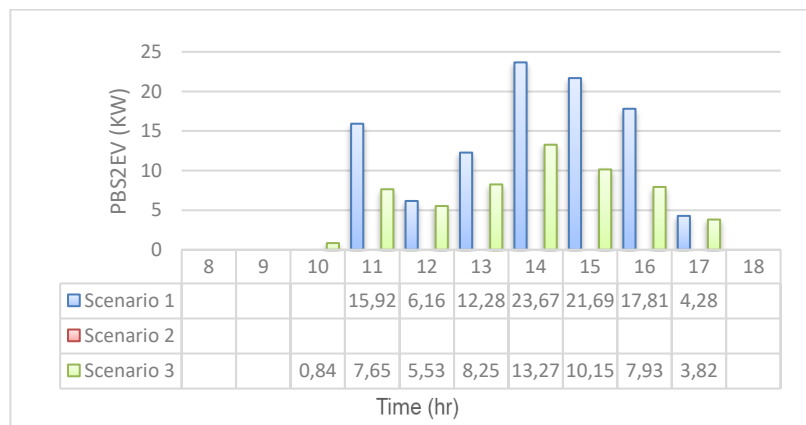


Figure 7. BS2EV Power in the baseline case

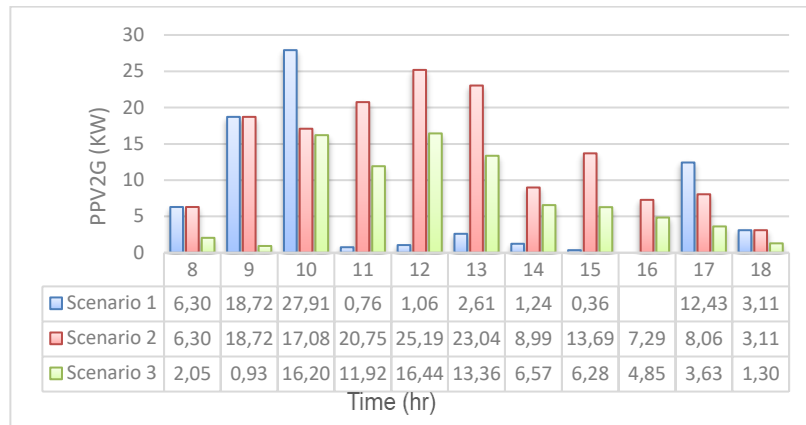


Figure 8. PV2G Power in the baseline case

Table 3 highlights the significant shortcomings of the base-case, single-objective formulations: when the grid, PV system, or EV fleet optimizes its own cost in isolation, the other stakeholders incur disproportionately high expenses. For instance, under the grid-only minimization, the utility achieves its lowest possible cost at the expense of PV revenue and EV charging affordability. Similarly, when PV cost alone is minimized, the grid forfeits potential revenue and EV owners face higher charging costs, and vice versa for the EV-only scenario. These outcomes demonstrate that unilateral optimization inherently penalizes the non-targeted parties and fails to deliver equitable value across the ecosystem. Consequently, Table 3 underscores the necessity of a cooperative framework in which all participants jointly share the economic benefits. This realization motivates the development of our proposed Nash-equilibrium transactive model, which aligns the objectives of the grid, PV, and EV stakeholders to realize a true "win-win" solution.

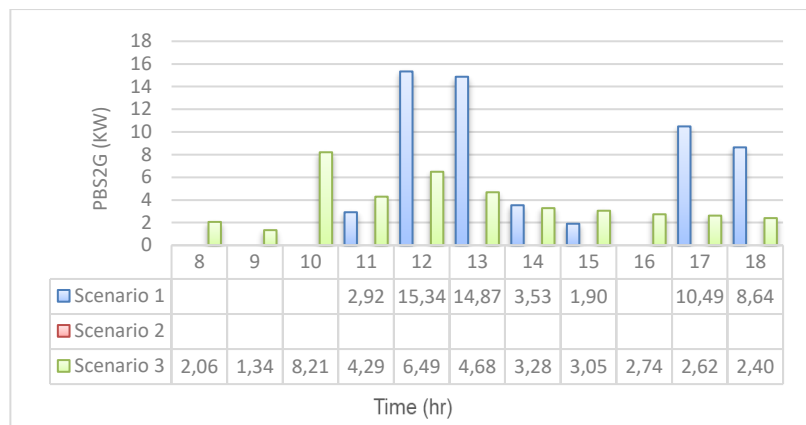


Figure 9. BS2G Power in the baseline case

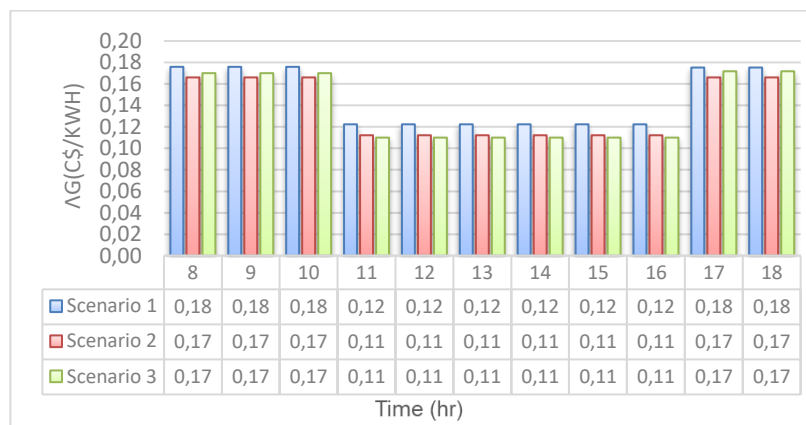


Figure 10. Variable grid cost in the baseline case

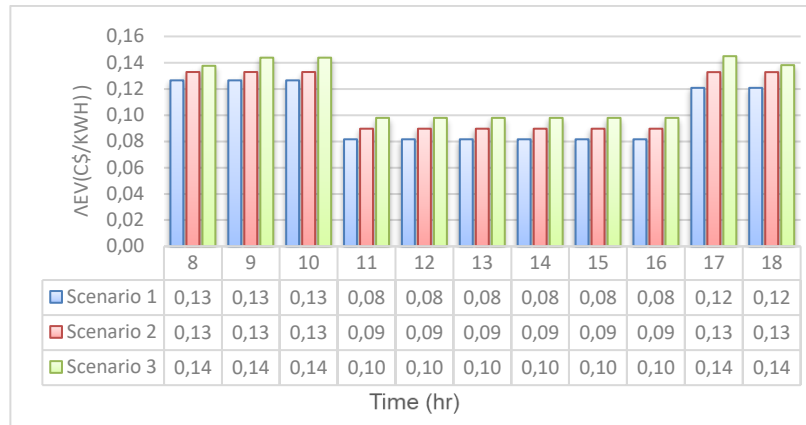


Figure 11. Variable EV cost in the baseline case

Table 3. Cost Optimization Results of the baseline case

	Minimizing Grid Cost	Minimizing PV Cost	Minimizing EV Cost
C_g	5.1	17.3	13.6
C_{pv}	33.2	-13.4	24.7
C_{ev}	12.5	13.9	8.8

5.2. Proposed case

In the proposed case, the application of the Nash equilibrium is strategically engineered to ensure an equitable allocation of benefits among all stakeholders, namely the grid, PV systems, and EVs, within the TE framework. The results reveal a complete cessation of G2V power transactions, underscoring that EVs no longer rely on grid-supplied energy under this optimized model. Figure 13 highlights a significant transformation in power dynamics, demonstrating that EVs exclusively source their energy requirements from PV systems, which provide a more cost-effective supply. Conversely, the grid actively procures power from EVs through V2G transactions, signifying a strategic pivot wherein EVs emerge as net energy suppliers to the grid. Figure 14 presents the power output from the PV system directed toward charging the BESS, revealing a critical observation: during on-peak hours, the PV system allocates a negligible amount of power to the BESS. Figure 15 and Figure 16 illustrate the energy transactions wherein the PV system and BESS supply power to EVs, with a notable pattern that no power is provided to EVs during on-peak hours. This behavior is attributable to the deliberate redirection of available power from the PV system and BESS to the grid, aligning with the grid's objective to maximize power procurement during peak demand periods. Concurrently, EVs exclusively source all their energy requirements from the PV system and BESS, abstaining from any grid-supplied power. Figure 17 and Figure 18 depict the power contributions from the PV system and the BESS to the grid, with the graphical representations clearly indicating a substantial increase in power delivery during on-peak hours.

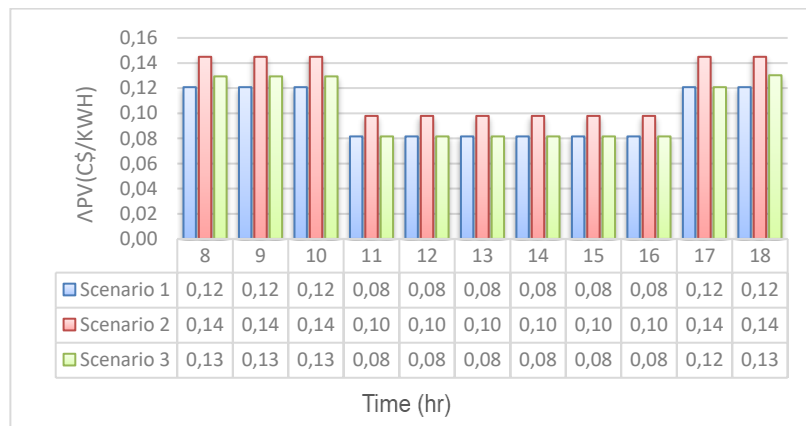


Figure 12. Variable PV cost in the baseline case.

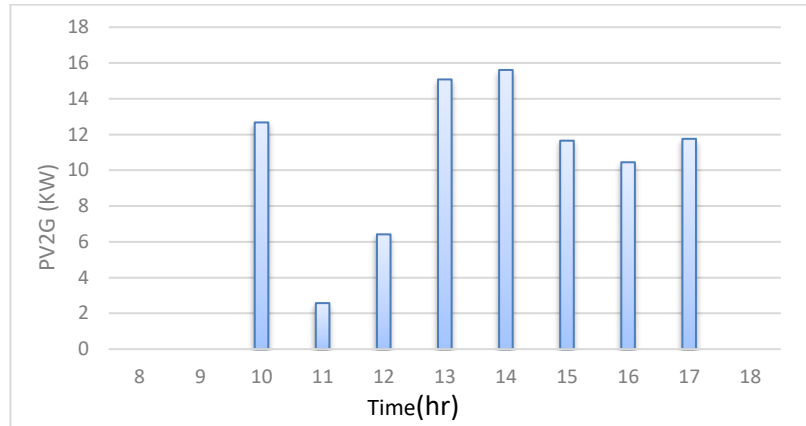


Figure 13. V2G Power in the proposed case

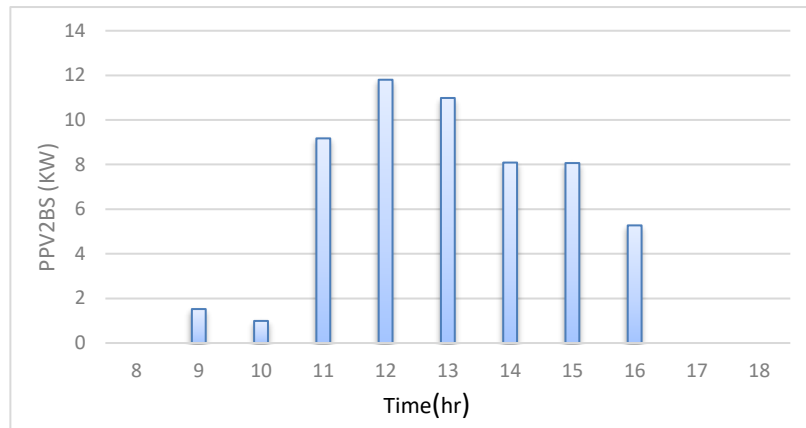


Figure 14. PV2BS Power in the proposed case

This surge in power supply from both the PV system and the BESS underscores their critical role in supporting grid demand during periods of heightened electrical load, thereby enhancing overall system stability and efficiency. Figure 19, Figure 20, and Figure 21 present the variation in energy prices for the grid, EVs, and PV systems, respectively. These figures highlight how pricing dynamically adjusts in response to system demands and operational strategies. The observed price trends demonstrate a coordinated movement across all energy agents, reflecting the transition towards a more cooperative energy management framework. In this cooperative model, price signals are aligned in such a way that no single entity experiences extreme costs or gains. Instead, all players operate under moderate pricing conditions, which facilitates fair cost and benefit distribution.

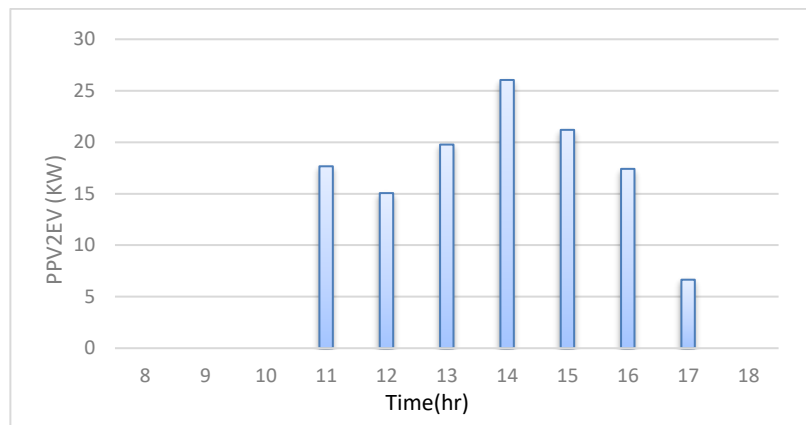


Figure 15. PV2EV Power in the proposed case

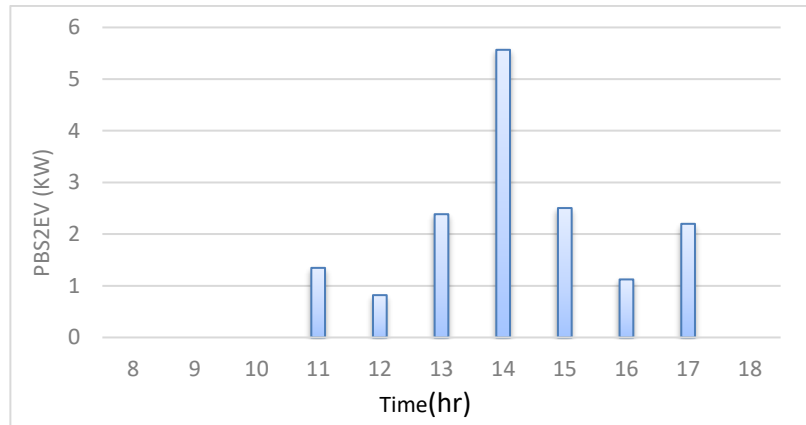


Figure 16. BS2EV Power in the proposed case

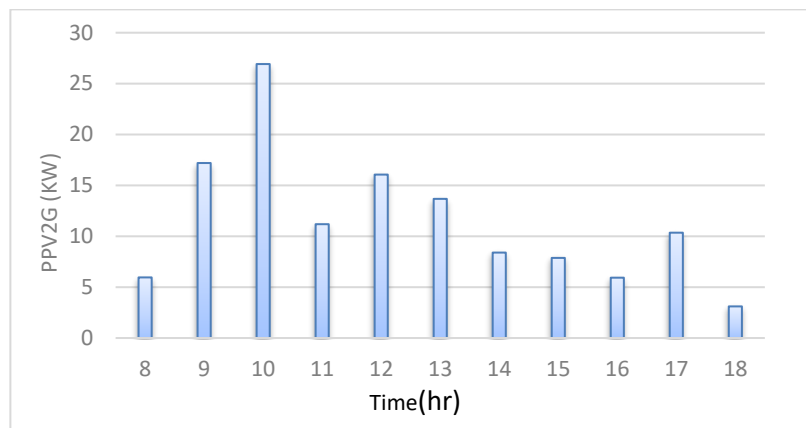


Figure 17. PV2G Power in the proposed case

The grid benefits from stabilized procurement costs, PV systems achieve consistent revenue streams, and EVs are charged at reasonable rates. This balance ensures that each participant's objectives are partially satisfied without undermining the performance of others. *Table 4* also presents a comparative analysis of costs with and without the Nash equilibrium. The data clearly show that, under the Nash framework, all costs are maintained within a moderate range between the minimum and maximum observed values. This confirms the role of Nash-based optimization in preventing extreme price fluctuations and fostering a more balanced and cooperative market environment. Ultimately, the system moves toward an equilibrium where the pricing structure encourages collaboration over competition. By aligning incentives and maintaining equitable cost levels, the cooperative framework enhances system-wide efficiency and ensures sustainable energy trading among the grid, PV systems, and EVs.

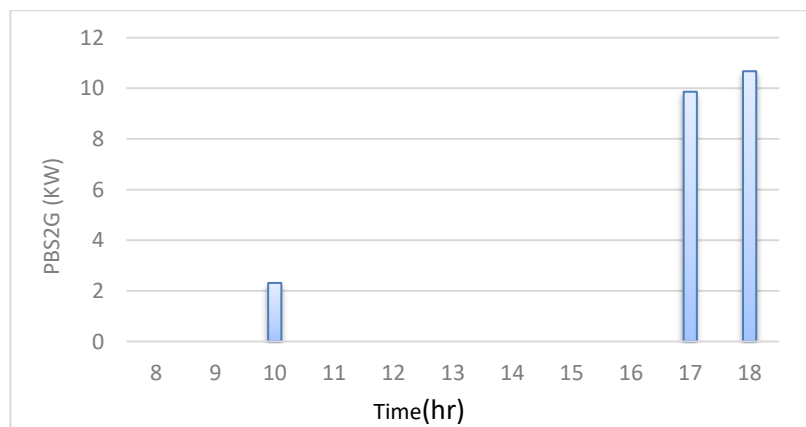


Figure 18. BS2G Power in the proposed case

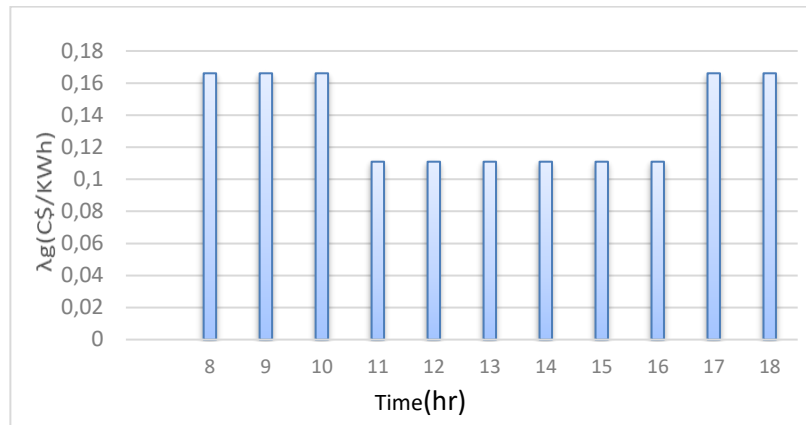


Figure 19. Variable grid cost in the proposed case

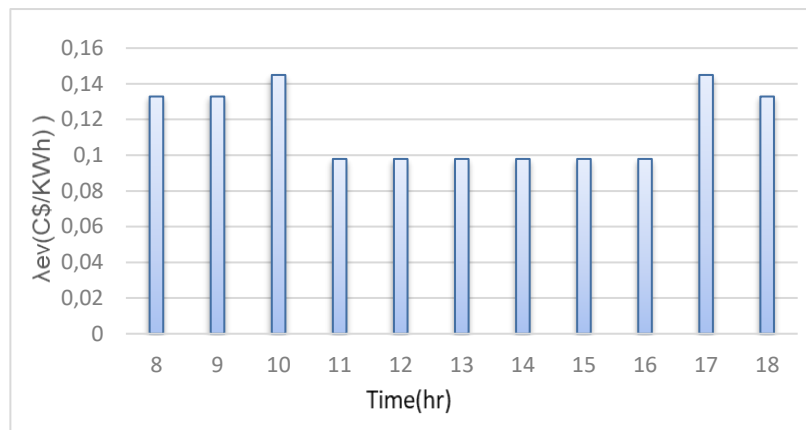


Figure 20. Variable EV cost in the proposed case

Table 4. Cost Comparison With and Without Nash Equilibrium

	Conventional models without utilizing Nash		Proposed model after utilizing Nash
	Min	Max	
Grid (Cg)	5	17.25	11.4
PV (Cpv)	-13.4	33.2	1.3
EV (Cev)	8.8	13.9	9

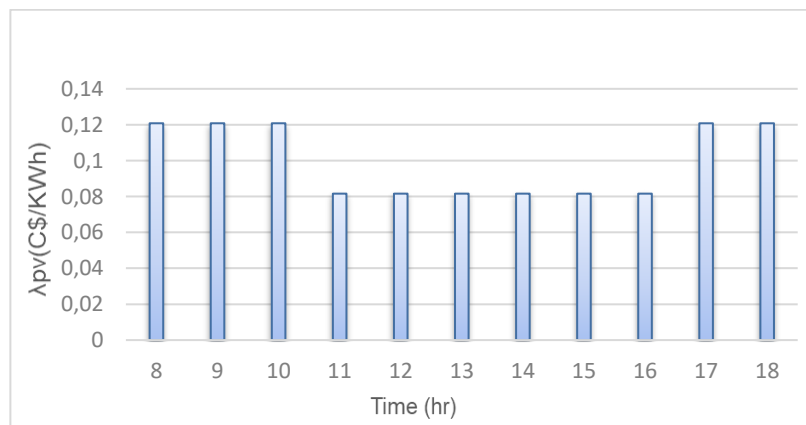


Figure 21 Variable PV cost in the proposed case

6. POLICY AND REGULATORY IMPLICATIONS

The technical results show that P2P TE can work in a commercial parking lot. Nevertheless, these decentralized energy trading methods are not yet supported by the regulatory environment in many regions. It is necessary to navigate and maybe change current policies in order to implement a TE system with EVs, PV, and BESS in practice. Main policy and regulatory obstacles to peer-to-peer energy trading systems are discussed in this section, along with how future regulatory changes may facilitate the model's broader implementation.

REGULATORY OBSTACLES FOR PEER-TO-PEER ENERGY TRADING: Current electricity markets and regulations were mainly designed for a centralized system in which consumers receive energy from large utility generators. Rooftop PV and other distributed generation typically sell back to the grid through tightly regulated programs like feed-in tariffs or net metering. P2P transactions between consumers or prosumers are frequently banned by current regulations or fall into a gray area [25]. Among the primary regulatory obstacles are:

- **Market Structure and Licensing:** Only authorized utilities or suppliers are permitted to sell power in many areas. Allowing prosumers to sell energy directly could require creating new market participant categories or changing licensing rules. Regulators need to clarify how P2P sellers and buyers are classified, like mini-retailers or energy exchanges, and ensure they meet market operation standards [25].

- **Tariff Design and Grid Fees:** P2P trades that happen over the public distribution network raise questions about grid usage charges and tariffs. Utilities usually recover grid maintenance costs through volumetric charges on electricity usage. If neighbors trade energy directly, it's unclear how much they should pay to use the wires. To guarantee that infrastructure expenses are distributed equitably and to prevent cost-shifting to non-participants, new tariff structures, such as localized network fees or transaction fees, may be required [26].

- **Consumer Protection:** Energy trading can be complicated for regular consumers. Regulators must ensure that P2P energy marketplaces have protections against fraud, errors, and high prices. This includes clear rules for contracts, billing, and dispute resolution. Participants should have access to their data and be protected by privacy laws, since detailed usage data will be exchanged in a TE system [27].

- **Cybersecurity and Data Standards:** The implementation of TE often relies on advanced metering, real-time data exchange, and sometimes blockchain or other IT platforms. Ensuring the privacy of user data and the cybersecurity of the trading platform is vital. Regulations may need to establish guidelines for data handling and require certain cybersecurity measures for approved P2P trading platforms [28].

In many areas, regulators are already testing sandbox programs and pilot projects that allow limited P2P energy trading to evaluate its impact before making permanent rule changes. For example, in some U.S. states and European countries, experimental licenses have been granted for community energy trading or microgrids where participants can trade energy within a neighborhood. These initiatives help inform long-term policy by identifying what rules can be adapted or relaxed [29].

P2P energy trading and TE frameworks offer significant benefits for enhancing grid resilience, improving energy efficiency, and empowering consumers to become more active participants in the energy system. Recognizing this, policymakers are becoming more concerned about enabling these innovations. To advance P2P trade, governmental frameworks must change as the market does, according to [30]. In order to facilitate two-way power flows at the distribution level, they suggest redefining participant responsibilities, creating guidelines for peer transaction measurement and settlement, and revising interconnection rules.

This study shows how Nash-based coordination effectively balanced costs across the grid, EVs, and PV/ESS participants. It demonstrates that, with proper design, P2P energy systems may offer both efficiency and fairness. However, the successful integration of P2P energy trading will depend not only on technology but also on adaptable and innovative regulations. To create safe, inclusive, and scalable market frameworks, cooperation between regulators, researchers, and innovators will be crucial.

7. CONCLUSION

This study has rigorously demonstrated the effectiveness of a Nash equilibrium-based TE framework in optimizing the economic and operational performance of a system integrating the utility grid, EVs, battery energy storage systems (BESS), and photovoltaic (PV) systems. Through a detailed numerical analysis utilizing a non-linear Programming (NLP) model implemented in the General Algebraic Modeling System

(GAMS) over a 24-hour operational cycle, the proposed methodology has been validated against a baseline case comprising three independent, single-objective optimization scenarios. The baseline analysis revealed the limitations of isolated cost minimization strategies—where optimizing the grid, PV systems, or EVs individually resulted in significant economic penalties for non-targeted stakeholders, unless underscoring the need for a cooperative approach. The introduction of the Nash equilibrium-based model marks a paradigm shift, achieving a balanced and equitable distribution of benefits across all participants. The cooperative framework results in several notable benefits: EVs transition from grid dependence to become net energy suppliers through V2G transactions; the PV and BESS units play a strategic role in meeting peak grid demand; and all players operate within a moderate pricing band, avoiding extreme costs or losses. Comparative cost analyses, as presented in **Error! Reference source not found.**, confirm that Nash-based optimization maintains costs within the cost boundaries and fosters a cooperative market environment. These outcomes highlight the model's ability to achieve a system-wide win-win equilibrium where no single agent is disadvantaged. The findings underscore the viability and importance of adopting Nash equilibrium strategies in TE systems. By promoting fair resource allocation and economic collaboration, the model enhances operational efficiency, supports grid stability, and sets the foundation for a more resilient and sustainable energy ecosystem.

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