Designing a Peer-to-Peer Energy Trading Market to Improve Prosumer Participation in a Community: A Numerical Case Study

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***Abstract*—Peer-to-peer (P2P) energy trading has emerged as a transformative approach to electrical power distribution, empowering individuals and communities to directly exchange energy resources within local networks. Challenges arise in modeling the behavior of prosumers (market participants who can both buy and sell electricity). Understanding how prosumers interact in the market is crucial for determining prices and the feasibility of energy transactions. Their decisions to buy or sell energy depend on various factors, which influence market dynamics and the overall success of P2P energy trading. This paper proposes a trilevel framework for buyers who determine their purchase quantities and the fraction of power to purchase from each seller. Sellers determine the prices that maximize profit based on the buyer's demand. A numerical case study involving five prosumers – two sellers and three buyers – is presented and results in an equilibrium state for prosumer transactions in this P2P energy trading market. The trilevel approach successfully balances supply and demand in the P2P energy market where the sellers maximize revenue by adjusting prices and buyers meeting their energy demands.**

***Index Terms*—Peer to Peer Energy Trading, Prosumer, Trilevel Problem, Algorithms, Electricity Market**

I. Introduction

In recent years, the concept of Peer-to-Peer (P2P) energy trading has emerged as an opportunity for electric power distribution. This market structure allows consumers and prosumers, i.e., participants who can buy and sell electricity, to engage in direct transactions using Distributed Energy Resources (DERs), such as rooftop solar, to supply local communities without the need of an intermediary [1]. Despite its potential, P2P energy trading markets face several challenges, including lack of incentive-based market participation and challenges integrating with existing grid infrastructure [2]. Additionally, the variability and unpredictability of renewable energy sources pose challenges in maintaining a reliable energy supply [3]. Thus, developing robust algorithms and market mechanisms to efficiently match supply and demand is critical for the success of P2P energy trading markets. Additionally, the success of these market structures may depend on the market and algorithm design.

The methodology presented in this paper extends concepts from [4]. The Evolutionary Game Theory model in this work discusses how decision-making strategies evolve in a population (a group of prosumers) based on their relative success of buying and selling power. This work extends this model by using a trilevel approach to depict the calculation for the fraction of power sold by each seller to each buyer. In the first level, buyers maximize their welfare from power consumption by strategically selecting power quantities and allocating purchases among sellers to minimize costs. The second level is designed using a game-theoretic framework to analyze strategic interactions between consumers and prosumers. The fraction of power that a buyer will purchase from a seller is found in the second level problem. The third level maximizes a seller's welfare to determine their profit by determining prices in response to the demand from the buyers.

The extended model of the welfare function describes the coupling between buyers' demands and sellers' power allocations. The paper also develops an iterative approach to finding the best response to the buyers' demands and sellers' prices that reflect various conditions such as preference of power amounts that influence the prosumers' strategies. Lastly, a numerical case study is presented using five prosumers to demonstrate the implementation of solving a trilevel problem. The case study variants provide an analysis of participant behaviors in a P2P energy trading market. The methodology seeks to demonstrate the financial benefits for prosumers through optimized trading strategies by increasing their revenue from surplus energy.

The remainder of this paper is organized as follows. Section II presents a literature review and describes this paper's contributions. Section III introduces the market model and associated notation that is considered in this paper. Section IV presents the proposed trilevel model for prosumer strategies in this P2P Energy Trading market. Additionally, the algorithms are discussed in this section. Section V discusses a five prosumer numerical case study and the results of the evolutionary algorithms. Finally, Section VI concludes the paper and outlines direction for future research.

II. Literature Review and Contributions

A. Literature Review

A range of studies have explored the allocation of supply and demand in P2P Energy Trading. Long et al. is one of the earlier P2P energy trading works that involves three market paradigms: bill sharing, mid-market rate, and auction-based pricing strategies [5]. This work provides detailed business models, local energy exchange prices, and quantified individual customer's energy costs, validated through examples in a residential community microgrid with PV systems. Paudel et al. focused on price and seller selection competition using evolutionary and Stackelberg game theory [4]. Long et al. incorporated the Shapley value to address conflicting prosumer interests and promote cooperation [6].

In Malik et al., this work is extended by introducing a cooperative game theory framework to maximize the total profit of the coalition in a P2P energy trading mechanism [7]. Tushar et al. proposed a P2P energy trading scheme based on a canonical coalition game, which was shown to be consumer-centric and sustainable [8]. Finally, Zhang et al. emphasized the potential of P2P energy trading to improve the local balance of energy generation and consumption, and to facilitate this balance through the increased diversity of generation and load profiles [9]. Overall, these studies demonstrate that P2P energy trading can bring both economic and technical benefits to participants while improving local energy balance. These studies collectively highlight the potential of game theory in addressing the complexities of P2P energy trading.

B. Contributions

This paper provides several contributions to the study of P2P energy trading markets:

- The paper formulates a trilevel problem that addresses prosumer interactions in P2P markets, accounting for decentralized decision-making and the influence of market rules on prosumer behavior.
- A numerical case study is presented, enhancing the transparency of P2P transactions and demonstrating the implementation of the proposed framework.

These contributions advance the understanding of P2P markets and provide guidance for P2P market design and operation.

III. Prosumer and P2P Market Formulation

A. General Description of a P2P Market Community

In this study, each prosumer within the community system is equipped with a photovoltaic (PV) generation system. The prosumers are assumed to be interconnected through bidirectional power and communication infrastructures, allowing for energy exchange and information flow. It is also assumed that prosumers operate in a decentralized market, making decisions and transactions without the need for a central operator. Given that the prosumers are geographically close and the amount of energy traded in the P2P market is relatively small, we consider distribution and transmission losses, as well as transmission costs, to be negligible. While this paper focuses on the P2P energy trading market algorithms, detailed discussions on the communication systems, battery energy storage systems, smart meters, and physical infrastructures within the community are beyond its scope.

B. Prosumer Notation

Let the set of prosumers in the P2P energy trading market be $\mathcal{N} = \{1, 2, \ldots, n\}$, where n is the number of prosumers. Define B as the set of buyers, i, where $i \in B$. Similarly, let S be the set of sellers, j, where $j \in S$. The set of all prosumers is the union of buyers and sellers. The model represents a single time period during which each prosumer knows the outputs of their PV generator. We collect these PV generator outputs in the vector G:

$$G = \begin{bmatrix} G_1 & G_2 & \ldots & G_n \end{bmatrix}^T. \tag{1}$$

In this P2P energy trading market, prosumers utilize a quadratic utility function to evaluate their purchasing decisions. This utility function serves to quantify the satisfaction gained from purchasing sufficient power, ensuring that buyers achieve maximum utility from their transactions. Designing the utility function as a quadratic captures the diminishing returns on utility as buyers purchase larger quantities of energy. For prosumer $i \in \mathcal{N}$, the utility function $u_i(x_i)$ is defined as:

$$u_i(x_i) = \lambda_i x_i - \frac{1}{2}\theta_i x_i^2, \quad x_i \geq x_{i,min}, \tag{2}$$

where x_i is the amount of power consumed and the constants λ_i and θ_i are associated with the prosumer's behavior and preferences for using power. The parameter λ_i is the prosumer's preference characteristic for power consumption. As the value of λ_i for a buyer, $i \in B$, becomes larger, they will prefer to receive a larger amount of power from sellers in the P2P energy trading market. The parameter $x_{i,min}$ ensures that buyers cannot request negative power, thereby preventing unrealistic energy demands.

The prosumers seek to maximize their welfare functions in order to balance their desire for consuming power with financial considerations. Additionally, prosumers who are classified as buyers will have a level of self-consumption. The welfare function, $W_i(x_i, \gamma_j)$, of buyer i is:

$$W_i = \lambda_i(G_i + \sum_{j=1}^{J} x_{i,j}) - \frac{1}{2}\theta_n(G_i + \sum_{j=1}^{J} x_{i,j})^2 - \sum_{j=1}^{J} \gamma_j \pi_j x_{i,j}, \tag{3}$$

where π_j is the price decided by seller j. The variable γ_j is the fraction of power that buyer i is seeking to purchase from seller j. According to these definitions, we note that $0 \leq \gamma_j \leq 1$ and $\sum_{j=1}^{J} \gamma_j = 1$. We also define $x_{i,j} = \gamma_j x_i$.

IV. Proposed Method

A. Trilevel Problem

In this problem formulation, the first level of the problem framework focuses on a prosumer who is modeled as a buyer, i, that is maximizing their welfare (happiness) by determining the amount of power to demand from the sellers, $j \in S$. In the second level of the problem, the objective of a buyer, i, is to determine the value of γ_j, the fraction of power buyers are seeking from sellers, $j \in S$. The third level of the problem involves a seller, j, seeking to maximize their individual welfare (profit) by determining a price for the power demanded by buyers, $i \in B$. This can be represented by:

$$x_i^* = argmax(W_i(x_i, \gamma_j^*, \pi_j^*)) \tag{4}$$

s.t:

$$x_i \geq x_{i,min}. \tag{5}$$

$$\gamma_j^* = argmax(W_i(x_i^*, \gamma_j, \pi_j^*)) \tag{6}$$

s.t:

$$0 \leq \gamma_j \leq 1, \tag{7}$$

$$\sum_{j=1}^{J} \gamma_j = 1. \tag{8}$$

$$\pi_j^* = argmax(W_j(x_i^*, \gamma_j^*, \pi_j)) \tag{9}$$

s.t:

$$\pi_j \geq \pi_{j,min}. \tag{10}$$

The solution of the upper-level problem is:

$$x_i = \frac{\lambda_i - \sum_{j=1}^{J} \pi_j^t \gamma_j^t - \theta_i G_i}{\theta_i}. \tag{11}$$

The third level problem is represented by (9). The value of γ_j is determined by matching the buyer with the most inexpensive seller, ensuring the most cost-effective energy trades occur first. By optimizing these interactions, the equilibrium solution ensures that the buyers' demand for power is met in a cost-effective manner, reflecting their preferences and enhancing the overall efficiency of the P2P energy trading market.

B. Algorithm One: A Buyers' Game

Two algorithms are used in this paper to show the efficiency and effectiveness of P2P energy trading markets. These algorithms are designed to iteratively find equilibrium states for the amount of power the buyers will buy (x_i) and how the buyers will distribute their purchases among the sellers (γ_j), and the sellers' prices (π_j).

In the buyer's algorithm, a prosumer is modeled as a buyer within the P2P energy trading market. This algorithm receives an energy price π_j from the sellers and begins with an initial fraction of power buyers will buy from each seller γ. This algorithm evaluates (11) to determine their optimal demand for power.

From this strategic interaction, buyers can adjust the γ_j by ϵ, a tuning parameter that represents a shift in the amount of power they wish to buy from each seller:

$$\gamma_j^* = \frac{\gamma_j}{\gamma_j + \epsilon}. \tag{12}$$

These values are adjusted while the price is fixed, allowing the focus to be on optimizing the power allocation based on buyer-seller interactions. The details of the buyers' algorithm are shown below.

Algorithm 1 A Buyer's Game

```
Input: Price Vector π = [π_1, π_2, ..., π_S] and Initial
  Fraction of Purchased Power, γ = [γ_1, γ_2, ..., γ_S]
Output: Optimal response based upon (11) and (12)
ϵ = 1 × 10^-6
k = 0;
while true do
    Compute x_i^* according to (4), ∀i ∈ B
    Increment γ_j according to (12)
    if |γ_{j+1} − γ_j| < ϵ then
        Break
    end if
end while
```

C. Algorithm Two: Sellers' Stackelberg Game

Algorithm 2 represents the role of a prosumer who is modeled as a seller. A seller engages in a Stackelberg game where they are leading by setting the prices. After receiving the amounts of power ($x_{i,j}$) to be purchased from each seller from Algorithm 1, the sellers use Algorithm 2 to adjust their prices according to (13) and increase their profit. This involves determining a competitive price for the electricity being sold in the P2P market. The algorithm evaluates how different price points affect the quantity of electricity sold and adjusts prices to maximize the sellers' revenue. By iterating this process and leveraging the results from Algorithm 1, Algorithm 2 iteratively adjusts the prices until convergence is achieved. The price updating strategy is given by:

$$\pi_j(l+1) = \pi_j(l) - \epsilon \left[P_{ex,j} - \sum_{i=1}^{J} x_{i,j}^* \right]. \tag{13}$$

Sellers aim to set prices that maximize their revenue. Once convergence is reached, the optimized price variables are fed back into Algorithm 1 to iteratively refine the optimal strategies for both buyers and sellers. This bidirectional interaction between pricing optimization and strategy refinement facilitates the achievement of efficient outcomes in the P2P energy trading system.

Algorithm 2 A Seller's Game

```
Input: Buyer's Demand Vector x* = [x_1, x_2, ..., x_B] and
  Fraction of Purchased Power, γ* = [γ_1, γ_2, ..., γ_J]
Output: Optimal Response based upon (13), the Updated
  Price Vector π = [π_1, π_2, ..., π_J]
Compute Σ_{i=1}^{J} x_{i,j}^* γ_j^*
Compute (13), ∀i ∈ B
```

V. Numerical Case Study

A. Overview of Case Study

This section details the results of a case study with four variants using different parameter values to evaluate the efficiency of the proposed P2P energy trading market variants using the buyers' and sellers' algorithms within a trilevel framework for a prosumer-based community. The study considers five prosumers – three buyers and two sellers. Here, the buyers are represented by prosumers 1, 2, and 4. Prosumers 3 and 5 are sellers. This market structure has been determined by the prosumers' λ and θ characteristics defined for the individual preferences for determining the buyer's utility function values. The generation and load profiles for these prosumers were chosen to illustrate the algorithms' behavior.

Each prosumer is equipped with a solar PV system. This simulation determines an equilibrium state for the trading interactions regarding the optimal power demand in (11) and price adjustments in (13). The study shows how the P2P market framework effectively balances supply and demand, optimizing energy distribution and market efficiency.

The following initializations and parameters are used in this case study: $\pi_{init,j}$, the initial price of power announced by a seller j, and $\gamma_{init,j}$, the initial fraction of power, in kW, purchased by each buyer i from each seller j. Here, it is assumed that the initialization of γ_j for each seller is uniform and abides by (7) and (8). The other parameters used in finding the equilibrium states of the buyers and sellers algorithms are prosumer generation, G and surplus power, $P_{export,j}$, of seller, j. The differences in the initialization of λ_i throughout the test case variants affect the outcomes of x_i^* and π_j^*. This initial result highlights the sensitivity of the model and needs further investigation.

B. Buyers' Algorithm Test Cases 1 and 2

In the buyers' algorithm test cases, the goal is to illustrate straightforward examples where buyers observe fixed prices and choose to purchase their power from the seller offering the lowest price. These tests define an initial value of the parameter $\gamma_{init,j}$, which represents the fraction of power that buyers purchase from sellers. For simplicity, the values for prosumers 3 and 5 (sellers) are set to $\gamma_{init,3} = 0.50$ and $\gamma_{init,5} = 0.50$. As a reminder, these values abide by (8). Therefore, prosumers 1, 2, and 4 (buyers) are initially seeking to receive 50% from prosumer 3 and 50% from prosumer 5.

As the value of λ_i for a buyer, $i \in B$, becomes larger, they will prefer to receive a larger amount of power from sellers in the P2P energy trading market. In Table I, it is evident that prosumer 1 (buyer) prefers to purchase more power than prosumers 2 and 4 (buyers). As mentioned earlier, the sellers' prices, $\pi_{fixed,j}$ are fixed in test cases 1 and 2. These prices are fixed to only observe the decision-making process of the buyers in absence of the sellers changing their prices based upon the buyers' demand.

Furthermore, if the initialization state of gamma was set to different values, the same outcome is expected in the execution of the buyers' algorithm. In test case 2, the values for prosumers 3 and 5 (sellers) are set to $\gamma_{init,3} = 0.10$ and $\gamma_{init,5} = 0.90$. Here, prosumers 1,2, and 4 (buyers) are initially seeking 90% from the more expensive option offered by prosumer 5 at $\pi_{fixed,j} = 0.05\$/kW$. The execution of the buyers' algorithm dynamically adjusts the purchasing strategies of the buyers based on the fixed prices among sellers.

TABLE I
DATA IN BUYERS' ALGORITHM TEST CASE 1

Variables	Units	P1	P2	P3	P4	P5
$\pi_{fixed,j}$	\$/kW	0	0	0.01	0	0.05
$\gamma_{init,j}$	unit less	0	0	0.50	0	0.50
$P_{export,j}$	kW	0	0	4.0	0	3.0
G_i	kW	2	3	10	3	10
λ_i	\$/kW	7	6	5	6	5
θ_i	$\$/kW^2$	0.5	0.5	0.5	0.5	0.5

TABLE II
EQUILIBRIUM STATES FOR BUYERS' ALGORITHM TEST CASE 1

Variables	Units	P1	P2	P3	P4	P5
x^*	kW	11.980	8.980	0	8.980	0
γ^*	unit less	0	0	0.9999	0	0.0001
π^*	\$/kW	0	0	0.01	0	0.05

The value of prosumer 3 (seller), γ_3, gradually increases from the initial value of $\gamma_{init,3} = 0.10$ to reach an equilibrium value close to 1. This indicates that prosumers 1, 2, and 4 (buyers) are seeking 100% of their power demand from prosumer 3 who represents the lowest price in the P2P energy trading market variant. The value of prosumer 5 (seller), γ_5 shows a gradual decrease from $\gamma_{init,5} = 0.90$ to an equilibrium near zero, due to possessing a higher fixed price.

TABLE III
DATA IN BUYERS' ALGORITHM TEST CASE 2 FOR A P2P ENERGY TRADING MARKET SCENARIO

Variables	Units	P1	P2	P3	P4	P5
$\pi_{fixed,j}$	\$/kW	0	0	0.01	0	0.05
$\gamma_{init,j}$	unit less	0	0	0.10	0	0.90
$P_{export,j}$	kW	0	0	4.0	0	3.0
G_i	kW	2	3	10	3	10
λ_i	\$/kW	7	6	5	6	5
θ_i	$\$/kW^2$	0.5	0.5	0.5	0.5	0.5

TABLE IV
EQUILIBRIUM STATES FOR BUYERS' ALGORITHM TEST CASE 2 IN A P2P ENERGY TRADING MARKET SCENARIO

Variables	Units	P1	P2	P3	P4	P5
x^*	kW	11.980	8.980	0	8.980	0
γ^*	unit less	0	0	0.9999	0	0.0001
π^*	\$/kW	0	0	0.01	0	0.05

By demonstrating that buyers will gradually select the least expensive energy options, the buyers' algorithm effectively identifies the optimal γ_j^* value, ensuring cost-efficiency in the purchasing process when the sellers' prices are fixed. In the next subsection, the significance of finding this γ_j^* value lies in its ability to capture the market dynamics, showing how price competition among sellers will influences buyers' behavior in the next test cases where the sellers' prices will not be fixed in the simulation.

C. Test Cases 3 and 4 for Buyers' and Sellers' Algorithms

In order to study the equilibrium states of the buyers' and sellers' algorithms iteratively working together, test cases 3 and 4 are the same except for the difference in the initialization state, $\gamma_{init,j}$, for each case. By comparing the results of these test cases, we find that the initialization is affecting the final results. As shown Table V, the algorithms initialization values for the buyers and the sellers result in all of the buyers receiving a different fraction of power from each seller. Now, buyers 1, 2, and 4 are all receiving approximately 57% of their power from seller 3 and 43% from seller 5.

TABLE V
DATA IN TEST CASE 3

Variables	Units	P1	P2	P3	P4	P5
$\pi_{init,j}$	\$/kW	0	0	0.01	0	0.05
$\gamma_{ini,j}$	unit less	0	0	0.50	0	0.50
$P_{export,j}$	unit less	0	0	4.0	0	3.0
G_i^t	kW	2	3	10	3	10
λ_i	\$/kW	7	6	5	6	5
θ_i	$\$/kW^2$	0.5	0.5	0.5	0.5	0.5

TABLE VI
EQUILIBRIUM STATES FOR TEST CASE 1 IN A P2P ENERGY TRADING MARKET SCENARIO

Variables	Units	P1	P2	P3	P4	P5
x^*	kW	4.333	1.333	0	1.333	0
γ^*	unit less	0	0	0.5682	0	0.4318
π^*	\$/kW	0	0	3.82	0	3.85

Test cases 3 and 4 yielded similar results in the final prices, (π_j^*) and final gamma (γ_j^*) values, indicating consistent outcomes across different scenarios. The final x_i^* values, representing the power traded between buyers and sellers, were also precise. This highlights that while the allocation of power varied slightly, the overall distribution and pricing remained stable in terms of P2P transaction decisions based upon the sellers' surplus power and buyers' preferences .

TABLE VII
DATA IN TEST CASE 2 FOR A P2P ENERGY TRADING MARKET SCENARIO

Variables	Units	P1	P2	P3	P4	P5
$\pi_{init,j}^t$	\$/kW	0	0	0.01	0	0.04
$\gamma_{ini,j}^t$	unit less	0	0	0.60	0	0.40
$P_{export,j}$	unit less	0	0	4.0	0	3.0
G_i^t	kW	2	3	10	3	10
λ_i^t	\$/kW	7	6	5	6	5
θ_i^t	$\$/kW^2$	0.5	0.5	0.5	0.5	0.5

VI. Conclusion and Future Work

This paper presented a trilevel framework for a P2P market to improve the dynamic interactions between prosumers within a community. By modeling the first level as buyers optimizing their energy purchasing strategies, and utilizing the buyers' and sellers' algorithms to improve the efficiency of matching supply and demand, the framework adapts prosumer strategies to market prices set by sellers. A numerical case study with five prosumers—two sellers and three buyers—demonstrates that the proposed model enables sellers to maximize their revenue through optimized trading strategies, while allowing buyers to efficiently meet their energy needs. The results of test cases from the buyers' algorithm and the combined approach between both algorithms illustrate convergence to equilibrium pricing and power demand. In future work, the proposed methodology in this paper can be integrated into a hybrid model for electrical distribution network. This could lead to research exploring the impacts of larger networks and varying market conditions to further validate the scalability and robustness of the proposed framework.

TABLE VIII
EQUILIBRIUM STATES FOR TEST CASE 2 IN A P2P ENERGY TRADING MARKET SCENARIO

Variables	Units	P1	P2	P3	P4	P5
x^*	kW	4.333	1.333	0	1.333	0
γ^*	unit less	0	0	0.5748	0	0.4252
π^*	\$/kW	0	0	3.84	0	3.83

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