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Framework of Transactive Energy Market Strategies for Lucrative Peer-to-Peer Energy Transactions

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Abstract: Leading to the enhancement of smart grid implementation, the peer-to-peer (P2P) energy transaction concept has grown dramatically in recent years allowing the end-users to successfully exchange their excess generation and demand in a more profitable way. This paper presents local energy market (LEM) architecture with various market strategies for P2P energy trading among a set of end-users (consumers and prosumers) in a smart residential locality. In a P2P fashion, prosumers/consumers can export/import the available generation/demand in the LEM at a profit relative to utility prices. A common portal known as the transactive energy market operator (TEMO) is introduced to manage the trading in the LEM. The goal of the TEMO is to develop a transaction agreement among P2P players by establishing a price for each transaction based on the price and trading demand provided by the participants. A few case studies on a location with ten residential P2P participants validate the performance of the proposed TEMO.

Keywords: locality energy market; market-clearing strategies; peer-to-peer energy market; renewable energy resources; transactive energy management systems

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1. Introduction

Over the last century, the traditional energy sector has been sustained by significant use of conventional power plants such as thermal, nuclear and gas. However, these plants emit massive amounts of CO_2, which have a harmful influence on the environment. Furthermore, the depletion of existing energy resources demands the search for new energy sources to fulfill the world's increasing demand [1]. Nevertheless, due to their appealing characteristics, non-conventional power sources such as solar and wind–small hydro are gaining popularity. Concurrently, these types of distributed energy resources have some disadvantages, such as very intermittent and site-specific power generation. End-users are increasingly interested in installing small-scale distributed energy resources to support their energy demands, either totally or partially [2]. Furthermore, consumers would want to install more renewable energy resources (RERs) in order to drastically minimize their reliance on the grid. As the consumer demand patterns and RER power generation are dynamic, the effective utilization of generated RER power may not be possible, resulting in inefficient investment on RER. As a result, the users look for alternative techniques to increase their earnings and to save the money. In the traditional peer-to-grid (P2G) market, the prosumers autonomously exchange their net demand (demand minus generation) with the utility at utility-defined pricing [3]. If consumer demand exceeds generation, the surplus electricity must be purchased from the utility at the utility retail price (utility selling price). If the generation of the prosumer exceeds the demand, the additional energy must be sold to the utility at the utility feed-in-tariff (FiT) (utility buying price). The FiT plan is meant to encourage the installation of RER.

However, new installations surged rapidly over a decade; in response, regulatory bodies began to dramatically reduce FiT pricing, resulting in a lengthy investment payback period for RER installations. FiT programs have been phased down in certain regions of the world, including Queensland, Australia [4]. Because of power system network operation and stability limits, electricity exported to the grid in the P2G market should not exceed the Power Injection Limit (PIL) [3]. As a result, the prosumers are looking for new business models/frameworks for the energy market to generate large returns. One such model is transactive energy, which allows for the sharing of excess generation or demand with neighboring consumers/prosumers for a higher profit than a utility. As a result, new chances to establish the peer-to-peer (P2P) market have emerged, which can balance energy and confirm more everlasting energy transactions via transmission networks [5]. Residents who have a surplus generation and can supply it to the grid (prosumers) are capable of satisfying consumer demand under this scenario [6].

As the number of prosumers grows, customers will have more options for finding the most economical solution to their needs. The most profitable approach may be identified by implementing a P2P energy transaction model along with a clear market price structure. This type of transactions technique has several advantages: effective use of demand-side resources, resulting in lower total energy consumption; reducing load from major electrical providers, which tie with consumption techniques in demand-side management (DSM) [7], resulting in lower overall prices; significant economic benefits for both types of participants (consumer and prosumer) by allowing the prosumers to generate money from their excess generation and allowing the consumers to choose the most economically advantageous version for their immediate wants. The lack of a middleman in transactions, as well as automation, improves the system's security and dependability [8]. The smart contract, which is based on blockchain technology, is one of the technologies that may deliver such a service [9].

The number of prosumers with capabilities for producing excess power is expected to grow significantly in the future. As a result, the demand and need for a new power plant for DSM should be minimized. From an economic standpoint, an end-user who has excess energy generation beyond the demand must make a profit by exporting it. At the same time, people who do not have the chance to produce their own power seek to obtain it at a low cost. To be able to negotiate on behalf of two parties, an easy, lucrative, and flexible trade system that satisfies both sides' desires is required. Furthermore, the prosumers may enhance themselves in the P2P market by using smart energy management systems and energy storage techniques. The energy management systems enable optimal energy use and delivery to other microgrid users. Energy storage devices such as batteries can preserve energy during a power interruption or when PV panels are not producing electricity, such as at night.

Numerous studies have recently been undertaken in this field of P2P energy market [10–13]. In [14], the authors developed a computational transactive market architecture for energy transaction between the prosumers and consumers in wholesale electricity markets. In this study, the price of a transaction is determined using double auctions with midpoint pricing. In each round of auctions, the Roth–Erev reinforcement learning algorithm is utilized to calculate the bidding/offering prices. In [15], the authors presented a bi-level trading framework for the prosumers who manage themselves. An independent scheduling approach that would protect users' privacy was encouraged by the inner layer. The outer layer was created to maximize the benefits obtained. A P2P energy trading architecture with four-layers was suggested in [16]. Further, the interdependence of the proposed model was investigated. In [17], the authors presented an auction-based P2P energy trading system in which both the importers and the exporters input their pricing and the best matching and prices are chosen based on their topology. Several P2P works are compared in [18–21].

In smart grid paradigm, demand response and transactive energy techniques under demand-side management are assuring more economic and operational benefits to end-users as well as utilities. Hence, the smart grid research societies of all countries are initiating more projects on DSM schemes. For instance, "*Olympic Peninsula GridWise*" project is intended to validate the transactive energy with variations in energy price for sort time scale. "*Clean Energy and Transactive Campus*" is proposed with the objective of implementation of transactive energy in large buildings with massive penetration of distributed energy resources. The operation of transactive control for smart residential buildings is validated in the "*Connected Homes*" project. Real-time demonstration of blockchain-based peer-to-peer energy trading between the prosumers is performed in "The Brooklyn microgrid". A cloud-based energy trading software platform has been demonstrated in "*TeMiX*" to meet the objective as automated power transaction. Considering solar generation-based prosumers, the peer-to-peer electricity market is implemented in "*Kealoha*". A transactive energy platform has been developed in "*PowerMatcher*" to coordinate the smart devices and power system operators. In "*EMPower*", a new locality electricity market has been proposed to improve the energy trading by advancing the role of active prosumers. A blockchain-based peer-to-peer electricity trading market has been proposed in "*Powerpeers*" for smart residential buildings. "*Share&Charge*" demonstrates the blockchain-based electricity market for electric vehicle charging. In addition to these works, projects such as "*Piclo*", "*Vandebron*", "Peer Energy Cloud" and "*Sonnen Community*" are intended to develop the energy transaction software platform for peer-to-peer energy trading between end-users and network operators.

The preceding literature did not explore the influence of prosumer's trade participation on the profit gain of the prosumer and the set of prosumers. A framework of transactive energy market operator (TEMO) is suggested in this study to enable power trading between households via a P2P energy market named local energy market (LEM). In the suggested strategy, a set of prosumers collaborates by trading their surplus generation/demand to lower the locality's grid reliance and their energy expenditures. Based on each participant's energy price and trading power, the TEMO develops a transaction agreement between them. Furthermore, various market-clearing strategies are proposed to ensure reliable and lucrative energy transactions between the participants.

The aim of the work is to suggest a suitable market-clearing strategy to have profitable energy trading in the peer-to-peer energy market. Further, the major contributions of the paper are described as given below.

- A transactive energy market operator (TEMO) framework is developed to facilitate power trading between residential buildings through a peer-to-peer energy market.
- A new local energy market with different market-clearing strategies is presented to ensure profitable power transaction between the neighboring end-users.
- The proposed trading strategies are extended to increase the market reliability by penalizing the participants for their abnormal activities in energy trading.

The structure of this article is as follows: the proposed TEMO architecture is detailed in Section 2; the mathematical modeling of the different market-clearing strategies are discussed in Section 3; the case study simulation and its results are discussed in Section 4. The conclusions are expressed in Section 5.

2. Framework of TEMO

The proposed model of multi-agent-based transactive energy market framework is expressed in Figure 1. The proposed model is made up of various autonomous agents, including the participants, a TEMO, and a utility. These actors interact, negotiate, and work with one another to attain individual and collective goals. The goal of the market participants is to minimize individual energy consumption bills, and the collective goal is to lessen the community's reliance on the grid by boosting self-consumption. In real time, the TEMO can be a component of either the distribution grid operator or the autonomous system operator [22]. The utility is a unique actor that sells and buys power at predetermined rates and is responsible for the system's reliability and security.

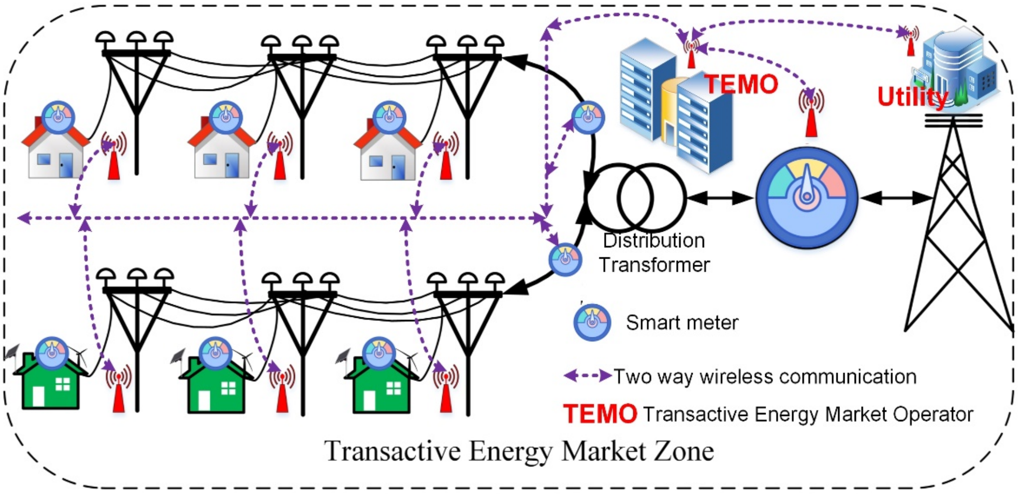


Figure 1. Architecture of proposed P2P energy market.

The TEMO collects trading information from the participants such as trading power and other pricing details prior to the start of any trading interval. The TEMO clears the LEM using an appropriate market-clearing mechanism and produces transaction agreements between the participants based on the stated data. The expected demand of any participants inside the locality for an interval t can be computed as

$$E_n^t = ED_{n,NFL}^t + ED_{n,FL}^t + ED_{n,B}^t \tag{1}$$

where n represents the participants and $n \in \mathcal{N} \triangleq [1, 2, \ldots N]$. $\mathcal{N}$ expresses the set of participants involved in P2P energy trading and N gives the maximum number of trading participants during the trading interval t. $ED_{n,NFL}^t$ represents the expected demand of non-flexible load (essential loads such as light, fan cooking appliances), $ED_{n,FL}^t$ is the expected demand of flexible load (such as washing machine, well pump) and $ED_{n,B}^t$ is the expected battery power exchange ($ED_{n,B}^t > 0$—Battery in charging mode; $ED_{n,B}^t < 0$—Battery in discharging mode). The trading power (δ_n^t) of the participant can be computed by considering the expected generation (G_n^t) from the installed in-house renewable energy resources for the same interval, which is shown in (2).

$$\delta_n^t = E_n^t - G_n^t \tag{2}$$

All the LEM participants would be interested in selling available generation at a greater price or meeting their unmet demand at a lesser price than the utility energy purchasing or selling price, respectively. To govern the LEM, the TEMO serves as a central interface in which each participant is expected to report his/her final trading power and appropriate offer (for remaining generation)/bid (for unmet demand) price. Simultaneously, the convenient market-clearing strategy is created by estimating the transaction price for the trading interval. The TEMO classifies players as importers (owing more demand) or exporters (owing more generation) based on players' final trading power. When participant's δ_n^t is higher than 0, the participant is regarded as an importer, and when δ_n^t is lower than 0, the participant is deemed as an exporter. The TEMO prefers to implement boundary constraints in the LEM in order to build a sustainable and economical energy market. Any participant's (importer/exporter) quoted trading power must fall between the predetermined minimum and maximum limitations as shown in (3).

$$\begin{aligned} \delta^t_{I,min} \le \delta^t_n \le \delta^t_{I,max} \quad & \forall n \in \mathcal{N}^t_I \\ \delta^t_{E,min} \le \left|\delta^t_n\right| \le \delta^t_{E,max} \quad & \forall n \in \mathcal{N}^t_E \end{aligned} \tag{3}$$

Where $\delta^t_{I,min}$ and $\delta^t_{I,max}$ are the minimum and maximum boundary demand limit for the importers, $\delta^t_{E,min}$ and $\delta^t_{E,max}$ are the minimum and maximum boundary generation limit for exporters, respectively. $\mathcal{N}^t_I$ and $\mathcal{N}^t_E$ are the set of the importers and exporters of an interval t, respectively. The TEMO computes the net energy demand of the considered locality using energy trading information from all the participants by subtracting the aggregated exporters' generation from the importers' demand as illustrated in (4).

$$\Gamma^t = \alpha^t - \beta^t \tag{4}$$

$$\alpha^t = \sum_{n \in \mathcal{N}^{\sqcup}_{\mathcal{I}}} \delta^t_n \tag{5}$$

$$\beta^t = \sum_{n \in \mathcal{N}^{\sqcup}_{\mathcal{E}}} \left|\delta^t_n\right| \tag{6}$$

The TEMO considers the utility as a participant in the transactive energy market since it may sell and buy energy at the same time for a prefixed bid/offer price. The electricity bill of any participant n during interval t while simply exchanging energy with the utility ($\Lambda^t_{P2G,n}$) may be determined as illustrated in (7).

$$\Lambda^t_{P2G,n} = \begin{cases} \delta^t_{P2G,n} \cdot \Delta^t_S \cdot dt & \forall n \in \mathcal{N}^t_I \\ \delta^t_{P2G,n} \cdot \Delta^t_B \cdot dt & \forall n \in \mathcal{N}^t_E \end{cases} \tag{7}$$

where Δ^t_S and Δ^t_B represent the t^{th} interval utility's energy selling and buying price, respectively. dt is the duration of the pricing interval. To have a profitable transaction via the LEM, the importers should fulfill their demand at a lower price than the utility selling price, and exporters should sell their excess generation at a higher price than the utility purchasing price. As a result, the participants in the reliable and economical energy market should have their market-clearing transaction price (λ^t) inside the utility border price, as indicated in (8).

$$\Delta^t_B < \lambda^t < \Delta^t_S \tag{8}$$

The TEMO clears the energy market based on the stated energy of individuals, benefiting all the locality participants and grids. The active participation of the LEM players contributes to the success of transactive energy systems. Furthermore, adopting appropriate market tactics for the LEM may improve the participants' interest in it. The LEM should be developed with due consideration to the participants' dynamics in consumption patterns and utility dynamics in operational parameters (selling price and buying price). In order to have a lucrative energy transaction between the participants, various market techniques are presented in the upcoming section.

3. P2P Energy Market Strategies

The objectives of the TEMO are to determine the internal market price set after receiving the net demand profiles from all the market participants and broadcast it to all the market participants. In order to promote market players to enter the competitive market, the TEMO follows various market-clearing strategies to determine the profitable internal price.

3.1. Mid-Pricing Strategy (MPS)

Consider a locality in which all the end-users are interested in participating in the LEM. Calculating net energy demand (Γ^t) as stated in (4) may be used to determine the grid dependency of the entire locality. Based upon the computed Γ^t, two substrategies shall be followed under the category of mid-pricing strategies.

3.1.1. Higher Locality Demand ($\Gamma^t > 0$)

When a locality aggregated demand exceeds its total generation, the locality becomes a utility importer. In this case, the locality should rely on the grid to fulfill the surplus demand. However, unlike utility, the LEM lets the exporters and importers trade their surplus energy generation/demand with others for a higher profit. Under this market strategy, the market-clearing price for every exporter during a trading interval t can be stated as illustrated in (9).

$$\Lambda_E^t = \frac{\Delta_S^t + \Delta_B^t}{2} \tag{9}$$

The market-clearing price for every importer (λ_I^t) during interval t shall be obtained using the computed exporter price (λ_E^t) as expressed in (10).

$$\Lambda_I^t = \frac{\left(\Gamma^t \times \Delta_S^t\right) + \left(\lambda_E^t \times \beta^t\right)}{\alpha^t} \tag{10}$$

3.1.2. Higher Locality Generation ($\Gamma^t < 0$)

When the total generation of a locality exceeds the aggregated demand of all consumers, the locality acts as an exporter to utility. In this case, the market-clearing price for each importer during a trading period t may be expressed as shown in (11).

$$\Lambda_I^t = \frac{\Delta_S^t + \Delta_B^t}{2} \tag{11}$$

The market-clearing price for every exporter during interval t shall be obtained using the computed importer price (λ_I^t) as expressed in (12).

$$\lambda_E^t = \frac{\left(\alpha^t \times \lambda_I^t\right) + \left(\Gamma^t \times \Delta_B^t\right)}{\beta^t} \tag{12}$$

The P2P trading electricity bill ($\Lambda_{P2P,n}^t$) of any participant n during interval t under MPS market may be calculated as illustrated in (13).

$$\Lambda_{P2P,n}^t = \begin{cases} \delta_{P2P,n}^t \cdot \lambda_I^t \cdot dt & \forall n \in \mathcal{N}_I^t \\ \delta_{P2P,n}^t \cdot \lambda_E^t \cdot dt & \forall n \in \mathcal{N}_E^t \end{cases} \tag{13}$$

Since the suggested technique is straightforward, the computational time for market-clearing is reduced for any number of players. Furthermore, the mid-pricing-based LEM shall be predicted effortlessly, which increases players' interest in energy trading. However, regardless of the level of contribution in locality net demand, the exporters during higher locality demand and the importers during higher locality generation earn more profit. In order to address this limitation and create lucrative transactions for all types of players, the next subsection proposes the generation-to-demand ratio (GDR)-based market-clearing technique.

3.2. GDR Strategy (GDRS)

The locality generation-to-demand ratio during an interval t may be calculated by considering the aggregated net demand of all the exporters and importers as illustrated in (14).

$$\Psi^t = \frac{\beta^t}{\alpha^t} \tag{14}$$

The computed value of Ψ^t determines the state of locality in terms of utility as an importer ($\Psi^t < 1$) or exporter ($\Psi^t > 1$). As a result, two distinct strategies are presented as part of this market-clearing approach.

3.2.1. Higher Locality Demand ($\Psi^t < 1$)

When the locality acts as an importer in terms of utility, the market-clearing price for the locality exporters (λ_E^t) and importers (λ_I^t) can be calculated as expressed in (15) and (16), respectively.

$$\lambda_E^t = \frac{\Delta_S^t + \Delta_B^t\left(1 - \Psi^t\right)}{2} \tag{15}$$

$$\lambda_I^t = \left(\lambda_E^t \times \Psi^t\right) + \left(\Delta_S^t\left(1 - \Psi^t\right)\right) \tag{16}$$

3.2.2. Higher Locality Generation ($\Psi^t > 1$)

When the computed value of Ψ^t exceeds one, the locality acts as an exporter in terms of utility, and the market-clearing prices for the importers (λ_I^t) and exporters (λ_E^t) may be determined as shown in (17) and (18), respectively.

$$\lambda_I^t = \frac{\Delta_S^t - \Delta_B^t\left(1 - \frac{1}{\Psi^t}\right)}{2} \tag{17}$$

$$\lambda_E^t = \frac{\lambda_I^t + \Delta_B^t\left(\Psi^t - 1\right)}{\Psi^t} \tag{18}$$

The participant trading electricity bill under the GDRS market can be calculated using (13). The proposed market approach will have less computation time to clear the energy market compared to MPS. Further, when compared to utility, the importers and exporters will have profitable transactions in both the cases ($\Psi^t < 0$ and $\Psi^t > 0$). However, the proposed strategy is a cooperative nature and hence the net profit of the individual players merely rely on the net demand of the locality. When the demand of the locality is much more than the generation, the importers may not attain significant economic benefit through the LEM. On the other hand, the exporters may earn less when the locality's net demand is more negative. In order to increase the profit of players by considering the aforementioned limitations, the upcoming subsection describes the double auction pricing strategy.

3.3. Double Auction Strategy (DAS)

In the P2P energy market, the double auction strategy (DAS) is employed to calculate transaction price and energy. The TEMO serves as an intermediary to oversee negotiations between the exporters and importers. Because all the exporters' offers ($\Phi_n^t, n \in \mathcal{N}_E^t$) and the importers' bids ($\Phi_n^t, n \in \mathcal{N}_I^t$) are submitted to the TEMO at the same time, no one is aware of the bids and offers of others. The TEMO categorizes the participants as importer or exporter based on their sign of net demand (δ_n^t) after obtaining the data. The TEMO arranges the offers and bids of the exporters and importers into merit orders based on offering and bidding prices. The importers' (I_1, I_2, I_3, I_4 and I_5) bids are organized in descending order, whereas exporters' (E_1, E_2, E_3, E_4 and E_5) offers are listed in ascending order as shown in Figure 2. In Figure 2, δ_{min}^t and δ_{max}^t are the minimum and maximum power limit to participate in the LEM, respectively.

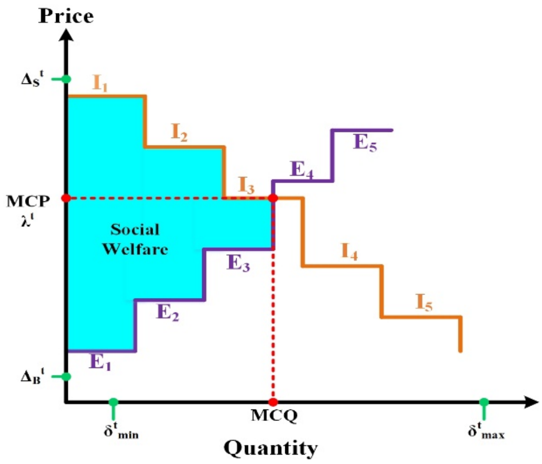


Figure 2. TEMO market-clearing mechanism using DAS.

The point of equilibrium for the P2P energy market, represented in Figure 2, is the intersection of these offers and bids that increases social welfare. Successful offers/bids are those made before the market-clearing quantity (MCQ), whereas failed offers/bids are those made after the MCQ. Social welfare of the market is defined as the region covered by successful generation and demand. The energy price at the MCQ is termed as the market-clearing price for all transactions between the importers and exporters. All the importers would give a price less than or equal to what they are willing to pay, and all the exporters would sell at a price more than or equal to what they agreed to offer. The electricity bill of the participants in the DAS-based P2P energy market shall be computed as expressed in (19).

$$\Lambda^t_{P2P,n} = \begin{cases} \delta^t_{P2P,n} \cdot \lambda^t \cdot dt & \forall n \in \begin{cases} \mathcal{N}^t_I \\ \textbf{\textit{Bids before MCQ}} \end{cases} \\ \delta^t_{P2P,n} \cdot \lambda^t_E \cdot dt & \forall n \in \begin{cases} \mathcal{N}^t_E \\ \textbf{\textit{Offers before MCQ}} \end{cases} \end{cases} \tag{19}$$

Even though the suggested DAS considerably boosts the trading return of the active players, there may be instances where the DAS fails to converge to discover optimal MCQ and MCP. Figure 3 depicts one such instance in which the importers and exporters' curves do not intersect. As a result, the importers and exporters are unable to reach an agreement on a trading price. Hence, a priority-based auction strategy is proposed in the following subsection to ensure effective trading in all scenarios.

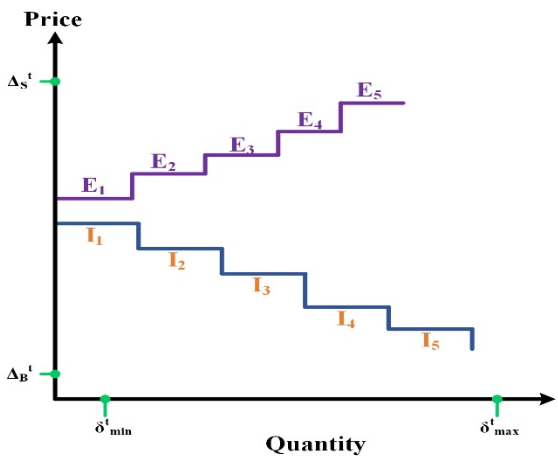


Figure 3. The DAS failure scenario.

3.4. Priority-Based Auction Strategy (PAS)

In priority-based auction strategy (PAS), the TEMO prioritizes the importers and exporters depending on the cited trading price. The highest price in the importer group and the lowest price in the exporter group are given precedence. As a result, the importer and exporter sets' lowest and highest prices receive the lowest priority. At the same time, when multiple players in each set quote the same price, the trader with the higher demand/generation takes precedence. The participants who are given high priority have more opportunities to sell or acquire excess generation or demand via the LEM. Figure 4 depicts the TEMO prioritization for the group of exporters (players: a, b, c, and d) and the group of importers (players: i, j, and k), where θ_a^t and δ_a^t are the t^{th} trading interval quoted offer price and trading generation for the exporter a, respectively.

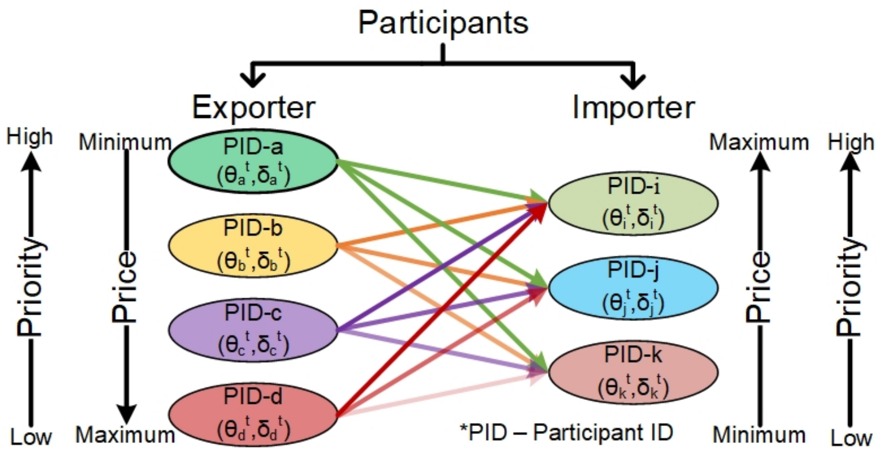


Figure 4. Prioritization of participants by TEMO.

The exchange of power between an exporter and importer is defined as a transaction. Each transaction reduces the potential trade power of both the exporter and importer. Transaction between a certain exporter/importer and other importers/exporters continues until the available trade power reaches zero. The TEMO may use an appropriate model to calculate the Price of the Transaction (PoT). In the current work, a basic mid-pricing approach is used. The PoT for a transaction between importer *i* and exporter *a* is denoted as η, which can be determined as illustrated in (20).

$$\eta_{i,\epsilon_i}^t = \eta_{a,\epsilon_a}^t = \frac{\theta_i^t + \theta_a^t}{2} \tag{20}$$

where ϵ_i represents the number of transactions carried out by the participant *i*. Based on the power traded in each transaction ($\delta_{i,\epsilon}^t$), the net transaction amount for importer participant *i* can be computed by aggregating all PoT, as stated in (21). In a similar fashion, the net transaction amount for exporter participant *a* can be computed using (22), where ϵ_a represents the number of transactions made by participant *a* and $\delta_{a,\epsilon}^t$ is the traded power during that transaction. The steps involved in PAS are depicted in Figure 5 as a flowchart.

$$\Lambda_{P2P,i}^t = \sum_{\epsilon=1}^{\epsilon_i} \left(\eta_{i,\epsilon_i}^t \cdot \delta_{i,\epsilon}^t \cdot dt \right) \tag{21}$$

$$\Lambda_{P2P,a}^t = \sum_{\epsilon=1}^{\epsilon_a} \left(\eta_{i,\epsilon_a}^t \cdot \delta_{a,\epsilon}^t \cdot dt \right) \tag{22}$$

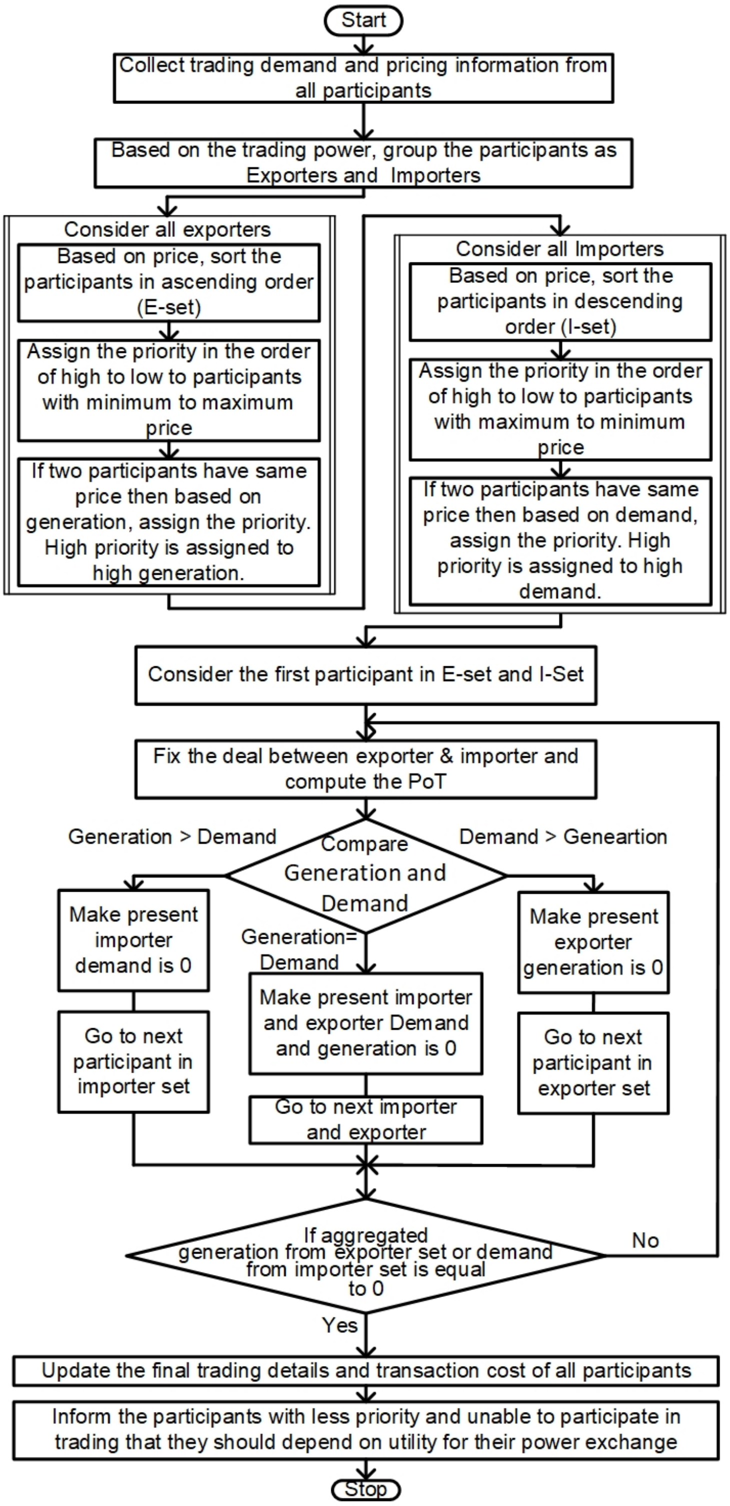


Figure 5. TEMO market-clearing mechanism flowchart using PAS.

The recommended market strategies are based on the quoted demand of the players. The individual participants' quoted demand is solely dependent on accurate renewable resources forecast and optimum scheduling of flexible loads. However, due to rapid changes in end-users' requirements, the user cannot rigorously maintain the quoted demand for all trading intervals. As a result, erroneous demand quotations may jeopardize the LEM's ability to trade lucrative demand in the TEMS. To address this issue, a violation fee is included in the computation of the participants electricity bill. The violation fee (Θ_n^t) can be computed as shown in (23). Furthermore, variations in quoted demand may cause changes in the participants' electricity bill. The difference in the electricity bill is referred to as the deviation cost, which can be calculated as given in (24).

$$\Theta_n^t = \left| \left(\delta_{A,n}^t - \delta_{Q,n}^t \right) \cdot \left(\frac{\Delta_S^t + \Delta_B^t}{2} \right) \cdot \vartheta^t \cdot dt \right| \tag{23}$$

$$\Omega_n^t = \begin{cases} \left(\delta_{A,n}^t - \delta_{Q,n}^t \right) \cdot \lambda_I^t \cdot dt; & \textbf{\textit{if}}\, 0 < \delta_{A,n}^t < \delta_{Q,n}^t \\ \left(\delta_{A,n}^t - \delta_{Q,n}^t \right) \cdot \lambda_E^t \cdot dt; & \textbf{\textit{if}}\, 0 > \delta_{A,n}^t > \delta_{Q,n}^t \\ 0 & else \end{cases} \tag{24}$$

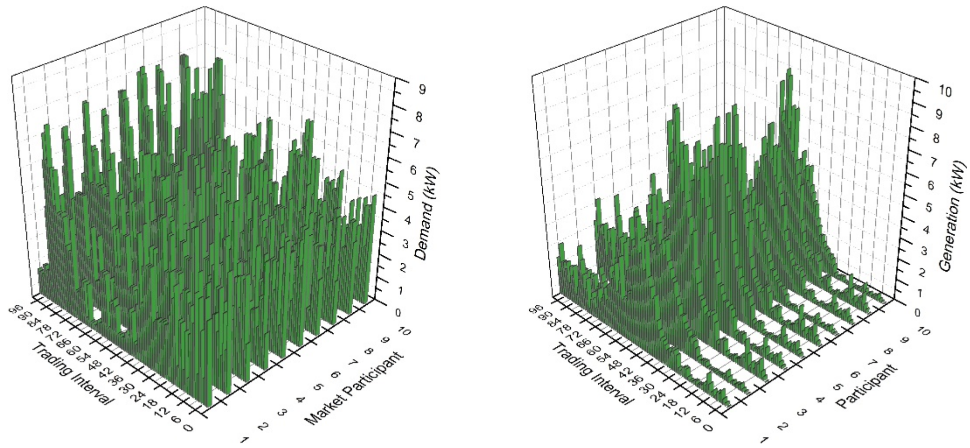
where $\delta_{A,n}^t$ and $\delta_{Q,n}^t$ are represented as the participant's actual and quoted net demands, respectively. The TEMO will decide the violation fee factor (ϑ^t) based on the dynamics of the locality. Considering the electricity bills under P2G and P2P markets, deviation cost and violation fee, the participant's net electricity bill during a trading interval may be calculated as described in (25).

$$\Lambda_n^t = \Lambda_{P2G,n}^t + \Lambda_{P2P,n}^t + \Omega_n^t + \Theta_n^t \tag{25}$$

4. Simulation Study

The recommended market strategies are compared using several case studies to highlight the importance of the TEMS in terms of participant electricity bill reductions. The considered residential locality is made up of ten prosumers who actively participate in the TEMS. Currently, residential buildings are outfitted with a plethora of sophisticated electrical and electronics appliances to make life easier [23]. The operation time of appliances varies depending on the participant. Residential users are advised to install in-house renewable energy resources to reduce their reliance on the grid and so enhance their electricity bill savings. In terms of resources, renewable energy generation via roof-top solar PV and small wind turbines is widely favored by residential users. Furthermore, people are interested in battery storage in order to lower their power expenditure by fulfilling critical demands during peak times. Because the quantity of the power generated from renewable energy resources determines the decrease in electricity bill, the prosumers may size their renewable resources and batteries by considering the space availability and cheap installation cost [24]. Considering the lengthy time span for each trading may severely affect the reliability of the peer-to-peer energy market. On the other hand, considering the narrow time span may improve consistency of the energy market. However, the computation complexity in the market-clearing mechanisms will be increased, which may ruin the energy market. Further, the end-users have manufacture-defined time limitations in the operation of flexible loads. Considering all this, the frequency of the trading ranges is fixed as 15 min.

To gain more profit via the LEM, participants need to optimally schedule the operation of appliances with due consideration to the user comfort and desire, power generation from in-house renewable energy resources and utility dynamics. Figure 6 depicts the optimal demand pattern and available generation from renewable resources throughout a day for all the participants within the considered locality. By considering the demand and generation of individual participants, the community power profile may be determined as depicted in Figure 7. Figure 8 depicts the monthly fluctuations in utility energy selling and buying prices. Figure 9 expresses the per day energy expenses of the locality participants in the P2G and P2P market paradigms. It is clear that the participants in the P2P paradigm profit economically more than those in the P2G paradigm. Further, the success and failure scenarios for the DAS-based market-clearing P2P energy market are expressed in Table 1 and Figure 10. In Case 1 (Figure 10a), the energy market is successfully cleared with the DAS technique. However, the DAS technique failed to find the market-clearing quantity and price in case 2 (Figure 10b).



(**a**) Optimal Demand (**b**) Available Generation

Figure 6. Participant's daily demand and generation pattern.

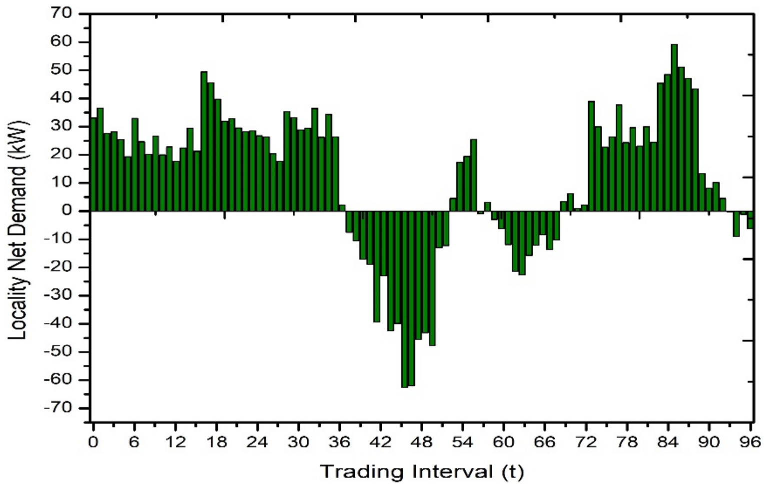
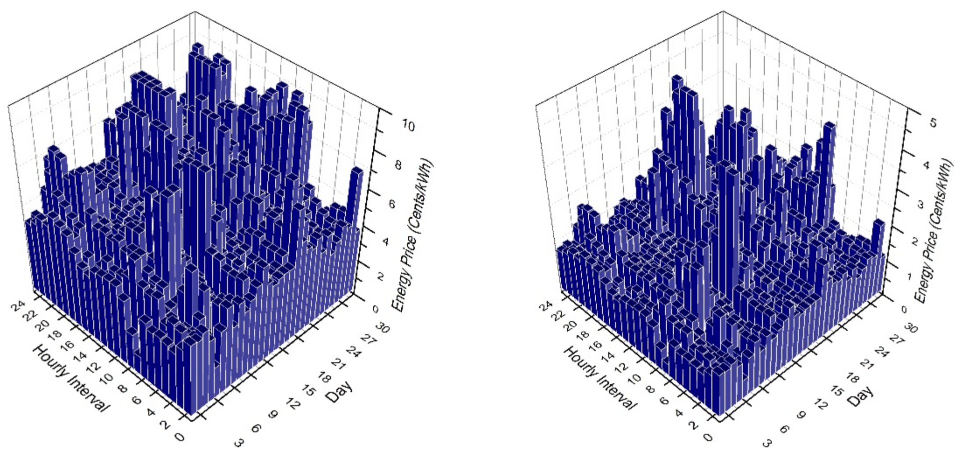


Figure 7. Participant's daily demand and generation pattern.



(**a**) Optimal Demand (**b**) Buying Price

Figure 8. Utility monthly price variations.

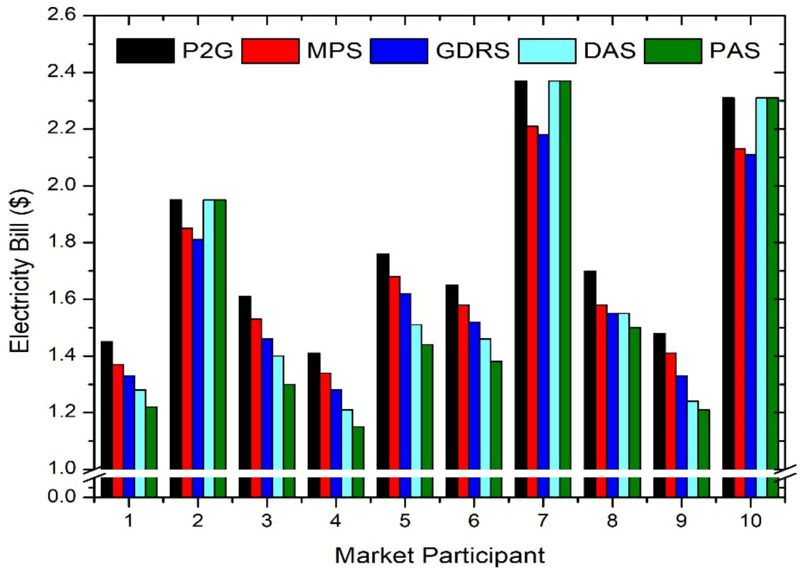
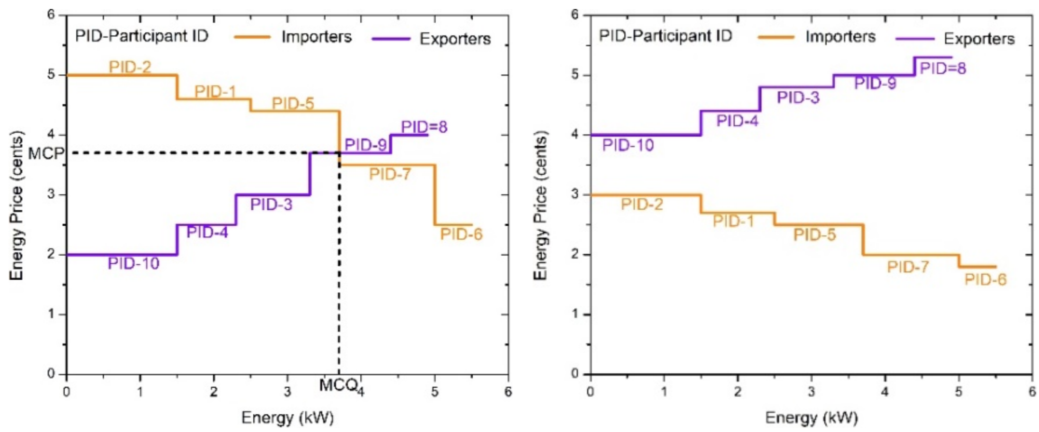


Figure 9. Participant daily electricity bill under P2G and P2P paradigms.

Table 1. Participants' quoted demand and price for P2P energy market.

Participant ID (PID)	$\delta^t_{Q,n}$ (kW)	Case 1 Θ^t_n(c)	Case 2 Θ^t_n(c)
1	1	4.6	2.7
2	1.5	5	3
3	−1	3	4.8
4	−0.8	2.5	4.4
5	1.2	4.4	2.5
6	0.5	2.5	1.8
7	1.3	3.5	2
8	−0.5	4	5.3
9	−1.1	3.5	5
10	−1.5	2	4



(**a**) DAS Case 1 (**b**) DAS Case 2

Figure 10. P2P energy market-clearing with DAS technique.

Table 2 displays the participants' monthly electricity bills for the different P2P market strategies. Table 2 also shows the participants' monthly electricity bills when no energy trading is promoted (P2G scenario) for better comparison. These findings demonstrate that the planned P2P energy trade benefits all the participants economically. According to the simulation results, the trading procedure decreases the electricity bill of all the participants in the locality as compared to when members are completely reliant on the utility.

Table 2. Participants' monthly electricity bill.

Participant	P2G	MPS		GDRS		DAS		PAS	
	Λ_n($)	Λ_n($)	S_n(%)	Λ_n($)	S_n(%)	Λ_n($)	S_n(%)	Λ_n($)	S_n(%)
1	108.8	104.25	4.19	100.49	7.64	96.93	10.91	96.21	11.58
2	110.2	105.48	4.29	101.93	7.51	98	11.08	97.13	11.87
3	93.69	84.32	10.01	87.1	7.04	83.13	11.28	80.73	13.84
4	95.95	88.12	8.17	89.27	6.97	85.92	10.46	81.59	14.97
5	95.83	86.36	9.89	88.34	7.82	84.14	12.2	82.82	13.58
6	96.24	90.77	5.69	87.94	8.63	85.29	11.38	81.61	15.21
7	112.04	107.86	3.74	102.18	8.81	97.21	13.24	94.23	15.9
8	99.23	92.51	6.78	92.36	6.93	88.42	10.9	86.93	12.4
9	94.64	89.91	5	85.61	9.55	83.86	11.4	81.27	14.13
10	111.77	107.07	4.21	103.12	7.74	100.3	10.27	96.47	13.69

Λ_n —Monthly electricity bill of participant n. S_n —Participants' percentage saving as compared to P2G.

Active involvement and precise projection of the predicted net demand increase participants' profits significantly [25]. Deviations in quoted demand, on the other hand, have a considerable impact on the electricity market. As a result, the TEMO imposed a trade agreement violation fee to control participants' changes in the quoted trading demand. To confirm this, the case study is analyzed over a trading interval with various deviations, and the associated findings for various market strategies are reported in Tables 3 and 4. The results show that the participants are penalized based on the percentage of deviance [26]. Furthermore, misleading data quotation in the energy market would have a significant detrimental influence on market-clearing characteristics such as market-clearing quantity and price. However, the participant will be heavily fined to compensate for the economic loss.

Table 3. MPS and GDRS-based penalty analysis for participants' deviations.

Participant	$\delta^t_{Q,n}$(kW)	$\delta^t_{A,n}$(kW)	Θ^t_n(c)	MPS (Cents)				GDRS (Cents)			
				$\Lambda^t_{P2P,n}$	$\Lambda^t_{P2G,n}$	Ω^t_n	Λ^t_n	$\Lambda^t_{P2P,n}$	$\Lambda^t_{P2G,n}$	Ω^t_n	Λ^t_n
1	1.5	1.7	0.21	6.6	1.08	0	7.89	6.3	1.08	0	7.59
2	−1	−0.8	0.21	−3.5	0	0	−3.29	−3.1	0	0	−2.89
3	1.5	1.5	0	6.6	0	0	6.6	6.3	0	0	6.3
4	2	2.5	0.53	8.8	2.7	0	12.03	8.4	2.7	0	11.63
5	−1.5	0.5	2.1	−5.25	2.7	5.25	4.8	−4.65	2.7	4.35	4.5
6	2.5	1.5	1.05	11	0	−4.4	7.65	10.5	0	−4.2	7.35
7	0.5	0.8	0.32	2.2	1.62	0	4.14	2.1	1.62	0	4.04
8	−2	−2	0	−7	0	0	−7	−6.2	0	0	−6.2
9	−0.5	−1.8	1.37	−1.75	−2.08	0	−2.46	−1.55	−2.08	0	−2.26
10	1	1	0	4.4	0	0	4.4	4.2	0	0	4.2

Utility parameters: $\Delta^t_S = 5.4$ cents; $\Delta^t_B = 1.6$ cents. TEMO parameter: $\vartheta^t = 0.3$. MPS-based LEM: $\lambda^t_I = 4.4$ cents; $\lambda^t_E = 3.5$ cents. GDRS-based LEM: $\lambda^t_I = 4.2$ cents; $\lambda^t_E = 3.1$ cents.

Table 4. DAS and PAS-based penalty analysis for participants' deviations.

Participant	$\delta^t_{Q,n}$ (kW)	$P^t_{Q,n}$ (c)	$\delta^t_{A,n}$ (kW)	Θ^t_n (c)	DAS (Cents)				PAS (Cents)			
					$\Lambda^t_{P2P,n}$	$\Lambda^t_{P2G,n}$	Ω^t_n	Λ^t_n	$\Lambda^t_{P2P,n}$	$\Lambda^t_{P2G,n}$	Ω^t_n	Λ^t_n
1	1.5	3.2	1.7	0.21	4.8	1.08	0	6.09	1.6	1.08	0	2.89
2	−1	3.2	−0.8	0.21	−3.2	0	0	−2.99	−3.45	0	0	−3.24
3	1.5	2.9	1.5	0	0	8.1	0	8.1	0	8.1	0	8.1
4	2	4.5	2.5	0.53	6.4	2.7	0	9.63	6.66	2.7	0	9.89
5	−1.5	2.7	0.5	2.1	−4.8	2.7	4.8	4.8	−5.175	2.7	5.175	4.8
6	2.5	4.2	1.5	1.05	8	0	−3.2	5.85	8.675	0	−3.7	6.025
7	0.5	2.5	0.8	0.32	0	4.32	0	4.64	0	4.32	0	4.64
8	−2	2.1	−2	0	−6.4	0	0	−6.4	−6.66	0	0	−6.66
9	−0.5	2.4	−1.8	1.37	−1.6	−2.88	0	−3.11	−1.65	−2.88	0	−3.16
10	1	2	1	0	0	5.4	0	5.4	0	5.4	0	5.4

Utility parameters: $\Delta^t_S = 5.4$ cents; $\Delta^t_B = 1.6$ cents. TEMO parameter: $\vartheta^t = 0.3$. DAS-based LEM: MCQ = 5 kW; MCP = 3.2 cents.

5. Conclusions

In this paper, different trading mechanisms are suggested to determine the price of each transaction between the LEM players using the proposed TEMO. The suggested techniques encourage the prosumers/consumers to actively engage in the LEM by selling/buying surplus generation/demand at a profit relative to the utility pricing. Various case studies are used to validate the suggested techniques. The simulation research findings show that, when compared to exchanging power with the grid (P2G scheme), all the LEM participants make a significant profit by implementing the proposed trading schemes. Compared to the P2G approach, the MPS technique increases the community average savings in the participants' monthly electricity bills to 6.19%. However, by using the GDRS approach, the average percentage savings has increased to 7.86%. On the other hand, dual auction strategies such as DAS and PAS improve the average percentage savings to 11.31% and 13.72%, respectively. These findings highlight the significance of transactive energy management systems in improving end-user social welfare. Furthermore, the penalty analysis for fault data injection threats enhances cyber security and reliability of P2P energy market.

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