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An Iterative Uniform-price Auction Mechanism for Peer-to-Peer Energy Trading in a Community Microgrid

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Abstract: With the rapid deployment of distributed photovoltaic (PV) systems in residential buildings, peer-to-peer (P2P) energy trading in a community microgrid is highly desired since it enables flexible and economical energy transactions among neighboring prosumers. An efficient trading mechanism is pivotal for the successful and sustainable implementation of P2P energy trading in a community microgrid. This paper proposes a novel iterative uniform-price auction (IUPA) mechanism. Depending on the comparison between the aggregated energy supply and demand, the P2P market is divided into the seller's market and the buyer's market. The proposed auction mechanism is respectively implemented in the two types of markets in order to determine a uniform trading price and an efficient energy allocation. To maximize economic benefits, competitive prosumers iteratively adjust their bids based on their own private information and the issued market information until reaching a state of Nash equilibrium. This differs from the continuous double auction (CDA) in terms of bidding formats and prosumers' trading strategies. Besides, the auction market self-adaption algorithm (AMSA) is designed for efficiently finding the equilibrium of the IUPA. Numerical studies demonstrate the effectiveness of the proposed mechanism in terms of finding fairer trading prices, saving total costs of the community, and promoting local transactions of excess PV energy.

Keywords: Community microgrid, prosumer, peer-to-peer energy trading, auction mechanism, Nash equilibrium.

1. Introduction

Environmental awareness and the reduction in installation costs of PV panels have motivated residential building owners to install PV systems. The distributed PV capacity of China reached 3.1GW in 2013 and increased to 62.63GW in 2019, corresponding to 17.47% and 30.54% of the total PV generation capacity of China [1]. Generally, the increasing penetration of non-dispatchable distributed energy into the utility grid will present challenges to the secure operation of the electric power system. In response, many countries' current energy policies advocate self-consumption of distributed PV energy [2,3]. The self-consumption depends on daily energy consumption patterns, which tends to vary among individual residents because of the differences in PV capacities, household electrical appliances, and energy usage habits. Traditional residential customers with the ability of both producing and consuming energy are now regarded as prosumers [4]. Through Feed-in Tariff (FiT) schemes, the prosumers sell their excess energy directly to the utility grid and buy energy from the utility grid in case of any energy deficit. Unfortunately, the economic benefits of prosumers via participating the FiT scheme are limited due to a continuous reduction of the tariff rates [5]. A promising way to increase the benefits of prosumers is to form a community microgrid by combining the prosumers in close proximity and enabling the mutual energy trading. In this way, the excess PV energy can be sufficiently consumed within the community microgrid. To manage the energy transactions among multiple local prosumers, the P2P model is widely introduced for its flexibility and economic benefits [6,7].

A proper trading mechanism, which determines the market's allocations of energy supply and demand with reasonable prices, is a pivotal ingredient for the success of P2P energy trading. Based on the theoretical foundation, the P2P trading mechanisms in the existing literature can be classified into three categories: bilateral contract-based mechanisms [8,9], game-theoretic-based methods [10-12], and auction-based mechanisms [13-15]. Bilateral contracts are generally designed for a fully decentralized P2P market, where prosumers can directly interact and negotiate with one another to decide the energy trading prices and quantities. For example, in [8], a bilateral energy trading contract is developed for choosing a mutually appropriate bilateral price. In [9], a bilateral contract network is proposed for P2P energy trading in real-time and forward markets. In a community-based P2P market, prosumers generally interact in a centralized way to trade their energy, which is hard to be captured by the bilateral contract-based mechanisms. Hence, the game-theoretic-based methods are widely adopted to model the decision-making process of prosumers in the community. Specifically, prosumers may behave in a collaborative manner (i.e., cooperative game) or a competitive way (i.e., noncooperative game). Ref. [10] utilizes a cooperative game to devise a P2P trading scheme which encourages sustainable prosumer participations. Ref. [11] introduces a price-incentive noncooperative game model for energy storage systems to achieve decentralized scheduling without relying on a central entity. Ref. [12] proposes a game-theoretic model for P2P energy trading in a community microgrid considering demand response and privacy of prosumers. Although the game-theoretic-based methods are quite suitable for simulating the ultimate outcome of P2P trading to evaluate the performance, they do not reveal the practical process of how prosumers interact to reach the stable equilibrium state. Therefore, double auctions (DAs) are widely applied for P2P energy trading [13,14]. The DA captures the interaction between a number of sellers and buyers to enable them to trade their energy in a step-by-step fashion [15].

The step-by-step process of the DA in P2P trading is shown as follows: 1) Buyer prosumers submit their bids to an auctioneer, and seller prosumers submit their offers to the auctioneer. 2) Bids are arranged in a decreasing order and offers are arranged in an increasing order. 3) Once bids and offers are ordered, the aggregated supply and demand curves are generated and intersected at an auction price. Buyer prosumers with bids higher than the auction price, and seller prosumers with offers lower than the auction price will eventually engage in the trading process. In other words, buyer/seller prosumers with bids lower than/offers higher than the auction price cannot trade energy in the P2P market. This implies that the total excess PV energy after self-consumption cannot be sufficiently traded within the community microgrid. Therefore, continuous double auctions (CDAs) which repeat implementing the DA for a certain number of rounds or within a prescribed time are adopted in [16,17]. Due to its great scalability and high efficiency, the CDA is viewed as a promising mechanism for distributed energy transactions. However, the pricing rule and trading strategies of the CDA have some limitations as follows, which need to be analyzed and improved.

The uniform pricing and discriminatory pricing are the most widely used pricing rules in the DA, among which the former results in a uniform clearing price, while the latter determines a separate trading price for each buyer-seller pair. Note that no matter which pricing rule is adopted, the CDA will undoubtably determine different trading prices for a series of P2P trading contracts since it repeatedly conducts the DA in an implementation. As a result, the CDA is unfair, in the sense that a buyer prosumer may pay more than other prosumers for buying the same quantity of energy. In addition, the trading prices generated by the CDA exhibit higher variation [18]. Hence, the CDA cannot perform the price discovery, which is the central function of an ideal trading mechanism and is the process of finding out a meaningful price of a given asset or commodity.

Different hypotheses about the trading strategy which determines a prosumer's bid or offer in the CDA-based market have been proposed [19-22]. These hypotheses fall into two categories with respective limitations. In the first category, the behavioral factors of prosumers are neglected. For example, a zero-intelligence trading strategy is used in [19], which assumes that prosumers are zero-intelligent and just randomly submit bids. A bidding-as-prediction trading strategy is proposed in [20], which supposes that the bids are based on the predicted average transaction price. However, ordinary prosumers want to earn profits or save costs in the P2P market, they will take the interactive relationship between their bidding behaviors and auction outcomes into consideration. In the second category, prosumers are required to have a strong learning ability. For example, Ref. [21] proposes a prediction-integrated strategy optimization model to solve the strategy optimization problem based on data-driven prediction. Ref. [22] introduces an optimal bidding strategy of residential houses based on the intraday demand response scheme. Note that prosumers in a community microgrid have higher trading frequency but lower professionalism level. In addition, the prosumers expect communication in the form that they would like to be communicated with, and in a language that they understand [23]. Therefore, if the trading strategy solved by a complex optimization model requires significant comprehension ability and computational power, the motivation for prosumers to accept the P2P energy trading at the early stage could be low.

While a multitude of mechanisms have been proposed for P2P energy trading in the existing literature, the auction-based mechanism is viewed as a promising way to enable practical interactions among multiple prosumers. Discriminatory DA [14,24], Uniform DA [13,25], and Vickrey-Clark-Groves DA [26,27] are commonly utilized in the auction-based P2P market. Note that the aforementioned auction mechanisms cannot sufficiently promote the transactions of excess PV energy in one implementation. To overcome this drawback, the CDA, which repeats implementing the DA for multiple rounds to promote P2P energy transactions, is introduced [16,17,21]. However, the CDA cannot realize a meaningful trading price that individuals both inside and outside the P2P market can use to make better consumption and investment decisions. In addition, in the CDA-based market, seldom studies consider the trading strategies which simultaneously reflect behavioral factors of prosumers and are easily to be perceived and executed by ordinary prosumers.

To bridge the knowledge gap, this paper designs a novel iterative uniform-price auction mechanism for P2P energy trading in a community microgrid. In the IUPA-based market, a community microgrid operator (CMO) is designed to administrate the P2P market by acting as an auctioneer. Prosumers are considered as self-interested identities which aim to pursue more economic benefits from P2P trading. In addition, prosumers are endowed with private information of the reservation price, i.e., the lowest acceptable selling price or the highest tolerable buying price when participating in P2P trading. Competitive prosumers iteratively adjust their bids until reaching a convergence state which determines the trading price and energy allocation. The CMO clears the market and issues market information in each iteration. Different trading scenarios are simulated and compared to demonstrate the effectiveness of the proposed P2P energy trading mechanism. In contrast with the existing literature, the prominent novelty and contribution of this paper are presented as follows:

(1) A novel iterative uniform-price auction mechanism is designed for P2P energy trading among local prosumers to sufficiently promote the transactions of excess PV energy within a community microgrid. An efficient energy allocation rule and a uniform pricing rule are proposed to ensure the fairness of P2P energy trading and perform the function of price discovery.

(2) A novel energy trading strategy which connects the private information of prosumers, the market information issued by the CMO, and the economic goals of prosumers is developed to improve the engagement of prosumers in P2P trading.

(3) The proposed auction mechanism can be formulated as a noncooperative game with incomplete information among prosumers. To efficiently solve the game, the auction market self-adaption algorithm is devised to implement the IUPA mechanism by finding a stable Nash equilibrium solution of the noncooperative game.

The reminder of this paper is organized as follows. Section 2 describes P2P energy trading structure of a community microgrid and introduces the basic models for PV prosumers. Section 3 elaborates the proposed auction mechanism and outlines the solution algorithm, followed by case studies and analysis of the results in Section 4. Section 5 concludes the paper.

2. P2P energy trading framework of community microgrid

According to the FiT schemes of many countries and cost reductions of energy storage, the typical configuration of prosumers in a community is shown in Fig. 1. Each prosumer is comprised of PV systems, energy storage systems (ESSs), loads, and smart meters. Due to the difference between energy buying and selling prices, self-consumption of PV energy is greatly encouraged. The excess energy after self-consumption is used for internal storage via ESSs or external transaction via energy trading markets.

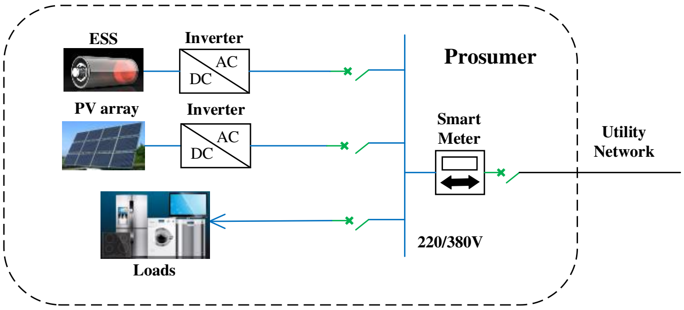
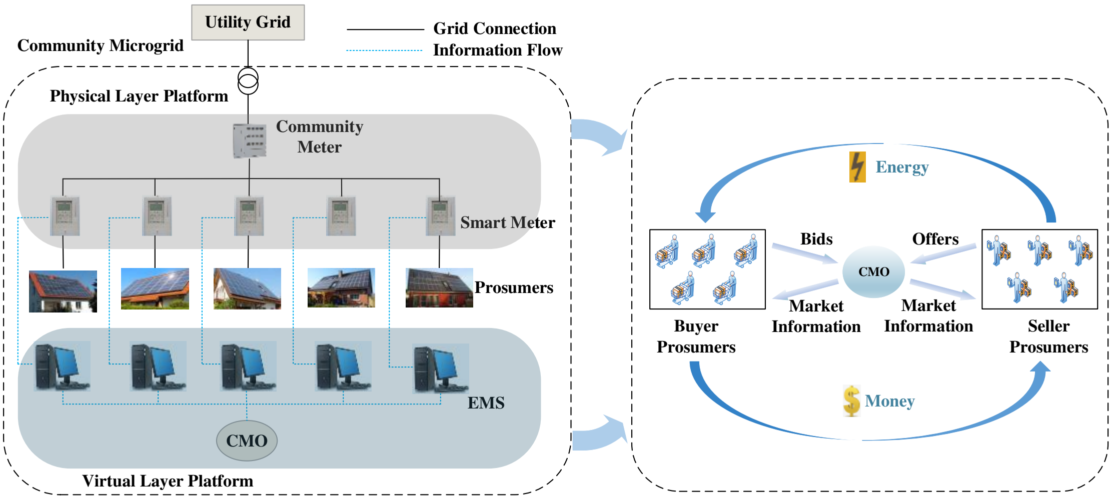


Fig. 1. Typical configuration of a prosumer

2.1. A two-layer platform for P2P energy trading

The P2P energy trading structure of the community microgrid is shown in Fig. 2. All prosumers are connected to one another through the bidirectional energy and information flows, and the whole community is linked to the utility grid via a network connection point. Based on this structure, the prosumers can trade their excess PV energy with others, instead of directly trading with the utility grid. As shown in Fig. 2(a), P2P energy trading among prosumers is operated via a two-layer platform. The virtual layer platform provides a secure network environment for prosumers to decide on their energy trading parameters. The physical layer platform facilitates the energy transfer from sellers to buyers once trading agreements between the two parties are reached over the virtual layer platform.



(a) (b)

Fig. 2. P2P energy trading structure of the community microgrid: (a) physical and virtual layer platforms for P2P energy trading; (b) information, energy, and money flows among prosumers.

The grid-connected community microgrid is considered as the physical layer, which is linked to the utility grid for balancing the total energy surplus and deficit of the community. Smart meters are installed at those connection points, among which the community meter is able to evaluate the performance of P2P trading, for example, the total amount of energy sold to or purchased from the utility grid. The smart meter of each prosumer collects its private information, including PV generation, energy consumption, state-of-charge (SOC) of the ESS, and energy transactions with other prosumers or with the utility grid. In addition, the smart meter sends private information to the energy management system (EMS) for processing.

The virtual layer platform supports that all the prosumers have equal access to the P2P market, where an auction mechanism is utilized to match the energy surplus from seller prosumers and energy deficit of buyer prosumers. The virtual layer platform consists of a CMO and the EMSs installed at prosumers. The CMO plays the two roles of dispatcher and auctioneer to reliably and securely operates the community microgrid system and administrates the P2P market. Due to the proximity of prosumers within the community and the small amount of energy traded among local prosumers, the transmission loss and transmission cost are considered negligible [12,28]. As shown in Fig. 2(b), the CMO acts as an auctioneer to receive offers/bids from seller/buyer prosumers and then clears the market based on defined auction rules. In addition, the CMO issues market information, including the total available energy surplus, the total unmet energy deficit, and the market clearing outcomes to all prosumers. According to private information from the smart meter and market information from the CMO, the EMS integrated with the energy trading algorithm computes the optimal bidding strategy to participate in the P2P market on behalf of the prosumer. Financial settlements are finally carried out upon successful energy transactions over the virtual layer platform.

2.2. Energy behavior model

With the existing infrastructures explained, the primary aim of this paper is to propose an auction-based trading mechanism to realize P2P energy trading in the community microgrid. This section provides a basic model about the energy behavior of prosumers in the community and the dynamics of the ESS, laying foundations for designing a P2P trading mechanism.

We consider that the community consisting of N prosumers, where $N = |\mathcal{N}|$, and $\mathcal{N} = \{1,2,\dots,N\}$ is the set of prosumers. The energy demand profile of prosumer n during the operation time period can be expressed as:

$$E_{n,d} = \left(E_{n,d}^{1}, E_{n,d}^{2}, \dots, E_{n,d}^{T}\right), n \in \mathcal{N}. \tag{1}$$

where $T = |\mathcal{T}|$ is the number of time slots over the operation time period. Denote $\mathcal{T} = \{1,2,\dots,T\}$ as the set of all time slots and suppose each time slot $t \in \mathcal{T}$ has equal interval Δt.

The PV generation profile of prosumer n during the same operation time period can be expressed as:

$$E_{n,\mathrm{pv}} = \left(E_{n,\mathrm{pv}}^{1}, E_{n,\mathrm{pv}}^{2}, \dots, E_{n,\mathrm{pv}}^{T}\right), n \in \mathcal{N}. \tag{2}$$

Since the energy generated from the PV system has very low marginal costs, it is reasonable to assume that each prosumer prefers consuming energy from its own PV generation to meet its demand. Thus, at any time slot t, the amount of energy consumed by the prosumer n from its own PV generation is:

$$E_{n,c}^{t} = \min\left\{E_{n,d}^{t}, E_{n,\mathrm{pv}}^{t}\right\}, n \in \mathcal{N}, t \in \mathcal{T}. \tag{3}$$

Depending on the values of $E_{n,d}^{t}$, $E_{n,\mathrm{pv}}^{t}$, and $E_{n,\mathrm{c}}^{t}$, the prosumer n at time slot t can act either as a seller prosumer to sell its energy surplus $E_{n,sur}^{t}$ or as a buyer prosumer to purchase its energy deficit $E_{n,def}^{t}$. Here,

$$E_{n,sur}^{t} = E_{n,\mathrm{pv}}^{t} - E_{n,c}^{t}, \tag{4}$$

$$E_{n,def}^{t} = E_{n,d}^{t} - E_{n,c}^{t}, n \in \mathcal{N}, t \in \mathcal{T}. \tag{5}$$

Let $\mathcal{N}_s^t$ and $\mathcal{N}_b^t$ represent the set of seller and buyer prosumers, respectively. Clearly, $\mathcal{N}_s^t \cup \mathcal{N}_b^t = \mathcal{N}$ and $\mathcal{N}_s^t \cap \mathcal{N}_b^t = \emptyset$. Also, denote $N_s^t = |\mathcal{N}_s^t|$ and $N_b^t = |\mathcal{N}_b^t|$ as the number of seller and buyer prosumers at time slot t, respectively.

Each PV system is usually coupled with an ESS. The dynamics of the energy level of the ESS and its operational constraints are modeled as follows [29]:

$$B_n^t = B_n^{t-1} + (u_n^t P_{n,ch}^t \eta_{n,ch} - v_n^t P_{n,dch}^t / \eta_{n,dch})\Delta t \tag{6}$$

$$B_n^{min} \le B_n^t \le B_n^{max} \tag{7}$$

$$u_n^t + v_n^t \le 1 \tag{8}$$

$$u_n^t P_{n,ch}^{min} \le P_{n,ch}^t \le u_n^t P_{n,ch}^{max} \tag{9}$$

$$v_n^t P_{n,dch}^{min} \le P_{n,dch}^t \le v_n^t P_{n,dch}^{max} \tag{10}$$

where B_n^{t-1} and B_n^t denote the energy level of the ESS at the beginning and end of time slot t. B_n^{min} is the minimum capacity that prevents the ESS from deep discharge and B_n^{max} is the maximum capacity. $P_{n,ch}^t$ and $P_{n,dch}^t$ refer to the charging and discharging power during time slot t. $P_{n,ch}^{min}$ and $P_{n,ch}^{max}$ represent the minimum and maximum charging power. $P_{n,dch}^{min}$ and $P_{n,dch}^{max}$ stand for the minimum and maximum discharging power. $\eta_{n,ch}$ and $\eta_{n,dch}$ denote the charge and discharging efficiency. u_n^t and v_n^t are binary variables representing the charging and discharging state of the ESS.

Equation (6) describes the dynamics of the amount of energy stored in the ESS. The energy level of the ESS is restricted within a range, according to Equation (7). Equation (8) indicates that charging and discharging at the same time slot is not permitted. The charging and discharging power of the ESS are constants, which are respectively limited by Equations (9) and (10).

The frequent charge and discharge would do harm to the lifetime of the ESS. To capture this phenomenon, the cost of ESS usage at time slot t is introduced as follows [30]:

$$C_{n,\mathrm{ESS}}^{t} = \psi(u_n^t P_{n,ch}^t + v_n^t P_{n,dch}^t)\Delta t. \tag{11}$$

where ψ denotes the levelized cost of energy (LCOE) of the ESS.

In the conventional peer-to-grid (P2G) energy trading, the excess PV energy of a prosumer is charged into the ESS until reaching the maximum capacity and the remaining surplus is fed into the grid. In case of any energy deficit, the stored energy is used to cover it. The remaining deficit, if there is any, is covered by purchasing from the utility grid. From the perspective of prosumers, two significant defects of P2G trading are listed: 1) The frequent charge and discharge of the ESS increase its maintenance cost and decrease its lifetime, resulting in a high cost of the ESS usage. 2) A prosumer with energy deficit covers its remaining deficit from the grid at the electricity price p_e. However, at another time slot when the same prosumer has energy surplus, it sells the remaining surplus to the gird at the FiT price p_{FiT}. In general, $p_{FiT} \ll p_e$, indicating that the prosumer obtains very limited economic benefits from trading with the grid. As a consequence, the prosumers within the community are more willing to directly trade energy among themselves.

In P2P energy trading, if any prosumer has PV energy surplus, the first priority is to sell to other prosumers that have energy deficit in the community. The second priority is to charge the ESS until reaching the maximum capacity. Finally, to sell to the grid. On the contrary, if any prosumer has PV energy deficit, the first priority is to buy energy from other prosumers that have energy surplus, followed in order by using the stored energy, and by purchasing from the grid until all energy deficit are covered. Furthermore, the stored energy in the ESS cannot be sold in the P2P market. It is because if prosumers are allowed to sell their stored energy, the prosumers with both a high PV capacity and a high storage capacity are able to store a large amount of energy during certain time slots and influence the market in other time slots. The potential of market manipulation will discourage ordinary prosumers to participate in P2P trading. Note that prosumers are usually exposed to the same solar radiation and temperature at the same time slot within the community. Therefore, the output power of the PV systems has a high similarity. However, the energy status (surplus or deficit) differs among prosumers since they have different PV capacities and energy consumption schedules. Accordingly, P2P energy trading among prosumers within the community microgrid is possible.

2.3. Reservation price model

Reservation prices are widely considered in auction mechanism designs. In many auction markets, a seller reserves the right to not trade the object if the price determined in the auction is lower than a specific threshold. Such a threshold is called the reservation price [31]. On this basis, a seller prosumer will not trade its energy surplus in the P2P market if the trading price determined by the auction mechanism is lower than its reservation price. Similarly, a buyer prosumer will not purchase its energy deficit from other prosumers if the trading price exceeds its reservation price. As the upper or lower price limit, the reservation price of each prosumer depends on its best outside option besides P2P trading. The best outside option of a seller prosumer is the optimal disposition of energy surplus between charging the ESS and selling to the grid. Note that the best outside option is closely related to the existing energy level of the ESS. To see why, suppose that the seller prosumer has an amount of energy surplus not exceeding the maximum capacity of the ESS. As the existing energy level of the ESS increases from the minimum to maximum capacity, the best outside option of the seller prosumer changes from charging all surplus into the ESS to selling all to the grid.

Each prosumer has a reservation price, i.e., the lowest/highest acceptable trading price of a seller/buyer prosumer, which makes a prosumer indifferent between getting its best outside option or trading in the P2P market at the reservation price. The reservation price of prosumer n at time slot t is defined as a function of the SOC of the ESS, FiT price p_{FiT}, and electricity price p_e, that is,

$$r_n^t = p_e - S_n^t(p_e - p_{FiT}),\ n \in \mathcal{N}, \tag{12}$$

where S_n^t is SOC of the ESS installed at prosumer n at time slot t, which is defined as [32]:

$$S_n^t = \left(\frac{B_n^{t-1} - B_n^{min}}{B_n^{max} - B_n^{min}}\right) \times 100\%. \tag{13}$$

From (12), the reservation price of a prosumer decreases as the SOC increases and is limited between the FiT and electricity price. When S_n^t changes from 0 to 100%, the best outside option of a seller prosumer changes from charging the ESS to trading with the grid, leading a drop of the reservation price (the lowest acceptable buying price). Especially for $S_n^t = 1$, that is, the ESS reaches the maximum capacity. In this case, the best outside option, also the only option, for the seller prosumer is to sell its energy surplus to the grid at the price p_{FiT}. Note that as S_n^t changes from 0 to 100%, the best outside option of a buyer prosumer, in turn, changes from trading with the grid to discharging the ESS. Clearly, the reservation price (the highest acceptable buying price) will be higher when there is a higher proportion of transactions with the grid. For $S_n^t = 0$, that is, the ESS cannot be discharged anymore, in this case the best outside option for the buyer prosumer is to purchase its energy deficit from the grid at the price p_e. In addition, both prosumers who are equipped with only PV system and traditional consumers who have neither PV system or the ESS can participate in P2P energy trading. Furthermore, the prosumers have the reservation price p_e when acting as buyers or the reservation price p_{FiT} when as sellers, while the consumers can only act as buyers with the reservation price p_e.

3. IUPA mechanism for P2P energy trading

The energy markets can be classified as long-term and short-term markets. In long-term markets, two parties usually negotiate the trading price and quantity for future long-time horizons, such as for one month. There exist three typical forms of short-term markets, including day-ahead, hour-ahead, and real-time markets in which energy trading respectively takes place on a daily [33], hourly [12,34], and quarter-hourly [16,21] basis. Competitive auctions are commonly utilized in short-term markets. Without loss of generality, an hour-ahead market is considered in this paper. Specifically, we design an auction-based P2P energy trading mechanism to provide economic benefits to the community by restructuring a competitive hour-ahead P2P market.

3.1. IUPA-based market description

For application of the auction mechanism in a way that benefits all prosumers, the following basic requirements are considered:

(1) The offers/bids submitted by seller/buyer prosumers and the trading price determined by the auction mechanism should be bounded between p_{FiT} and p_e. Note that if a seller prosumer submits an offer higher than p_e, no buyer prosumer is willing to purchase energy from the seller prosumer since buying from the grid is more profitable. Moreover, an offer of a seller prosumer is the price it seeks for trading its energy surplus in the P2P market, which certainly exceeds p_{FiT}. The situation is similar when a buyer prosumer submits a bid. Since the trading price is determined by the offers/bids from all seller/buyer prosumers, it certainly limited between p_{FiT} and p_e.

(2) The supply-demand relationship plays an important role in auction designs. In economic terms, typical markets can be divided into buyer's and seller's markets. The buyer's market refers to a situation where supply exceeds demand, giving buyers an advantage over sellers in price negotiations. On the contrary, the seller's market occurs when demand exceeds supply. Accordingly, the comparison outcome between the aggregated energy surplus and deficit categorizes the P2P market into the buyer's and seller's market. In the seller's market, all seller prosumers form a coalition that aims to sell the lumped energy surplus via competition among buyer prosumers. To this end, the auction mechanism is designed to soliciting bids from buyer prosumers. In the buyer's market, in turn, all buyers form a coalition. Here, the auction mechanism is designed to balance the lumped energy deficit via asking for offers from seller prosumers. Note that it is rare for the aggregated energy surplus to equal deficit, and once this happens, randomly choosing one party to form a coalition while another party performs competition.

(3) In the seller's market, the reservation price of the seller prosumer coalition is p_{FiT}, which is publicly known. However, the reservation price of each buyer prosumer is its own private information that is not public. Instead, in the buyer's market, it is common knowledge that the reservation price of the buyer prosumer coalition is p_e and the reservation price of each individual seller prosumer is its private information.

Taking all the above requirements in mind, we propose the IUPA mechanism to sufficiently promote local transactions of excess PV energy. The trading process of the IUPA-based market in one cycle is illustrated in Fig. 3. A complete trading cycle consists of the preparation, implementation, and settlement phases. In the preparation phase, depending on the energy behavior regarding the predicted PV generation and energy consumption, prosumers compute their energy surplus and deficit through Equations (4)~(5). Subsequently, the IUPA mechanism is implemented to balance the lower one between the aggregated energy surplus and deficit. The implementation procedure of the IUPA is explained as follows.

- Prosumers register into the P2P market as a seller or a buyer prosumer. Each seller/buyer prosumer submits its energy surplus/deficit quantity to the CMO.
- The comparison between the aggregated energy surplus and deficit determinates whether the offering or bidding window should be opened. We only explain the case where the offering window opens in the buyer's market. The opposite case can be similarly explained.
- In the buyer's market, all buyer prosumers form a coalition which appoints the CMO to purchase the lumped energy deficit from seller prosumers. To this end, the CMO sends an offering request to each seller prosumer, who then returns an offer.

- With offers from all seller prosumers, the CMO clears the market and issues some market information, including the uniform trading price, the amount of energy each seller prosumer supplies in the next time slot, and partial offers information.
- After receiving issued market information from the CMO, each seller prosumer would have a chance to adjust its offer based on it and any other available information, and resubmits a new offer to the CMO.
- With new offers from seller prosumers, the CMO clears the market and issues the same amount of market information again. This process will be implemented iteratively until no seller prosumer is willing to adjust its offer anymore.
- The final trading price and ultimate energy surplus allocation are determined in the convergence state. Note that the IUPA market ends with P2P energy trading contracts.

In the settlement phase, the physical energy delivery is conducted according to the trading contracts determined in the implementation phase. Meanwhile, the unsold energy surplus/uncovered energy deficit will be cleared by charging into/discharging from the ESS. The remaining surplus or deficit, if there is any, trading with the utility grid. Financial settlements of all trading contracts are executed at the end of the trading cycle.

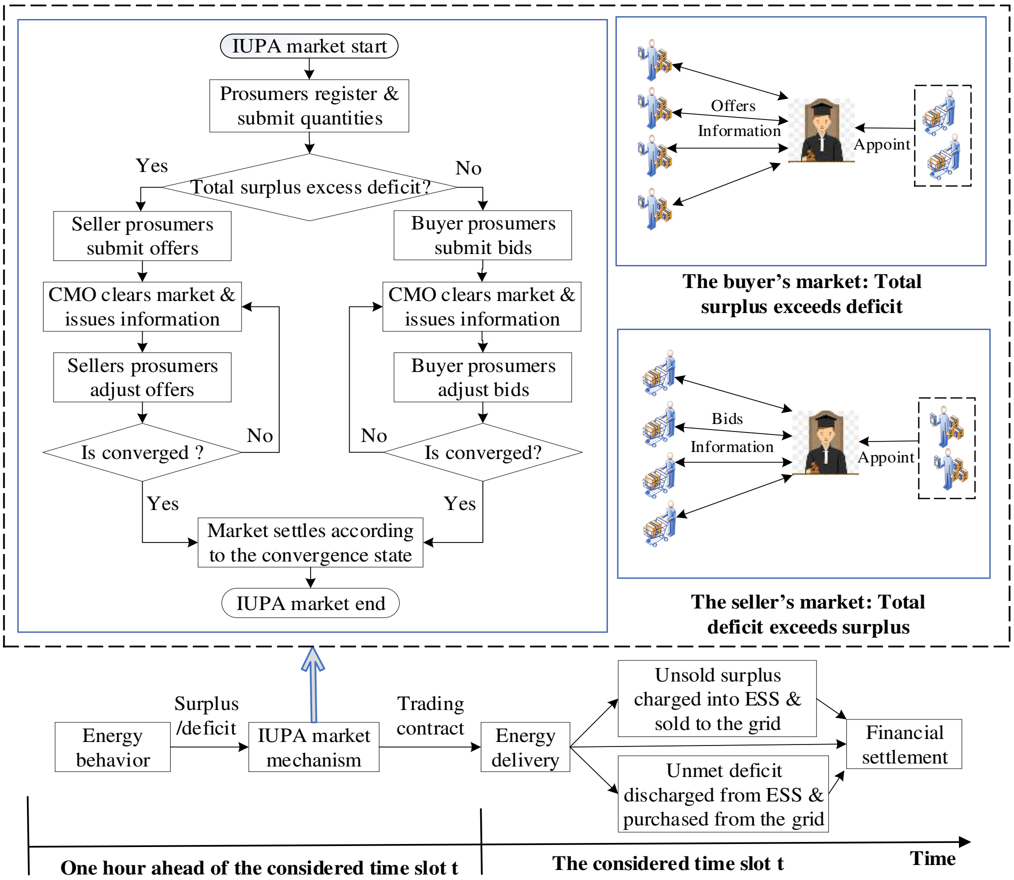


Fig. 3. IUPA-based market trading process in one cycle

3.2. Market clearing rule of IUPA

The market clearing rule consists of the energy allocation rule and the pricing rule. The IUPA efficiently allocates energy based on the 'price priority' principle. That is, the aggregated energy surplus will be first allocated to the buyer prosumer with the highest bid. Meanwhile, the aggregated energy deficit will be first provided by the seller prosumer with the lowest offer. In contrast to the CDA, the IUPA results in a uniform clearing price which applies to all trading contracts in the same time slot. One the one hand, the uniform pricing rule is fair, in the sense that a buyer prosumer never pays more than other prosumers for buying the same quantity of energy. On the other hand, the uniform pricing rule enables the IUPA-based P2P market to perform to the function of price discovery. That is, aggregating the bids from prosumers into a meaningful price that assists individuals both inside and outside the P2P market to make better consumption and investment decisions. Mathematical descriptions of the IUPA's market clearing rule in the buyer's and seller's market are respectively presented in the next two sections.

3.2.1. The buyer's market

In the buyer's market, the aggregated energy surplus exceeds deficit. All buyer prosumers form a coalition which appoints the CMO to purchase the lumped deficit on behalf the coalition. To this end, the IUPA is implemented to solicit offers from seller prosumers who compete to provide their energy surplus. The buyer's market occurs at time slot t refers that:

$$\sum_{n\in\mathcal{N}_s^t} E_{n,sur}^t > \sum_{n\in\mathcal{N}_b^t} E_{n,def}^t. \tag{14}$$

With the energy surplus quantities and offers from all seller prosumers, which are denoted by $\boldsymbol{E_s^t} = \left\{E_{n,sur}^t\right\}_{n\in\mathcal{N}_s^t}$ and $\boldsymbol{b_s^t} = \left\{b_{n,s}^t\right\}_{n\in\mathcal{N}_s^t}$, the CMO first arranges offers in ascending order. Next, the last winner, the first loser, and the set of winners (i.e., seller prosumers with a positive allocation) are determined in the following:

$$b_{1,s}^t \leq b_{2,s}^t \leq \cdots \leq b_{N_s^t,s}^t, \tag{15}$$

$$k_s^t = \min\left\{j \middle| \sum_{i=1}^{i=j} E_{i,sur}^t \geq \sum_{n\in\mathcal{N}_b^t} E_{n,def}^t, j = 1,2,\ldots,N_s^t\right\}. \tag{16}$$

Here, we refer to seller prosumer k_s^t the last winner and seller prosumer $k_s^t + 1$ the first loser. Also, denote $\Delta(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}) = \{1,2,\ldots,k_s^t\}$ as the set of winners. Finally, the energy allocation rule $\{x_{n,s}^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t})\}_{n\in\mathcal{N}_s^t}$ and the uniform trading price $p_s^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t})$ are defined as follows:

$$x_{n,s}^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}) = \begin{cases} E_{n,sur}^t & if\ n < k_s^t \\ \sum_{n\in\mathcal{N}_b^t} E_{n,def}^t - \sum_{i=1}^{i=k_s^t-1} E_{i,sur}^t & if\ n = k_s^t \\ 0 & if\ n > k_s^t \end{cases}, \tag{17}$$

$$p_s^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}) = \begin{cases} b_{k_s^t,s}^t & if\ x_{k_s^t,s}^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}) < E_{k_s^t,sur}^t \\ b_{k_s^t+1,s}^t & if x_{k_s^t,s}^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}) = E_{k_s^t,sur}^t \end{cases}. \tag{18}$$

From (17), the aggregated energy deficit is balanced since the allocation rule satisfies:

$$\sum_{n\in\mathcal{N}_s^t} x_{n,s}^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}) = \sum_{n\in\mathcal{N}_b^t} E_{n,def}^t. \tag{19}$$

In addition, the allocation rule defined in (17) states that the IUPA allocates the aggregated energy deficit to the seller prosumer with the lowest offer. If that seller prosumer's surplus cannot cover all deficit, the IUPA allocates what remains of the deficit to the seller prosumer with the second-lowest offer, and so on until the total amount has been allocated. From (18), the uniform trading price, which applies to all trading contracts, is set to be either the offer of the last winner or the offer of the first loser, depending on whether the last winner is allocated all of its energy surplus. Fig. 4(a) further illustrates the market clearing rule of the IUPA in the buyer's market.

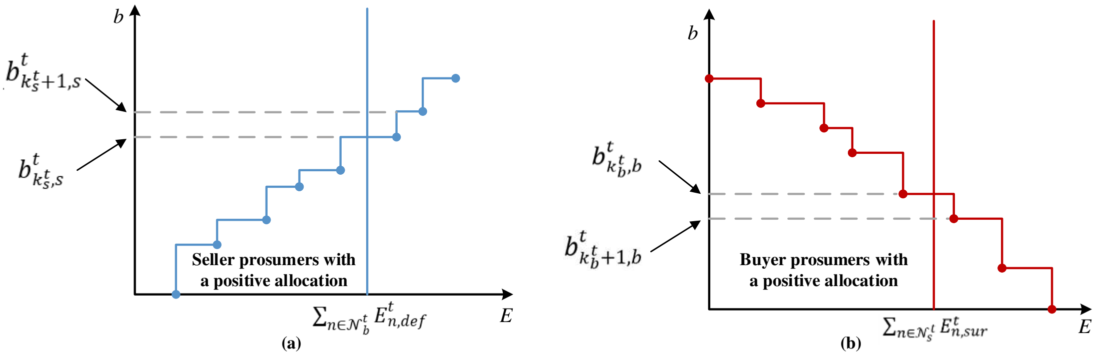


Fig. 4. Allocation and pricing rule of IUPA in the two markets: (a) the buyer's market; (b) the seller's market.

3.2.2. The seller's market

In the seller's market, in turn, the aggregated energy deficit exceeds surplus. All seller prosumers unite to sell out the aggregated energy surplus in the P2P market with the aid of the CMO. To this end, the CMO implements the IUPA to solicit competitive bids from buyer prosumers. Similarly, the seller's market occurs at time slot t implies that:

$$\sum_{n\in\mathcal{N}^t_b} E^t_{n,def} > \sum_{n\in\mathcal{N}^t_s} E^t_{n,sur}. \tag{20}$$

With the energy deficit quantities and bids from all buyer prosumers, which are denoted by $\boldsymbol{E^t_b} = \{E^t_{n,def}\}_{n\in\mathcal{N}^t_b}$ and $\boldsymbol{b^t_b} = \{b^t_{n,b}\}_{n\in\mathcal{N}^t_b}$, the CMO first arranges bids in descending order. Next, the last winner, the first loser, and the set of winners are similarly determined as follows:

$$b^t_{1,b} \geq b^t_{2,b} \geq \cdots \geq b^t_{N^t_b,b}. \tag{21}$$

$$k^t_b = \min\left\{j \middle| \sum_{i=1}^{i=j} E^t_{i,def} \geq \sum_{n\in\mathcal{N}^t_s} E^t_{n,sur}, j = 1,2,\dots,N^t_b\right\}. \tag{22}$$

Here, buyer prosumer k^t_b is the last winner and buyer prosumer $k^t_b + 1$ is the first loser. Also, denote $\Delta(\boldsymbol{E^t_b}, \boldsymbol{b^t_b}) = \{1,2,\dots,k^t_b\}$ as the set of winners. Finally, the allocation rule $\{x^t_{n,b}(\boldsymbol{E^t_b}, \boldsymbol{b^t_b})\}_{n\in\mathcal{N}^t_b}$ and uniform trading price $p^t_b(\boldsymbol{E^t_b}, \boldsymbol{b^t_b})$ are respectively defined as follows:

$$x^t_{n,b}(\boldsymbol{E^t_b}, \boldsymbol{b^t_b}) = \begin{cases} E^t_{n,def} & if\ n < k^t_b \\ \sum_{n\in\mathcal{N}^t_s} E^t_{n,sur} - \sum_{i=1}^{i=k^t_b-1} E^t_{i,def} & if\ n = k^t_b \\ 0 & if\ n > k^t_b \end{cases}, \tag{23}$$

$$p^t_b(\boldsymbol{E^t_b}, \boldsymbol{b^t_b}) = \begin{cases} b^t_{k^t_b,b} & if\ x^t_{k^t_b,b}(\boldsymbol{E^t_b}, \boldsymbol{b^t_b}) < E^t_{k^t_b,def} \\ b^t_{k^t_b+1,b} & if x^t_{k^t_b,b}(\boldsymbol{E^t_b}, \boldsymbol{b^t_b}) = E^t_{k^t_b,def} \end{cases} \tag{24}$$

From (23), the total energy surplus is balanced since the allocation rule satisfies:

$$\sum_{n\in\mathcal{N}^t_b} x^t_{n,b}(\boldsymbol{E^t_b}, \boldsymbol{b^t_b}) = \sum_{n\in\mathcal{N}^t_s} E^t_{n,sur}. \tag{25}$$

From (24), the uniform trading price is set to be either the bid of the last winner or the bid of the first loser, depending on whether the last winner is allocated full of its energy deficit. The allocation and pricing rule in the seller's market, respectively defined by (23) and (24), are further shown in Fig. 4(b).

3.3. Noncooperative game among prosumers

In contrast to the DA mechanism, the IUPA also involves information flows and communication processes rather than just a market clearing rule. The reason is that the IUPA is an iterative, semi-open auction, in the sense that bids or offers are submitted iteratively and the CMO issues market information in the auction process. Specifically, each time a bid or offer profile is received, the CMO clears the market and then issues the market clearing outcome, including the uniform trading price and the amount of energy allocated to each prosumer. In addition, the bids/offers of losers who receive a zero allocation are issued while for winners, their bids/offers remain undisclosed. After receiving the issued market information from the CMO, prosumers would have a chance to adjust their bids/offers based on it and any other available information and resubmit updated bids/offers to the CMO. The CMO clears the market and issues the same amount of information again. This process will be implemented repeatedly until reaching a stable convergence state in which no prosumer is willing to adjust its bid or offer anymore.

As the bidding format, the market clearing rule, and information flows of the IUPA have been elaborated, it remains to be answered what trading strategies prosumers will adopt to determinate their bids or offers in each iteration. In this paper, we assume prosumers adopt a unified trading strategy, which maps their private information of the reservation price and market information issued by the CMO into the utility-maximizing bid or offer. Here, we define the utility function of a prosumer as its extra economic benefit from participating in the IUPA. The mathematical definition of the utility function is given as follows:

Definition 1: At time slot *t*, if the buyer's market occurs, then the utility function of seller prosumer n is:

$$U_{n,s}^{t}(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}) = x_{n,s}^{t}(\boldsymbol{E_s^t}, \boldsymbol{b_s^t})(p_s^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}) - r_n^t). \tag{26}$$

Otherwise, the seller's market occurs, then the utility function of buyer prosumer n is:

$$U_{n,b}^{t}\left(\boldsymbol{E_b^t}, \boldsymbol{b_b^t}\right) = x_{n,b}^{t}\left(\boldsymbol{E_b^t}, \boldsymbol{b_b^t}\right)\left(r_n^t - p_b^t\left(\boldsymbol{E_b^t}, \boldsymbol{b_b^t}\right)\right). \tag{27}$$

Here, $x_{n,s}^{t}(\boldsymbol{E_s^t}, \boldsymbol{b_s^t})$ and $p_s^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t})$, computed from (17) and (18), respectively denote the amount of energy that seller prosumer n is allocated and the uniform selling price in the buyer's market. r_n^t is the reservation price of seller prosumer n. Similarly, $x_{n,b}^{t}\left(\boldsymbol{E_b^t}, \boldsymbol{b_b^t}\right)$ and $p_b^t\left(\boldsymbol{E_b^t}, \boldsymbol{b_b^t}\right)$, computed from (23) and (24), respectively represents the amount of energy that buyer prosumer n is allocated and the uniform buying price in the seller's market. r_n^t is the reservation price of prosumer n when it acts as a buyer. From (26), the utility of a seller prosumer is the extra money it earns from participating in the IUPA, compared with its best outside option. Similarly, the utility of a buyer prosumer defined in (27) is its amount of cost savings from participating in the IUPA.

It is of interest that prosumers can actively adjust their bids or offers, according to real-time market information issued by the CMO. When the CMO issues the market clearing outcome and bids or offers from losers of the current iteration, all prosumers observe them. Take the seller's market as an example, if there exists a buyer prosumer who can increase its utility by unilaterally adjusting its bid in the current bid profile, it then adjusts its bid to the utility-maximizing point in the next iteration. Otherwise, prosumers keep their bids unchanged. The mathematical description of the trading strategy is expressed as follows:

$$b_{n,s}^{t(j+1)} = \underset{b\in[p_{FiT},p_e]}{\operatorname{argmax}}\ U_{n,s}^{t}\left(\boldsymbol{E}_{\boldsymbol{s}}^{\boldsymbol{t}},\left(b,\boldsymbol{b}_{-\boldsymbol{n},\boldsymbol{s}}^{\boldsymbol{t(j)}}\right)\right), \tag{28}$$

$$b_{n,b}^{t(j+1)} = \underset{b\in[p_{FiT},p_e]}{\operatorname{argmax}}\ U_{n,b}^{t}\left(\boldsymbol{E}_{\boldsymbol{b}}^{\boldsymbol{t}},\left(b,\boldsymbol{b}_{-\boldsymbol{n},\boldsymbol{b}}^{\boldsymbol{t(j)}}\right)\right), \tag{29}$$

where $b_{n,s}^{t(j+1)}$ is the offer of seller prosumer n in the $(j+1)$th iteration when the buyer's market occurs at time slot t. The offer profile of the jth iteration id $\boldsymbol{b}_{\boldsymbol{s}}^{\boldsymbol{t(j)}} = \left(b_{n,s}^{t(j)},\boldsymbol{b}_{-\boldsymbol{n},\boldsymbol{s}}^{\boldsymbol{t(j)}}\right)$, which comprises the offer of seller prosumer n and the offers of other seller prosumers. When the seller's market occurs at time slot t, buyer prosumer n in the $(j+1)$th iteration would adjust its bid to $b_{n,b}^{t(j+1)}$, given the bid profile in the jth iteration is $\boldsymbol{b}_{\boldsymbol{b}}^{\boldsymbol{t(j)}} = \left(b_{n,b}^{t(j)},\boldsymbol{b}_{-\boldsymbol{n},\boldsymbol{b}}^{\boldsymbol{t(j)}}\right)$.

Based on the aforementioned trading behaviors of prosumers, the IUPA can be formulated as a noncooperative game, where prosumers are game players, and their strategies for playing the game are to submit offers or bids in each iteration. Convergence in the iterative offering or bidding process is highly desired, because it would indicate the existence of a Nash equilibrium. The Nash equilibrium is a profile of bids or offers that can achieve a consensus among competitive prosumers by enabling more effective energy trading and more equitable energy allocation [7]. A Nash equilibrium of the IUPA is defined as follows:

Definition 2: In the buyer's market, an offer profile $\boldsymbol{b}_{\boldsymbol{s}}^{\boldsymbol{t}} = \{b_{n,s}^{t}\}_{n\in\mathcal{N}_s^t}$ is a Nash equilibrium if for all $n\in\mathcal{N}_s^t$ and $b\in[p_{FiT},p_e]$, the following inequity holds:

$$U_{n,s}^{t}\left(\boldsymbol{E}_{\boldsymbol{s}}^{\boldsymbol{t}},\left(b_{n,s}^{t},\boldsymbol{b}_{-\boldsymbol{n},\boldsymbol{s}}^{\boldsymbol{t}}\right)\right) \geq U_{n,s}^{t}\left(\boldsymbol{E}_{\boldsymbol{s}}^{\boldsymbol{t}},\left(b,\boldsymbol{b}_{-\boldsymbol{n},\boldsymbol{s}}^{\boldsymbol{t}}\right)\right). \tag{30}$$

In the seller's market, a bid profile $\boldsymbol{b}_{\boldsymbol{b}}^{\boldsymbol{t}} = \{b_{n,b}^{t}\}_{n\in\mathcal{N}_b^t}$ is a Nash equilibrium if for all $n\in\mathcal{N}_b^t$ and $b\in[p_{FiT},p_e]$, the following inequity holds:

$$U_{n,b}^{t}\left(\boldsymbol{E}_{\boldsymbol{b}}^{\boldsymbol{t}},\left(b_{n,b}^{t},\boldsymbol{b}_{-\boldsymbol{n},\boldsymbol{b}}^{\boldsymbol{t}}\right)\right) \geq U_{n,b}^{t}\left(\boldsymbol{E}_{\boldsymbol{b}}^{\boldsymbol{t}},\left(b,\boldsymbol{b}_{-\boldsymbol{n},\boldsymbol{b}}^{\boldsymbol{t}}\right)\right). \tag{31}$$

Definition 2 states that in the buyer's market, an offer profile constitutes a Nash equilibrium if no seller prosumer can increase its utility by unilaterally adjusting its offer, when keeping the offers of other seller prosumers unchanged. An equilibrium bid profile can be similarly interpreted. Next, we devise an auction market self-adaption algorithm (AMSA) to implement the IUPA such that a Nash equilibrium is obtained via multiple iterations. The AMSA algorithm is outlined in the following.

Algorithm 1: The AMSA algorithm for the implementation of IUPA.

```
1: for each time $t \in \{1,2,\dots T\}$ do
2:     Each seller prosumer $n \in \mathcal{N}_s^t$ submits its energy surplus $E_{n,sur}^t$ to the auctioneer.
3:     Each buyer prosumer $n \in \mathcal{N}_b^t$ submits its energy deficit $E_{n,def}^t$ to the auctioneer.
4:     if $\sum_{n\in\mathcal{N}_s^t} E_{n,sur}^t > \sum_{n\in\mathcal{N}_b^t} E_{n,def}^t$ then
5:         Algorithm for the buyer's market terminates (line 11).
6:     else if $\sum_{n\in\mathcal{N}_s^t} E_{n,sur}^t < \sum_{n\in\mathcal{N}_b^t} E_{n,def}^t$ then
7:         Algorithm for the seller's market terminates (line 28).
8:     else
```

```
            Randomly terminating between Algorithm for the seller's and buyer's market.
            Termination criteria $\varepsilon$.
        Algorithm for the buyer's market
            Each seller prosumer $n \in \mathcal{N}_s^t$ submits its minimal reservation price $r_n^t$ to the auctioneer.
            Initialize $i$=0 and $\boldsymbol{b_s^t}(1) = \boldsymbol{r_s^t} = \{r_n^t\}_{n \in \mathcal{N}_s^t}$.
            do $i$=$i$+1;
                The allocation rule $x_{n,s}^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}(i))$ follows from (16) and the uniform trading price $p_s^t(\boldsymbol{E_s^t}, \boldsymbol{b_s^t}(i))$ is
                calculated via (17).
                for each $n \in \Delta(\boldsymbol{E_s^t}, \boldsymbol{r_s^t})$
                    if $\max_{b \geq r_n^t} U_{n,s}^t\left(\boldsymbol{E_s^t}, \left(b, \boldsymbol{b_{-n,s}^t}(i)\right)\right) > U_{n,s}^t\left(\boldsymbol{E_s^t}, \left(b_{n,s}^t(i), \boldsymbol{b_{-n,s}^t}(i)\right)\right)$ then
                        $b_{n,s}^t(i+1) = \operatorname{argmax}_{b \geq r_n^t} U_{n,s}^t\left(\boldsymbol{E_s^t}, \left(b, \boldsymbol{b_{-n,s}^t}(i)\right)\right)$
                    else
                        $b_{n,s}^t(i+1) = b_{n,s}^t(i)$
                    end if
                end for
                for each $n \in \mathcal{N}_s^t \backslash \Delta(\boldsymbol{E_s^t}, \boldsymbol{r_s^t})$
                    $b_{n,s}^t(i+1) = r_n^t(i)$
                end for
            while $\| \boldsymbol{b_s^t}(i+1) - \boldsymbol{b_s^t}(i) \| < \varepsilon$;
            Output $\boldsymbol{b_s^t}$.
        Algorithm for the seller's market
            Each buyer prosumer $n \in \mathcal{N}_b^t$ submits its maximal reservation price $r_n^t$ to the auctioneer.
            Initialize $j$=0 and $\boldsymbol{b_b^t}(1) = \boldsymbol{r_b^t} = \{r_n^t\}_{n \in \mathcal{N}_b^t}$.
            do $j$=$j$+1;
                The allocation rule $x_{n,b}^t(\boldsymbol{E_b^t}, \boldsymbol{b_b^t}(j))$ follows from (22) and the uniform trading price $p_b^t(\boldsymbol{E_b^t}, \boldsymbol{b_b^t}(j))$ is
                calculated via (23).
                for each $n \in \Delta(\boldsymbol{E_b^t}, \boldsymbol{r_b^t})$
                    if $\max_{b \leq r_n^t} U_{n,b}^t\left(\boldsymbol{E_b^t}, \left(b, \boldsymbol{b_{-n,b}^t}(j)\right)\right) > U_{n,b}^t\left(\boldsymbol{E_b^t}, \left(b_{n,b}^t(j), \boldsymbol{b_{-n,b}^t}(j)\right)\right)$ then
                        $b_{n,b}^t(j+1) = \operatorname{argmax}_{b \leq r_n^t} U_{n,b}^t\left(\boldsymbol{E_b^t}, \left(b, \boldsymbol{b_{-n,b}^t}(j)\right)\right)$
                    else
                        $b_{n,b}^t(j+1) = b_{n,b}^t(j)$
                    end if
                end for
                for each $n \in \mathcal{N}_b^t \backslash \Delta(\boldsymbol{E_b^t}, \boldsymbol{r_b^t})$
                    $b_{n,b}^t(j+1) = r_n^t(j)$
                end for
            while $\| \boldsymbol{b_b^t}(j+1) - \boldsymbol{b_b^t}(j) \| < \varepsilon$;
            Output $\boldsymbol{b_b^t}$.
    end if
end for
```

Finally, we prove that the AMSA algorithm returns a unique Nash equilibrium of the IUPA mechanism by logical arguments [31], which is widely adopted in equilibrium analysis in auction theory.

Theorem 1: The AMSA algorithm returns a unique Nash equilibrium of the IUPA.

Proof: To prove this theorem, it is sufficient to show that the bid/offer profile output by **Algorithm for the buyer's/seller's market** satisfies (30)/(31). Without loss of generality, we prove the conclusion in the buyer's market, and the similar proof can be conducted in the seller's market.

In the buyer's market, suppose that $\boldsymbol{b}_s^t$ is the output offer profile by **Algorithm for the buyer's market**, and at the same time, denote $\boldsymbol{r}_s^t$ as the profile of seller prosumers' reservation prices. Given the offer profile $\boldsymbol{b}_s^t$ and $\boldsymbol{r}_s^t$, the sets of winners are respectively denoted by $\Delta(\boldsymbol{E}_s^t, \boldsymbol{b}_s^t)$ and $\Delta(\boldsymbol{E}_s^t, \boldsymbol{r}_s^t)$. Also, in the winner set of $\Delta(\boldsymbol{E}_s^t, \boldsymbol{b}_s^t)$, denote $L_{k,s}^t$ as the last winner with the offering price $b_{k,s}^t$. First, as the algorithm starts with $\boldsymbol{r}_s^t$ and the initial winners will not change their offers to become losers, it then follows that $\Delta(\boldsymbol{E}_s^t, \boldsymbol{r}_s^t) \subset \Delta(\boldsymbol{E}_s^t, \boldsymbol{b}_s^t)$. On this basis, all seller prosumers can be classified into three categories, that is, $\mathcal{N}_s^t = \Delta(\boldsymbol{E}_s^t, \boldsymbol{r}_s^t) \cup (\Delta(\boldsymbol{E}_s^t, \boldsymbol{b}_s^t) \backslash \Delta(\boldsymbol{E}_s^t, \boldsymbol{r}_s^t)) \cup (\mathcal{N}_s^t \backslash \Delta(\boldsymbol{E}_s^t, \boldsymbol{b}_s^t))$. The first set represents the initial winners. The second set denotes the increased winners via the iterative offering process. The last set stands for the losers of the IUPA. Note that as shown in Steps 16~20, for any seller prosumer $n \in \Delta(\boldsymbol{E}_s^t, \boldsymbol{r}_s^t)$, it either chooses to change its offer to become the last winner for determining a higher uniform trading price, or keeps its offer unchanged. Furthermore, only seller prosumers in $\Delta(\boldsymbol{E}_s^t, \boldsymbol{r}_s^t)$ can change their offers to become the last winner, which implies that $L_{k,s}^t \in \Delta(\boldsymbol{E}_s^t, \boldsymbol{r}_s^t)$.

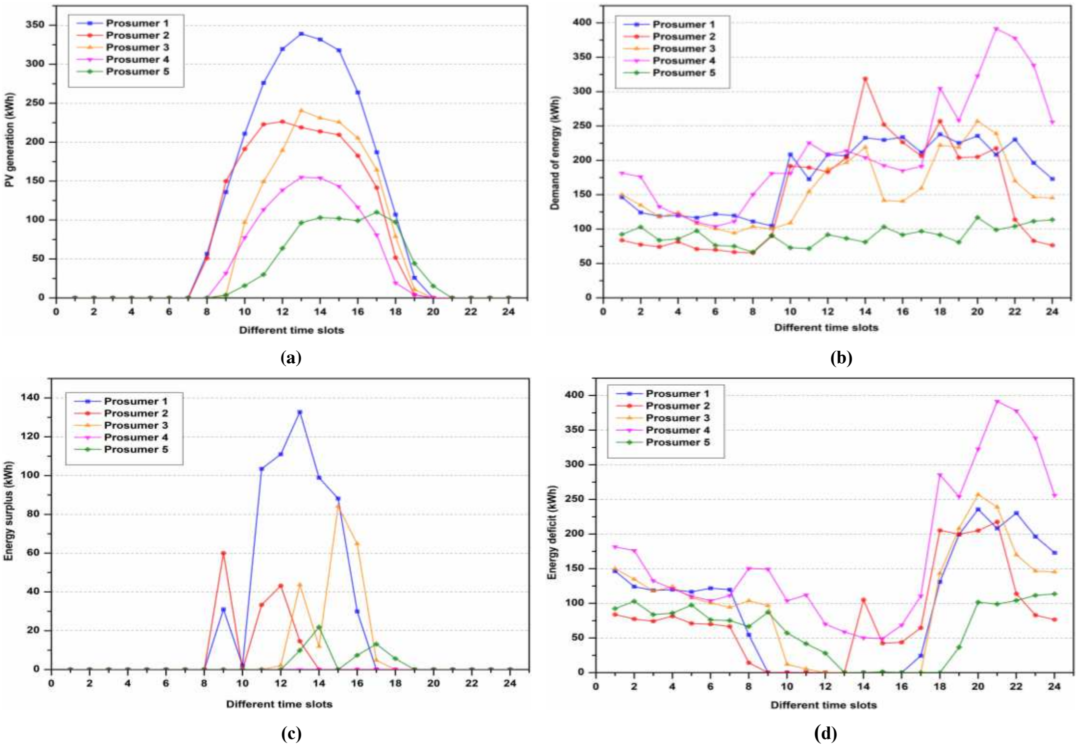
We then show that no seller prosumer is willing to unilaterally change its offer in $\boldsymbol{b}_s^t$. On the one hand, no seller prosumer can increase its utility by increasing its offer in $\boldsymbol{b}_s^t$. This claim is explained as follows. For a seller prosumer $n \in \Delta(\boldsymbol{E}_s^t, \boldsymbol{r}_s^t)$, the convergence of the algorithm implies that it will not increase its offer anymore. For a seller prosumer $n \in \Delta(\boldsymbol{E}_s^t, \boldsymbol{b}_s^t) \backslash \Delta(\boldsymbol{E}_s^t, \boldsymbol{r}_s^t)$, if it increases its offer to exceed $b_{k,s}^t$, then its utility will fall to zero since the allocation is equal to zero. Its utility will stay unchanged if it increases its offer to a level no more than $b_{k,s}^t$. All losers in $\mathcal{N}_s^t \backslash \Delta(\boldsymbol{E}_s^t, \boldsymbol{b}_s^t)$ have no incentive to change (decrease or increase) their bids. On the other hand, no seller prosumer can increase its utility by decreasing its offer in $\boldsymbol{b}_s^t$. This claim comes from the fact that all winners in $\Delta(\boldsymbol{E}_s^t, \boldsymbol{b}_s^t)$ other than $L_{k,s}^t$ sell their entire energy surplus at a price set by the last winner or the first loser, so lowering the offer does not affect their utilities. Moreover, the last winner $L_{k,s}^t$ has adjusted its offer up to the point where its utility is maximized. Thus, the last winner is not willing to decrease its offer either. According to **Definition 2**, the offer profile $\boldsymbol{b}_s^t$ is a Nash equilibrium of the IUPA in the buyer's market.

Finally, note that **Algorithm for the buyer's market** begins with the profile of reservation prices and every seller prosumer in each iteration simultaneously maximizes its own utility, the auction market self-adaption algorithm (AMSA) thus returns a unique Nash equilibrium of the IUPA. □

From **Theorem 1**, we obtain that on the one hand, the IUPA mechanism, a multiple player noncooperation game, always exists a Nash equilibrium. On the other hand, the equilibrium found by the AMSA is unique. Therefore, the proposed algorithm is capable of implementing the IUPA mechanism.

4. Case Study

In this section, we show the results of simulation studies to assess the performance of the IUPA mechanism, which is designed for P2P energy trading in a community microgrid. For a better presentation of equilibrium analysis process, we consider the community microgrid with 5 prosumers, and each prosumer is equipped with a PV system and an ESS. The operation time period $\mathcal{T}$ is taken as one day, which is divided into 24 hours. The PV generation and energy demand curves of each prosumer are taken from [2] and respectively shown in Figs. 4(a)~(b). Then, the daily energy surplus and deficit curves can be computed by Equations (3)~(4), and respectively shown in Figs. 4(c)~(d).



(a) (b) (c) (d)

Fig. 4. Energy surplus/deficit curve of a typical day in summer: (a) curve of prosumers' PV generation; (b) curve of prosumers' energy demand; (c) curve of prosumers' energy surplus; (d) curve of prosumers' energy deficit.

In addition, the FiT price p_{FiT} is set as 0.4 CNY/kWh and the electricity price p_e is assumed to be 1.0 CNY/kWh. Each prosumer has installed the ESS of 100 kWh maximum capacity. The minimum capacity is 0 kWh. The charging/discharging efficiency is set as 90% and the maximum charging/discharging power is taken as 50 kW. The ESS's levelized cost of energy ψ is set to 0.6 CNY/kWh. As shown in Figs. 4(c) and 4(d), the P2P market is active from 9:00 to 18:00, during which there exists both a positive amount of total energy surplus and deficit. At the start of the first trading time slot, as the state-of-charge of each prosumer's ESS is stochastic, we randomly choose it between [0, 100%]. According to the specific values of energy surplus and deficit, the prosumers can either behave as a seller or a buyer during the different P2P trading time slots. Table 1 shows the roles of all prosumers at each trading time slot. Moreover, trough the comparison outcomes between the aggregated energy surplus and deficit, the seller's market occurs at time slots 9-11, 14, and 16-18, while, the buyer's market forms at time slots 12, 13, and 15.

4.1. Equilibrium analysis

In order to show how the IUPA mechanism economically benefits prosumers as well as significantly reduces the impact of distributed PV generation on the utility grid, we first demonstrate the equilibrium results of the IUPA in different time slots. Without loss of generality, we choose time slots 13 and 14 for equilibrium analysis in the buyer's and seller's market, respectively.

Table 1. Role of each prosumer in different P2P trading time slots

Hour	**Role of prosumers (S: Seller prosumer/B: Buyer prosumer)**					**Total amount of energy surplus/deficit(kWh)**	
	Prosumer 1	**Prosumer 2**	**Prosumer 3**	**Prosumer 4**	**Prosumer 5**	**Energy surplus**	**Energy deficit**
9:00	S	S	B	B	B	91.13	333.42
10:00	S	B	B	B	B	2.15	172.99
11:00	S	S	B	B	B	136.82	159.26
12:00	S	S	S	B	B	156.25	98.15
13:00	S	S	S	B	S	200.96	58.87
14:00	S	B	S	B	S	132.7	155.33
15:00	S	B	S	B	B	172.29	92.81
16:00	S	B	S	B	S	102.17	112.45
17:00	B	B	S	B	S	17.88	199.67
18:00	B	B	B	B	S	5.66	765.04

Table 2. Equilibrium trading result of the IUPA for $t = 13, E_{Def}^{13} = 58.87\text{kWh}$

Seller prosumer	**Energy surplus (kWh)**	**SOC of the EES (at the start of 13)**	**Reservation price (CNY/kWh)**	**Equilibrium offer (CNY/kWh)**	**Flows of energy surplus(kWh)**			**SOC of the EES (at the end of 13)**
					Trading via P2P	**Storing in EES**	**Selling to grid**	
Prosumer 1	132.76	88.14%	0.47	0.8	44.27	13.18	75.31	100.00%
Prosumer 2	14.6	65.13%	0.61	0.61	14.6	0	0	65.13%
Prosumer 3	43.7	32.07%	0.81	0.81	0	43.7	0	71.40%
Prosumer 5	9.9	0	1	1	0	9.9	0	8.91%

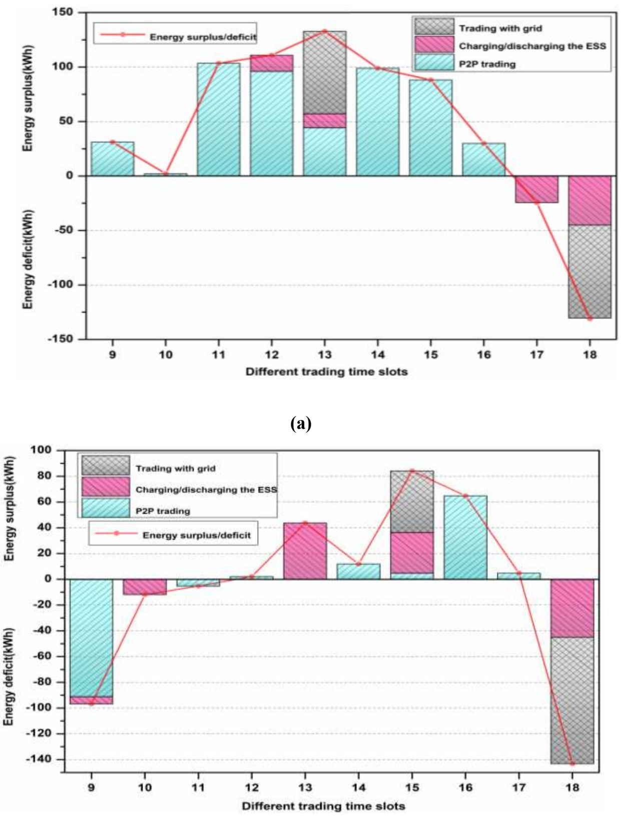
Table 3. Equilibrium trading result of the IUPA for $t = 14, E_{Sur}^{14} = 132.7\text{kWh}$

Buyer prosumer	**Energy deficit (kWh)**	**SOC of the EES (at the start of 14)**	**Reservation price (CNY/kWh)**	**Equilibrium bid (CNY/kWh)**	**Sources of energy deficit(kWh)**			**SOC of the EES (at the end of 14)**
					Trading via P2P	**Discharging from EES**	**Buying from grid**	
Prosumer 2	105.14	65.13%	0.61	0.4	82.51	25.14	0	39.99%
Prosumer 4	50.19	0	1	0.61	50.19	0	0	0

Table 2 shows that at time slot 13, Prosumer 4 is treated as a buyer who has energy deficit of 58.87 kWh, and the remaining four prosumers are sellers who compete to cover the deficit. The equilibrium result is: Prosumers 1 and 2 win the auction and the equilibrium offer of Prosumer 1 sets the uniform trading price of 0.8 CNY/kWh. The path that leads to the equilibrium is analysed as follows. First, given the SOC values of the four seller prosumers are 88.14%, 65.13%, 32.07%, and 0, their reservation prices are computed via Equation (12). Next, seller prosumers submit their reservation prices of 0.47 CNY/kWh, 0.61 CNY/kWh, 0.81 CNY/kWh, and 1 CNY/kWh, which determines the initial market clearing outcome is that Prosumer 1 provides 58.87 kWh to Prosumer 4 at the trading price of 0.47 CNY/kWh. However, the utility of Prosumer 1 is zero. Thus, Prosumer 1 would adjust its offer to the utility-maximizing offer of 0.8 CNY/kWh, while other losers keep their offers unchanged. Finally, after an adjustment, the equilibrium offer profile (0.8 CNY/kWh, 0.61 CNY/kWh, 0.81 CNY/kWh, 1 CNY/kWh) is attained. In the equilibrium profile, Prosumer 2, the first winner, trades all of its energy surplus, while Prosumer 1, the last winner, trades partial energy surplus of 44.27 kWh. The remaining surplus of Prosumer 1 is charged into its ESS until fully charged and eventually sold to the utility grid of 75.21 kWh. The losers, Prosumers 3 and 5, charge their energy surplus into their ESS.

Table 3 illustrates the equilibrium results of the IUPA at time slot 14. At this time slot, Prosumers 2 and 4 compete to purchase their energy deficit from the aggregated energy surplus of 132.7 kWh provided by the coalition formed by Prosumers 1, 3, and 5. The equilibrium outcome is: Prosumer 4 purchases all of its energy deficit of 50.19 kWh, while Prosumer 2 purchases partial deficit of 82.51 kWh from the P2P market and the remaining deficit is covered via discharging its ESS. The uniform trading price of 0.4 CNY/kWh is set by the equilibrium bid of the last winner, that is, Prosumer 2. Note that in the initial reservation price profile (0.61 CNY/kWh, 1 CNY/kWh), both Prosumers 2 and 4 have incentives to lower their bids. Especially for Prosumer 2, it speculates that the energy deficit of Prosumer 4 cannot exhaust all energy surplus and it certainly becomes the last winner to set the trading price. Therefore, Prosumer 2 would submit the minimum bid of 0.4 CNY/kWh to maximize its utility via minimizing the unit purchase cost.

The equilibrium of the IUPA determines energy transactions in the P2P market. For the energy surplus and deficit that cannot be cleared in the P2P market, it should be balanced via storage devices and transactions with the utility grid. Accordingly, the energy surplus of each seller prosumer flows to three directions: 1) P2P trading; 2) charging the ESS; 3) selling to the grid. Meanwhile, the energy deficit of each buyer prosumer stems from the corresponding three directions: 1) P2P trading; 2) discharging the ESS; 3) purchasing from the grid. At time slot 13, Table 2 shows every prosumer's quantity energy surplus that flows to each direction. Table 3 presents similar results at time slot 14. For each prosumer, we then show the flows/sources of its energy surplus/deficit across all different trading time slots. Without loss of generality, Figs. 5(a)~(b) respectively take Prosumers 1 and 3 as representatives.



(a)

(b)

Fig. 5. Flows/sources of energy surplus/deficit at different trading time slots: (a) Prosumer 1; (b) Prosumer 3.

Table 4. Calculation performance of the AMSA algorithm for different number of prosumers

Number of prosumers	Average number of iterations	Maximum number of iterations	Average convergence time/s	Maximum convergence time/s
10	1.7	3	0.0203	0.0469
20	2.4	8	0.025	0.0625
50	2.9	10	0.1313	0.4375
100	5.1	15	0.3907	0.7969

Next, we evaluate the calculation performance of the AMSA algorithm in finding the Nash equilibrium of the IUPA in simulation cases with different numbers of prosumers. Table 4 shows the calculation detail for communities with 10, 20, 50, 100 prosumers. We use the Monte Carlo methods to randomly generate the data of each prosumer's PV generation and energy demand and the trading processes are simulated 10 times for a given number of prosumers. Several conclusions can be observed from Table 4. First, the AMSA algorithm requires small number of iterations and converges rapidly to a Nash equilibrium and the number of prosumers has a slight influence on calculation performance of the algorithm. Second, the average convergence time is proportional to the average number of iterations and barely changes as the number of prosumers increases from 10 to100. At last, the maximum number of iterations corresponds to the maximum convergence time and does not exceed the number of prosumers. In general, we conclude that the AMSA algorithm is practically feasible in implementing the IUPA for a community and has a good computational performance.

4.2. Comparison of results

In this section, we compare the proposed trading method with state of the art from different aspects to evaluate its performance. We consider three trading methods: 1) P2P trading with the IUPA; 2) P2P trading with the DA. The intersection point of the aggregated supply and demand curves sets the trading price of the DA; 3) P2G trading. The three methods are evaluated and compared mainly from three aspects:1) The trading prices; 2) The total amount of energy purchased from and sold to the utility grid; 3) The overall cost of each prosumer in the community.

Fig. 6 shows the trading prices determined by the aforementioned three methods in all different trading time slots. As shown in Fig. 6, the trading prices of P2P trading are limited between p_{FiT} and p_e, which are the fixed selling and buying prices of P2G trading. Moreover, in the seller's market, the trading price determined by P2P trading with the IUPA is lower than that by P2P trading with the DA. The iterative bidding format of the IUPA leads to this result. That is, buyer prosumers have incentive to lower their bids in the iterative bidding process to maximize their utilities, resulting a lower trading price. In the buyer's market, on the contrary, the uniform trading price in P2P with the IUPA is higher than that in P2P with the DA. The reason is that competitive seller prosumers would increase their offers in the IUPA to attain the Nash equilibrium. In contrast to P2P with the DA, the trading price of P2P with the IUPA is determined in the stable equilibrium state. In addition, compared with the CDA which determines different trading prices for various P2P trading contracts, the IUPA results a uniform trading price to guarantee the equitableness of P2P trading. These results are significant as they demonstrate the superiority of the IUPA mechanism in finding more reasonable and fairer trading prices that reflect a consensus of competitive prosumers.

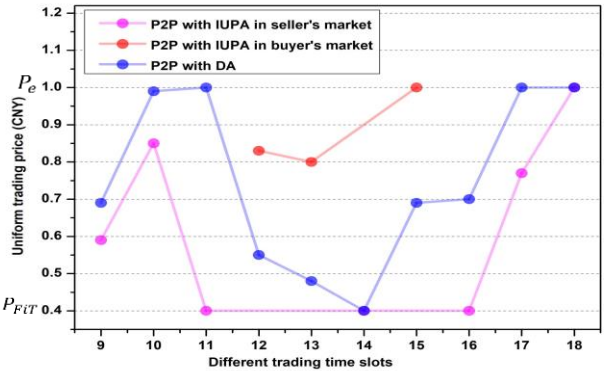


Fig. 6. Trading prices at different trading time slots

The total amount of energy purchased from and sold to the utility grid through the three trading methods are respectively shown in Figs. 7~8. The effects of P2P energy trading can be observed from the time slot 9 to 18. As observed from Figs. 7~8, the total amount of energy purchased from and sold to the grid significantly reduce with the application of P2P trading. Moreover, when comparing the two auction-based P2P trading mechanisms, Fig. 7 shows that the IUPA reduces the amount of energy purchased from the utility grid. However, as illustrated in Fig.8, the total amount of energy sold to the grid across all trading time slots between the IUPA and DA is nearly equal. To further compare the two auction mechanisms, Fig. 9 illustrates the total amount of energy traded in the P2P market. Note that the IUPA is able to sufficiently promote P2P trading by balancing the fewer one between the aggregated energy surplus and deficit. However, as shown in Fig. 9, the DA cannot promote energy transactions among prosumers to the maximum extent at time slots 8 and 16. Hence, Figs. 7~9 highlight that P2P trading with the IUPA reduces the dependence on the utility grid by sufficiently allocating all available energy surplus within the community microgrid.

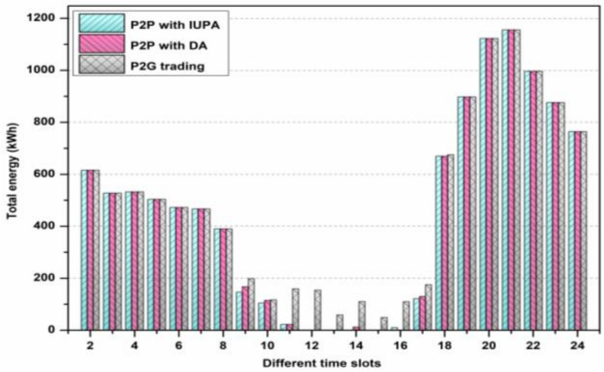


Fig. 7. Total energy purchased from the utility grid

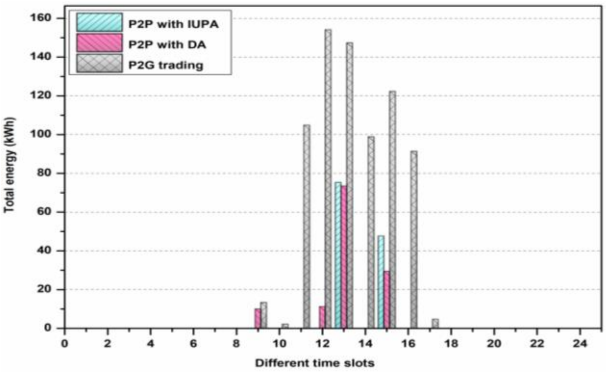


Fig. 8. Total energy sold to the utility grid

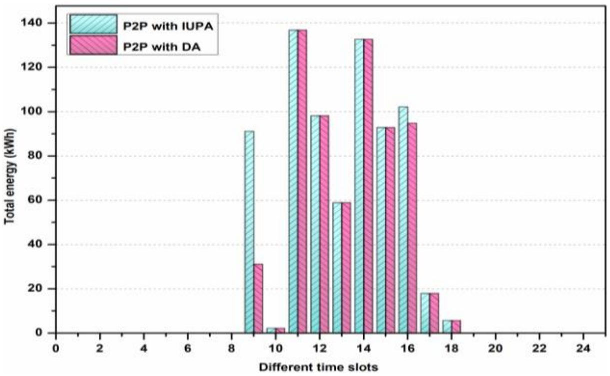


Fig. 9. Total energy traded in the P2P market

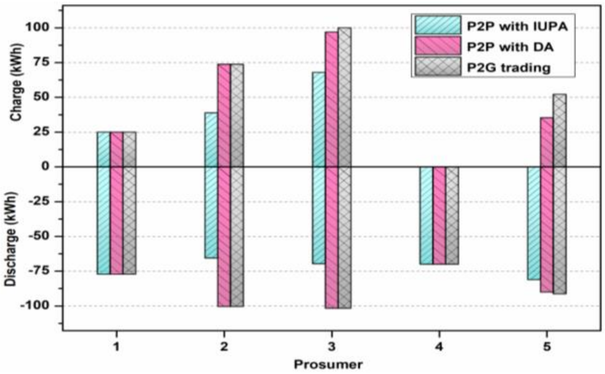


Fig. 10. Total energy charged into and discharged from the ESS across all trading time slots.

Table 5. Each prosumer's total cost of energy usage and the ESS usage across all trading time slots. The negative cost refers to the revenue of Prosumer 1 from selling its energy surplus to other prosumers and/or to the utility grid.

Prosumer	Cost of P2G trading(CNY)			Cost of P2P with DA(CNY)			Cost of P2P with IUPA(CNY)		
	Cost of energy usage	Cost of ESS usage	Total cost	Cost of energy usage	Cost of ESS usage	Total cost	Cost of energy usage	Cost of ESS usage	Total cost
Prosumer 1	-141.9	46.31	-95.59	-267.09	46.31	-220.78	-260.69	46.31	-214.38
Prosumer 2	343.75	60.25	404	272.33	60.25	332.58	266.58	39.33	305.91
Prosumer 3	125.69	61	186.69	91.05	61	152.05	94.31	41.76	136.07
Prosumer 4	994.9	42	1036.9	866.85	42	908.85	847.84	42	889.84
Prosumer 5	133.31	29.64	162.95	102.87	38.17	141.04	77.19	49.14	126.33
Total cost	1455.75	239.2	1694.95	1066.01	247.73	1313.74	1025.23	218.54	1243.77

The overall cost of each prosumer comprises: 1) cost of energy usage; 2) cost of the ESS usage. Each prosumer's total amount of energy charged into and discharged from the ESS across all trading time slots is shown in Fig. 10. Note that Prosumers 2, 3, and 5 charge and discharge a smaller amount in P2P with the IUPA, compared with P2P with the DA and P2G trading. In addition, the charge and discharge quantities of Prosumer 1 under the three trading methods are identical. Prosumer 4, with energy deficit across all time slots, discharges all stored energy. Fig. 10 reveals that the proposed P2P trading mechanism can save each prosumer's cost of the ESS usage by reducing the total amount of energy charged and discharged.

Table 5 presents the total cost of each of the five prosumers across all trading time slots. Several results can be drawn from Table 5. Firstly, P2P trading with the IUPA always outperforms P2G trading in terms of reducing the total cost and increasing the total revenue to each prosumer. For example, Prosumers 2~5 can save around 98.09 CNY, 50.62 CNY, 147.06 CNY, and 36.62 CNY or percentage savings of 24.28%, 27.11%, 14.18%, and 22.47%. Compared with selling its energy surplus to the grid in P2G trading, Prosumer 1 can increase its revenue about 118.79 CNY in P2P trading with the IUPA. Secondly, compared with the DA, although the IUPA results in a 2.9% revenue loss for Prosumer 1, the cost savings of the IUPA for other prosumers are substantial. For instances, Prosumers 2~5 can save around 26.67 CNY, 15.98 CNY, 19.01 CNY, and 14.71 CNY or percentage savings of 8.02%, 10.51%, 2.09%, and 10.43%, respectively. Finally, the sequence of the total energy usage cost from low to high is P2P trading with the IUPA, P2P trading with the DA, and P2G trading. Meanwhile, the sequence of the total ESS usage cost from low to high is P2P trading with the IUPA, P2G trading, and P2P trading with the DA. Therefore, P2P trading with the IUPA dominates the other two trading methods in terms of saving both energy and ESS usage costs for the community. On the whole, compared with P2G trading and P2P trading with the DA, the proposed trading method achieves the percentage of total cost savings for the community in a day is about 26.62% and 5.33%, respectively. Therefore, it is obvious from these results that the proposed trading method is effective in handling P2P trading and has the potential to bring economic benefits to the community microgrid on a daily basis.

5. Conclusions

In this paper, we have proposed a novel auction mechanism for P2P energy trading in a prosumer-based community microgrid. A prosumer participates in the P2P market either as a seller prosumer or a buyer prosumer. Based on the relationship of the aggregated energy surplus from all seller prosumers and energy deficit of all buyer prosumers, the P2P market is divided into the seller's and buyer's market. In the two types of market, the bidding format, market clearing rule, and information disclosure method of the IUPA mechanism are formulated. The prosumers are assumed to submit bids to maximize their own economic benefits depending on all available information. On this basis, the IUPA is modeled as a multiple players noncooperative game with incomplete information. The AMSA algorithm is devised to efficiently find an equilibrium solution of the game. By the simulation of P2P energy trading in different scenarios, the following conclusions could be drawn:

(1) The proposed AMSA algorithm could rapidly converge to a Nash equilibrium of the IUPA which determinates the uniform trading price and energy allocation in the P2P market. The market clearing outcome of the IUPA is more reasonable since it reflects a consensus among multiple competitive prosumers by allowing their iterative bidding adjustments.

(2) The trading strategy assumed in this paper captures the benefit-seeking nature of prosumers and requires relatively lower comprehension and computation power, which encourages prosumers to engage in P2P energy trading at the early age.

(3) Compared with conventional P2G trading and P2P trading with the DA, the proposed P2P trading with the IUPA sufficiently promotes local transactions of excess PV energy and significantly reduces the total costs consisting of energy usage costs and battery usage costs of the whole community.

Acknowledgement

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