Comparative Clearing Approaches in the Local Energy Market Based on the Prosumer Case Study

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ABSTRACT

In general, the clearing method in the local energy market is introduced based on two well-known methods: auction-based and game theory. However, both methods focus on different aspects; the auction-based method is based on economic equilibrium, whereas game theory is based on the concept of maximum profit. Therefore, to clarify the difference, the processes and algorithms of both methods are discussed and compared in this paper. In this study, the prosumer case study based on the non-cooperative day-ahead market is used to compare both methods. The prosumer is a good case because, as the lowest unit in the local market, it can apply to either seller or buyer. According to the case study, the comparative results focus on the difference between the local price and retail price, and the allocated energy quantity. The findings from the comparative results will advise the market operator on the most appropriate clearing method and market player for the bidding strategy design.

Keywords: Local Energy Market, Prosumers, Market Clearing Method

NOMENCLATURE

LCOE	Levelized cost of energy units generated
E	Energy produced by the generation unit
p	Local market energy price
P_{LMCP}	Local market clearing price of energy
P_{Retail}	Energy price in the retail market
Q_{Sell}	Quantity of energy units on the seller side
Q_{Buy}	Quantity of energy units on the buyer side
Q_{DSO}	Energy supplied by the upstream network
Q_d	Network energy demand
$P_{Bid-Pro}$	Bidding energy unit price for the prosumer
$Q_{Bid-Pro}$	Quantity of energy units bid by the prosumer
$Q_{Alc-Pro}$	Quantity of energy units allocated to the prosumer
LCOE_{Pro}	Levelized cost of energy units for the prosumer
Payoff_{Pro}	Payoff function of the prosumer

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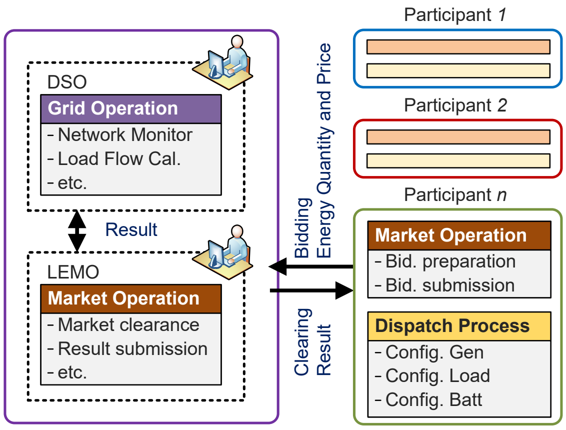


Fig. 1: *Example of the local energy market.*

1. INTRODUCTION

The integration of smart devices into the distribution network obviously enables active operation of the distribution system. From this perspective, local energy trading or transactive energy is one of the elements of an active distribution network [1, 2]. This concept allows consumer and generation units in the local area to trade or balance energy between each other. Regarding the consumer or the generation units in the distribution network, they could take a unit-based aggregator approach [3], such as a virtual power plant, microgrid, and prosumer. These are called market participants.

Fig. 1 presents an overview of energy trading and the structure of the local energy market. It can be observed that the local energy market operator (LEMO) is central to the market participants and distribution system operator (DSO). The market process begins by receiving bids from the market participants. After a time, the market operator needs to find out the market results, namely the electricity price and quantity of allocated power. Before sending these results to the market participants, the DSO must check the network constraints. It should be noted that this process is part of the day-ahead market.

In the market process, the market operator acts as a supervisor [4] and their decision must satisfy the participants as far as possible [5]. Thus, the market clearing approach is the key function for this purpose. In this case, the double-sided auction method and game theory are often applied [6–8]. The double-sided auction is based on an economic mechanism that the market equilibrium represents an intersection between demand and supply. While game theory is used to achieve

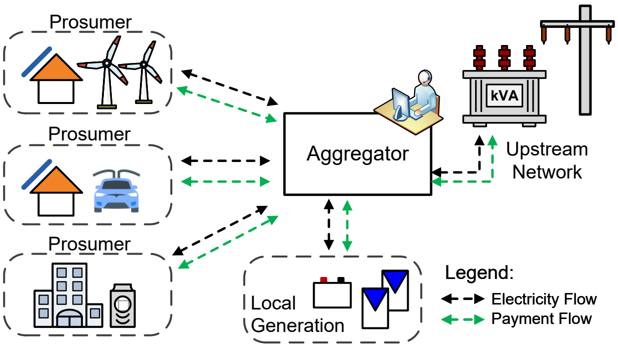


Fig. 2: *Overview of the aggregated model.*

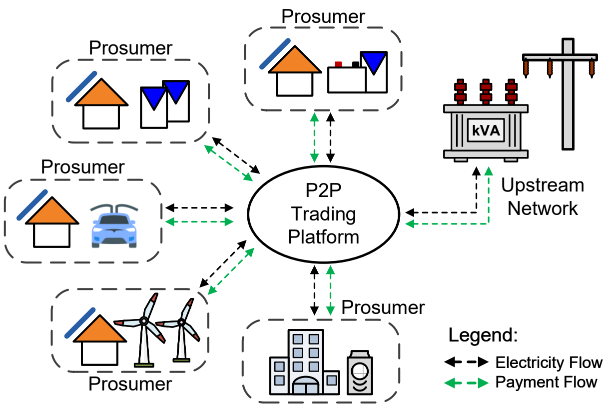


Fig. 3: *Overview of the peer-to-peer model.*

the maximum profit with multi-players and multiple strategies. It should be mentioned that both methods support a competitive local market [9].

To study the market clearing process, this study compares the double-sided auction method with game theory. The objective is to find the difference in the allocated energy quantity and local market price. This result leads to an effective energy management strategy between the market operator and the DSO or upstream network. The local prosumer market is considered in this study since the prosumer is the lowest unit in the local market and can manage selling or buying. The case study is simulated in a day-ahead market in order to observe the various scenarios.

The remainder of this paper is organized as follows. The prosumer business model is discussed in Section 2. The market processes based on the day-ahead market are detailed in Section 3. Section 4 presents the algorithm of both market clearing methods and the pricing mechanisms. The market constraints and support functions are given in Section 5. The study cases are presented and discussed in Section 6. Lastly the paper is concluded.

2. BUSINESS MODELS OF THE LOCAL ENERGY MARKET

Before describing the local energy market process and management strategy, it is important to first clarify the business models since the business models affect the transaction method and profit of the market players. At present, there are plenty of proposed business models, but the most well-known are the aggregated and peer-to-peer (P2P) models [10, 11]. To differentiate between the models, an overview and explanation are provided in the subsection. Since this paper focuses on the prosumer, the market players are defined by the prosumer units.

2.1 Aggregated Model

An overview of the aggregated model is presented in Fig. 2. In this business model, prosumers can only send their requirements or make transactions via an aggregator. The aggregator acts as an intermediary between prosumers and the upstream network or system operator. The aggregator is responsible for clearing the local market after prosumers have submitted their bids or offers. Additionally, the aggregator is given the opportunity to sign an ancillary service contract with the system operator to earn more profit when the prosumers in the control area have surplus energy. In this case, the prosumers will receive an extra payment. In [12], numerous aggregator companies are presented. This is proof that the aggregated model is already deployed in new market mechanisms.

2.2 Peer-to-Peer Model

Since an unfair intermediary in the aggregated model can cause an overcharging problem, the P2P model was originally developed to remove the intermediary in the energy trading system. The principle of the P2P model is that it offers direct negotiation between the buyer and seller. This means that prosumers can select the electricity transaction themselves, rather than be forced to accept whatever price the supplier chooses to set. However, this model requires a trading platform, as shown in Fig. 3. This trading platform is the center for negotiation and transactions. The platform does not create value in the energy trading system.

Another purpose of P2P trading is to minimize taxation, supplier costs, and network costs [13]. It should be noted that this business model is based on the use of third-party access, where prosumers must pay wheeling charges to the system operator as an extra cost for each energy transaction since there is no intermediary to manage this aspect.

In conclusion, the aggregated model represents a competitive scenario for market players, whereas the P2P model is a matching agreement between two market players. Thus, the aggregated model is selected in this work because the study of the market clearing process requires competitive conditions to achieve the maximum profit. The aggregated model is also suitable for the study of the market players' bidding strategies.

3. COMPETITIVE MARKET PROCESSES OF THE AGGREGATED MODEL

Since the aggregated model sets the market process, the market players or prosumers can only make energy

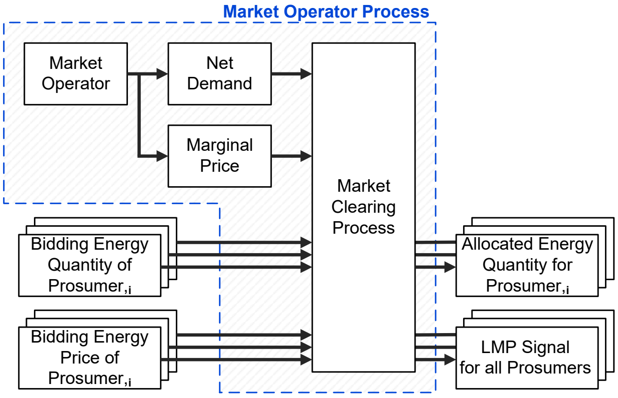


Fig. 4: *Market processes based on the day ahead market.*

transactions with the aggregator, and the energy sellers must then bid for their own energy quantity and price with the intermediary. The aggregator then calculates the market equilibrium price. This operation is called the competitive market. To explain the competitive market in detail, the market process, bidding energy quantity, and bidding price are discussed in this section. It should be noted that the explanation focuses on the day-ahead process in the local energy market.

3.1 Market Process Based on the Day-Ahead Market

In the competitive market, energy sellers must bid for both their proposed energy quantity and energy price in the market. Consequently, the aggregator or market operator plays an important role in organizing and allocating the energy requirement. Fig. 4 explains the day-ahead market. The working process functions in the following sequence. Initially, the energy sellers or aggregators must bid for the energy quantity and price in 24 slots. Meanwhile, the market operator prepares the net demand and marginal price for each slot. It should be noted that the information is usually based on historical data .

When all information has been collected, the market clearing process takes place to find the market equilibrium for each time slot. As soon as the bidding results are ready, the bidders have a certain time to accept the results or submit a new bid for recalculation. Once, all participants confirm the bidding results, the market operator will announce to them the allocated energy quantity and local market price (LMP). It should be noted that all the processes mentioned must be structured by time control, which depends on the agreement with the market regulator.

3.2 Bidding Energy Quantity and Bidding Price

The pre-market process determines the bidding energy quantity and bidding price for all market players or prosumers prior to entering the energy market. To bid for energy quantities, prosumers must organize their energy portfolios, i.e., buying and selling time slots. The energy portfolio is generally dependent on power generation capability, energy consumption behavior, and energy management strategy. Consequently, the bidding price is designed in accordance with the portfolio generated for each time slot. In this paper, the levelized cost of energy (LCOE) is applied to determine the bidding price. The calculation is

$$\text{Bidding Price} = \frac{\sum_{i=1}^{n} (\text{LCOE}_i \times E_i)}{\sum_{i=1}^{n} E_i} \tag{1}$$

where LCOE_i is the levelized cost of energy for each generation unit and E_i is the energy provided by the generation unit. i is the number of generation units assigned for energy trading.

It is obvious that the bidding price is only calculated for the selling time slot. For the buying time slot, the prosumer must accept the local market price. It seems that the buyer is a price-taker, but in fact, all market participants in the local energy market are price-makers. The energy demand-side of energy also has an effect on the local market price. Finding the market clearing price and the function of the demand-side are discussed in the following section.

4. MARKET CLEARING APPROACHES

The market clearing process is the key function of local market operation. This process is designed to allocate the energy quantity to the selling prosumer and set the price of the energy transaction. Moreover, the clearing process involves finding a settlement that all participants agree on. Economists call this situation an equilibrium point. To find the economic equilibrium, the auction-based method and game theory are discussed in this paper. Both methods are well-known and often applied to the energy trading market. The discussion objective is to investigate and compare both methods in the case of a prosumer-based local energy market. The pricing mechanism, market constraints, and support function are also mentioned in this section.

4.1 Auction-Based Method

The auction-based method is simple and concise. To find the economic equilibrium, the supply offers should be sorted in ascending order, and the demand bids in descending order, according to price. The crossing point between demand and supply is therefore the economic equilibrium or market clearing price. Depending on the status of market participants, i.e., whether they are sellers or buyers, the auction-based method can be divided into two types: single-sided and double-sided. The single-sided auction is where the seller or buyer is allowed to bid on their expected price. In energy trading, the seller is generally allowed to bid. This is referred to as generation planning in the transmission system and based on merit order. In the case of a double-sided

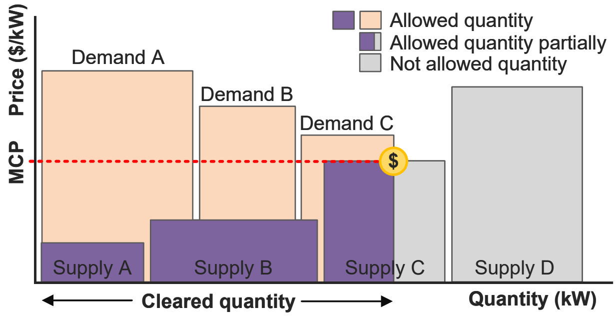


Fig. 5: Scenario of the double-sided auction.

auction, the seller and buyer must bid on the price they anticipate. Of the two methods, the double-sided auction is deemed suitable for the competitive market or free market, which is the main focus of this work. However, both methods will be analyzed in the case study section to differentiate between their advantages and limitations.

Fig. 5 illustrates the scenario of a double-sided auction. In terms of the seller, the arrangement is from supply A to supply D, the lowest price to the highest. On the buyer side, the arrangement is from demand A to demand C, the highest price to the lowest. Market clearing is the point at which the supply intersects with demand. The clearing result clarifies that supply A and B are allowed to sell the entire power quantity. The player C can partially sell, and none of player D is allowed to sell.

To establish the auction-based method for the market operator, the scenario process is formulated and programmed as shown in Algorithm 1. It can be observed from the algorithm that there are two main parts: data sorting and cross-section finding. When the market is clear, the local market price (p^*), based on the allocated energy of the seller (q_S^*), and the allocated energy of the buyer (q_B^*) are sent back to market participants. It should be noted that the algorithm presented is only for one time slot.

Algorithm 1 Auction-based method

Receive buyer's bid and seller's offer {*price, quantity*}
Sort all data
    demand bids in descending order
    supply offers in ascending order
Start initial $D = 1, S = 1$
while 1 **do**
  if intersect(demand, supply) **then**
    break
  end if
  if demand < supply **then**
    $D = D + 1$
  end if
  if demand > supply **then**
    $S = S + 1$
  end if
end while
Send p^*, q_S^*, q_B^* to all market participants

In summary in the auction-based method, it can be interpreted that the supplier, who can offer a lower price, tends to sell a higher quantity of energy. On the other hand, the higher the price demanded in the bid, the higher the quantity that can be bought.

4.2 Game Theory

According to the point of auction-based method, the energy transaction is based on the bidding price and energy quantity bid, which may result in a predatory situation. If some prosumer units submit very low bids, the unit will be a price-taker and can supply all the energy. To avoid this situation and to obtain the maximum profit, game theory should be considered. Game theory is based on a player performing better than the competition. Thus, it is necessary to consider the strategies of other participants. The best response for all players is to reach Nash equilibrium.

To find a solution to game theory, the Nikaido-Isoda function and relaxation algorithm (NIRA) is selected. The NIRA supports multiple strategies from the player perspective. The combination of the relaxation method and Nikaido-Isoda function is a mechanism for solving market equilibria in multi-player games with the different strategies adopted by players [14]. Accordingly, the market operator can relax the bidding strategy of the prosumer unit and obtain the maximum profit. In addition, the Nikaido-Isoda function is used to solve the equilibrium problem in a non-cooperative game.

Algorithm 2 presents a solution to the problem based on game theory. After receiving the bids, bidding strategy sets are created. The payoff function must be created as well (see lines 2 to 4). Afterward, the NIRA process begins and the best payoff is calculated for the energy price and allocated energy quantity.

Algorithm 2 Game theory method

1: Receive buyer's bid and seller's offer {*price, quantity*}
2: Set random range of quantity $[0, q]$
3: Set random range of price $[p, p_{retail}]$
4: Given the payoff function for both buyer and seller
5: Start initial value with lower boundary, and set $k = 0$
6: **while** 1 **do**
7:   $k = k + 1$
8:   Substitute price and quantity to all variables
9:   Calculate payoff for buyer and seller function
10:   Summarize all participants' payoff
11:   Calculate **NI**;
12:   **if** < 0.0001 **then**
13:     break
14:   **end if**
15:   Update p^*, q_S^*, q_B^* by **RA**, with step size
16: **end while**
17: Send p^*, q_S^*, q_B^* to all market participants

It can be observed that the payoff function is included in the calculation with game theory, which does not exist in the auction-based method. This is the main difference between these two methods. The formulation of the payoff function is explained in the next section.

4.3 Pricing Mechanism

In economics, the point at which the demand and supply curves cross each other's path is the equilibrium, meaning that every participant in the market is satisfied, and the pricing mechanism is one of its key features. It affects the bidding strategy and payoff function. In the local energy market, uniform pricing and pay-as-bid pricing are often applied, as in [15, 16]. In uniform pricing, all players will take the same clearing price, while for the pay-as-bid pricing, the settlement price is identical to the price expected by each participant. Therefore, pay-as-bid pricing might satisfy all participants in the market by giving them the price they anticipated. On the other hand, the sellers cannot get more money than they expected, and the buyers have no opportunity to buy energy at a lower price.

Consequently, uniform pricing is selected in this study due to the flexible and competitive behavior between each participant in the market. The market participants must therefore have their own strategy to get the highest return.

4.4 Market Constraints

To shape the results of market clearing, the constraints in terms of energy quantity and the local market clearing price must be defined.

Firstly, the energy quantity constraint is delivered as shown in Eq. (2). The energy quantity from the seller's perspective must be equal to that of the buyer. In addition, energy from the upstream network is registered to the seller and the local energy demand is registered to the buyer.

$$\left(\sum_{i=1}^{n} Q_{Sell,i} + Q_{DSO}\right) - \left(\sum_{j=1}^{m} Q_{Buy,j} + Q_d\right) = 0 \quad (2)$$

where Q_{Sell} and Q_{Buy} represent the allocated energy of the seller and buyer, respectively, Q_{DSO} is the energy supplied from the main grid or upstream network, and Q_d is the net energy demand.

Secondly, the local market clearing price constraint is considered. This constraint is based on the idea that all surplus energy in the local area must be completely delivered before taking energy from the upstream network. Thus, the local market clearing price constraint must be less than or equal to the retail price from the upstream network, as given in Eq. (3)

$$P_{LMCP} \leq P_{Retail} \quad (3)$$

It should be noted that both market constraints are applied to the market clearing calculation in the auction-based method and game theory.

4.5 Support Functions

Regarding the support functions, the local market clearing price and payoff are considered. It should be noted that both functions are only applied in game theory to maximize profits for all market participants.

Firstly, the local market clearing price function is developed using the linear function with a negative slope. The intersection of the y-axis can be assigned from the upper boundary of the local market clearing price constraint shown in Eq. (3). Regarding a negative slope, the numerator is the summation of the prosumer bidding price ($P_{Bid-Pro,i}$) and the prosumer bidding energy quantity ($Q_{Bid-Pro,i}$). The denominator is the summation of the available energy from all seller prosumers. This summation can be implied as an intersection point of the x-axis. The local market clearing price function can then be derived as

$$P_{LMCP} = P_{Retail} - \frac{\sum_{i=1}^{n} \left(P_{Bid-Pro,i} \times Q_{Bid-Pro,i}\right)}{\sum_{i=1}^{n} Q_{Bid-Pro,i}}. \quad (4)$$

The results from the Eq. (4) are used to declare the payoff function. The payoff function of the prosumer unit is divided into two categories: seller energy and buyer energy. For the seller, the payoff is defined by the difference between the P_{LMCP} and LCOE of the prosumer unit, multiplied by the allocated energy quantity ($Q_{Alc-Pro,i}$). For the buyer, the payoff is the multiplication of P_{LMCP} and allocated energy quantity. It should be noted that the plus refers to the seller and the negative to the buyer. As a result, the payoff functions are written as

$$\text{Payoff}_{Pro,i} = \begin{cases} Q_{Alc-Pro,i} \times \left(P_{LMCPi} - \text{LCOE}_{Pro,i}\right), & \text{seller} \\ -Q_{Alc-Pro,i} \times P_{LMCPi}, & \text{buyer} \end{cases} \quad (5)$$

It should be mentioned that the payoff function is formulated according to the proposed local market price function. If the local market price function is different, it not only affects the payoff function but also the market clearing results.

5. CASE STUDIES AND DISCUSSION

To study and compare the proposed market clearing methods in a non-cooperative market based on the prosumer case, the local energy market presented in Fig. 6 is examined. In the system, there are five prosumers, a network load, and market operator. Furthermore, the system is connected to the upstream network.

The prosumers have different generation technology and an internal load. Prosumer 1 is installed only on the solar system. Prosumers 2 and 3 occupy the solar system with a battery energy storage system (BESS). Wind turbines are utilized by Prosumers 4 and 5. In

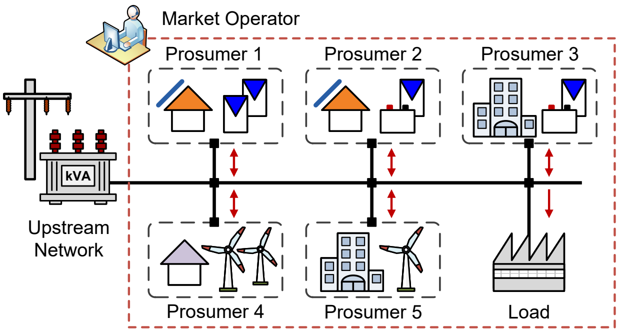


Fig. 6: *Examined local energy market network.*

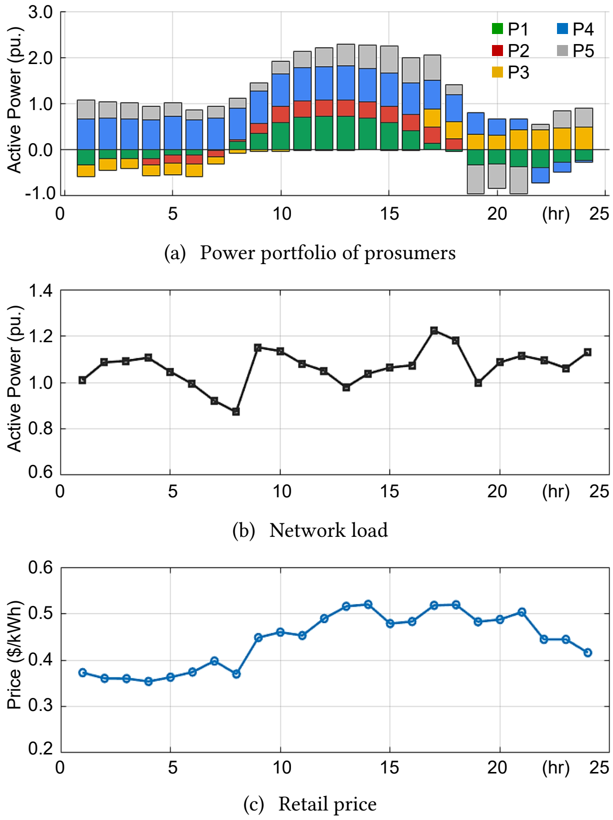


Fig. 7: *Input of the examined network; (a) power portfolio, (b) network load, and (c) retail price.*

Fig. 8: *Bidding price.*

terms of generational cost or selling cost, the LCOE of the generation technology is utilized. The LCOE of the solar system is 0.03574 $/kWh, the solar system with BESS is 0.057184 $/kWh, and the wind turbine is 0.12225 $/kWh [17].

The input for the market operator is a power portfolio, which all prosumers have to submit to the market operator prior to the clearing process. The power portfolio in this paper is considered as the net profile of the prosumer, as shown in Fig. 7(a). The positive value for quantity represents a production surplus and the willingness to sell energy. On the contrary, a negative value implies an energy shortage and the willingness to buy energy. The network load is also shown in Fig. 7(b). It should be noted that the base value for power is set at 20 kW.

In fact, the power portfolio can be managed based on the prosumer's own strategy. For example, Prosumer 3 planned for the surplus power generated during the daytime to be kept in the BESS, with the stored energy subsequently being sold in periods of power shortage or early in the evening to obtain a higher profit (see Fig. 7).

The retail price is assigned as the energy price for the upstream network. This price is modified from the wholesale market price [18]. Fig. 7(c) shows the retail price, which is changed hourly. It should be noted that the energy from the upstream network will be brought in only when there is an energy shortage in the local market.

The market clearing aspects of the auction-based method and game theory along with the comparative results are discussed in the following section. It should be noted the network congestion and wheeling charge are ignored in this study.

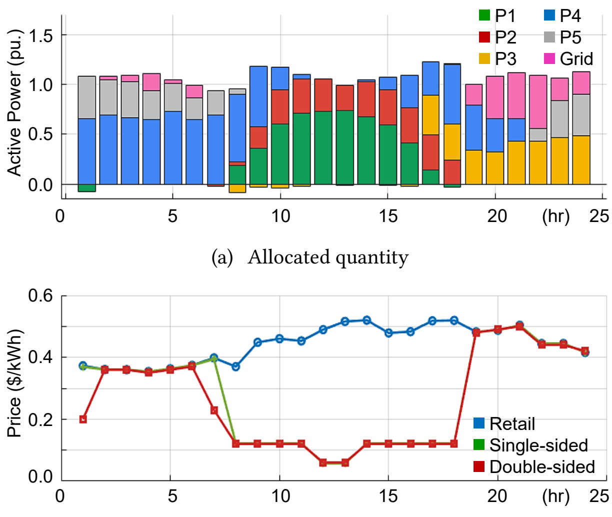
5.1 Market Clearing Using the Auction-Based Method

This study aims to demonstrate the difference between single-sided and double-sided auctions under the same power portfolio. According to the principle of a single-sided auction, the sellers bid for their expected selling price, whereas the buyers' price is referred to as the retail price. In contrast, the sellers and buyers can bid for their desired price in a double-sided auction. The bidding price of both auction methods are shown in Fig. 8. It should be noted that all prosumers must submit their bidding price and power portfolio to the market operator prior to the market clearing process.

The bidding price in Fig. 8 is for a double-sided auction. The positive price represents the seller side, and the negative price the buyer side. As previously mentioned, the seller is the only bidder in the single-sided auction, thus, the negative price is neglected.

According to Fig. 8, the selling price of each prosumer is set to the LCOE. The buying price varies. However, there is an assumption that the price in the early evening is higher than during other periods, and the price must be lower than the retail price. After collecting data from all participants, the market operator begins clearing the market. The market clearing results, i.e., allocated energy quantity and local equilibrium price, are shown in Figs. 9(a) and 9(b), respectively.

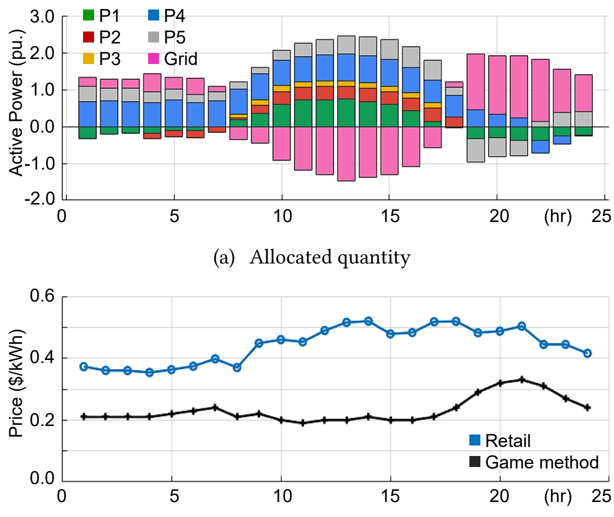
In terms of allocated energy, both auction methods return the same allocated energy quantity result because



(a) Allocated quantity

(b) Local market price and retail price

Fig. 9: *Auction-base market clearing results; (a) allocated energy quantity and (b) local market price.*



(a) Allocated quantity

(b) Local market price and retail price

Fig. 10: *Game theory market clearing results; (a) allocated energy quantity and (b) local market price.*

their intersection points are identical. It is obvious that the allocated energy quantity follows the power balance constraint. When the seller's energy quantity is insufficient to supply the local area, the excess demand is brought in from the upstream network. This can be observed from the energy used during the evening period. If the supplied quantity is more than the local demand, the prosumer, which has surplus energy, considers selling. However, the ultimate allocated energy quantity is decided by the principle of auction. The seller's quantity, placed on the righthand side after the equilibrium or intersection point, will be ignored and the auction is finished. This situation can be observed during midday, at which time Prosumers 4 and 5 cannot sell energy.

In terms of local market price, Fig. 9(b) illustrates the difference between the auction-based method and retail price. Firstly, the local price and retail price are equal. This situation becomes clearer when power is imported from the upstream network. Similarly, when the power can be managed inside the local area, the local price is designated by the auction-based method. Accordingly, the comparative results between a single-sided and double-sided auction is subsequently explained. The main difference occurs at 1:00 and 7:00. The buyer has the ability to set a price during certain intervals. For example, buyers can decrease the cost on the order to increase their cost savings. Conversely, the sellers lose some of their revenue because the settlement price is cheaper according to the principle of a double-sided auction.

In conclusion, the double-sided auction is more useful than the auction-based method for explaining the non-cooperative market due to its capability for competition among participants in the market. Furthermore, the equilibrium price could vary and protect the market from collusion and speculation by collective participants.

5.2 Market Clearing Using Game Theory

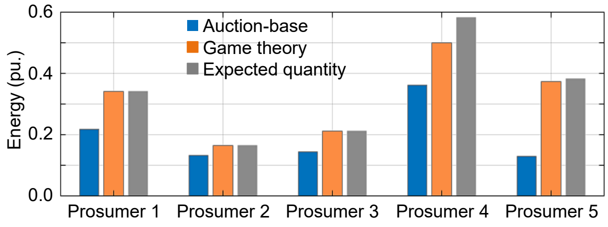
Market clearing using game theory is tested under the same conditions. The information input in Fig. 7 is applied. The bidding price in Fig. 8 is used as the initial condition for the payoff function, whereby the positive price applies to the seller prosumer and the negative price to the buyer prosumer.

In the clearing process, the game theory algorithm calculates and summarizes the payoffs for all participants. For this reason, every possible scenario will be considered in the algorithm until the maximum profit is achieved. This is known as the Nash equilibrium. The market clearing results using game theory are presented in Fig. 10.

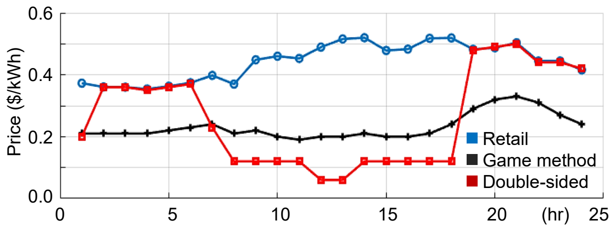
As can be observed from Fig. 10(a), using the allocated quantity method, prosumers are able to sell more power than in the auction-based method. The surplus power in the local area is sold to the upstream network during the midday period, which is significantly different to the auction-based method (see Fig. 9(a)). This is because the auction-based method considers only the situation before the intersection between the demand and supply curve. Hence, it can be clearly observed that game theory provides greater quantity allocation to market participants or prosumers.

The market clearing price is shown in Fig. 10(b). In this case, the price is lower than the retail price at all times. Furthermore, the local price trend in game theory follows that of the retail price. In periods of energy shortage, from 01:00 to 07:00 and 19:00 to 24:00, the local price is close to the retail price. In periods of energy surplus, from 08:00 to 18:00, a larger gap can be observed between the local price and retail price. This proves that the calculation function is correct.

In game theory, the local price is related to the proportion of the allocated energy quantity. The more



(a) Allocated energy quantity



(b) Local market price and retail price

Fig. 11: *Comparative results; (a) allocated energy quantity and (b) local market price.*

energy allocated, the lower the local price. This situation is correct based on game theory, which provides the maximum benefit to all market participants.

5.3 Comparative Result Discussion

In comparing both market clearing methods, the allocated energy quantity and the market price must be taken into account. Fig. 11(a) focuses on the allocated energy quantity and the expected energy of each prosumer throughout the day. It is obvious that the allocated energy quantity using game theory is higher than the auction-based method. The application of game theory method results in 96.7% of the total expected energy quantity. In contrast, the auction-based method provides 61.9% of the total expected energy quantity. The reason for this is that the calculation in auction-based method is stopped at the intersection of the demand and supply curve. Whereas in game theory, the calculation is stopped when the payoff function reaches the maximum level. Thus, the energy during the surplus period is delivered to the upstream network.

Fig. 11(b) shows the difference in clearing price between game theory and the double-sided auction method. In game theory, the price is always lower than the retail price and higher than the LCOE. However, in the auction-based method, the price swings toward the retail price and LCOE price. This swing occurs because not all seller prosumers can join the trading in every time slot. Game theory gives an average local price of 0.23 $/kWh, while the double-sided auction provides an average local price of 0.26 $/kWh. The average retail price is 0.44 $/kWh. Accordingly, it can be stated that game theory provides the lowest local price but offers the highest return to market participants.

Overall, in this prosumer case study, the application of game theory provides the best local price and highest allocated energy quantity.

6. CONCLUSION

One of the key features of establishing transactive energy in the distribution network or local market is the market clearing process, for which the market operator is responsible. The market operator must find the local market clearing price and allocated energy quantity. To achieve this, the auction-based method and game theory are investigated in this paper. The algorithm and support function of both methods are considered. Therefore, a comparative study is conducted in this paper.

To compare both methods, the non-cooperative market is considered, based on the prosumer case study. The prosumer provides a good example because it can act as either seller or buyer. The case studies are tested under the same conditions: bidding price, quantity of bidded energy, and market constraints. Consequently, the application of game theory results in a higher allocated energy quantity and lower average local price than the auction-based method. The reason for this is that game theory is calculated based on the maximum benefit to all prosumers. Whereas the auction-based method is considered at the intersection point between the demand and supply curves. In summary, energy allocation can vary in specific situations, depending on the energy proportions of each market participant. In terms of price, the local market clearing price was found to be cheaper or equal to the retail price.

REFERENCES

[1] M. Khorasany, D. Azuatalam, R. Glasgow, A. Liebman, and R. Razzaghi, "Transactive energy market for energy management in microgrids: The monash microgrid case study," *Energies*, vol. 13, no. 8, 2020, Art. no. 2010.

[2] Z. Liu, Q. Wu, S. Huang, and H. Zhao, "Transactive energy: A review of state of the art and implementation," in *2017 IEEE Manchester PowerTech*, 2017.

[3] O. Abrishambaf, F. Lezama, P. Faria, and Z. Vale, "Towards transactive energy systems: An analysis on current trends," *Energy Strategy Reviews*, vol. 26, 2019, Art. no. 100418.

[4] J. Momoh and L. Mili, Eds., *Economic Market Design and Planning for Electric Power Systems*. Hoboken, NJ, USA: John Wiley & Sons, 2009.

[5] H. Khajeh, H. Laaksonen, A. S. Gazafroudi, and M. Shafie-khah, "Towards flexibility trading at TSO-DSO-customer levels: A review," *Energies*, vol. 13, no. 1, 2019, Art. no. 165.

[6] J. Yang, J. Zhao, J. Qiu, and F. Wen, "A distribution market clearing mechanism for renewable generation units with zero marginal costs," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 8, pp. 4775–4787, Aug. 2019.

[7] L. Cheng and T. Yu, "Game-theoretic approaches applied to transactions in the open and ever-growing electricity markets from the perspective of power demand response: An overview," *IEEE Access*, vol. 7, pp. 25 727–25 762, 2019.

[8] S. Ø. Ottesen, A. Tomasgard, and S.-E. Fleten, "Prosumer bidding and scheduling in electricity markets," *Energy*, vol. 94, pp. 828–843, 2016.

[9] M. Bae, H. Kim, E. Kim, A. Y. Chung, H. Kim, and J. H. Roh, "Toward electricity retail competition: Survey and case study on technical infrastructure for advanced electricity market system," *Applied Energy*, vol. 133, pp. 252–273, 2014.

[10] W. Tushar, T. K. Saha, C. Yuen, D. Smith, and H. V. Poor, "Peer-to-peer trading in electricity networks: An overview," *IEEE Transactions on Smart Grid*, vol. 11, no. 4, pp. 3185–3200, Jul. 2020.

[11] D. Brown, S. Hall, and M. E. Davis, "Prosumers in the post subsidy era: an exploration of new prosumer business models in the UK," *Energy Policy*, vol. 135, 2019, Art. no. 110984.

[12] K. Baes and F. Carlot. "Virtual power plants –at the heart of the energy transition," Apr. 2018. Arthur D. Little. [Online]. Available: https://www.adlittle.com/en/insights/viewpoints/virtual-power-plants-heart-energy-transition

[13] S. Hall, D. Brown, M. Davis, M. Ehrtmann, and L. Holstenkamp, "Business Models for Prosumers in Europe," PROSEU - Prosumers for the Energy Union: Mainstreaming active participation of citizens in the energy transition (Deliverable No. D4.1), 2020. [Online]. Available: https://proseu.eu/sites/default/files/Resources/PROSEU_D4.1_Business%20models%20for%20collective%20prosumers.pdf

[14] J. Krawczyk and J. Zuccollo, "NIRA-3: An improved MATLAB package for finding Nash equilibria in infinite games," Dec. 2006. [Online]. Available: https://mpra.ub.uni-muenchen.de/1119/1/MPRA_paper_1119.pdf

[15] A. Akbari-Dibavar, B. Mohammadi-Ivatloo, and K. Zare, "Electricity market pricing: Uniform pricing vs. pay-as-bid pricing," in *Electricity Markets*, N. S. and Z. K., Eds. Cham, Switzerland: Springer Nature, 2020, pp. 19–35.

[16] S. Tierney, T. Schatzki, and R. Mukerji, "Uniform-pricing versus pay-as-bid in wholesale electricity markets:does it make a difference?," Analysis Group and New York Independent System Operator, Mar. 2008.

[17] U.S. Energy Information Administration, "Levelized cost of new generation resources in the annual energy outlook 2021," Feb. 2021. [Online]. Available: https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf

[18] "ENTSO-E transparency platform." European Network of Transmission System Operators for Electricity. https://transparency.entsoe.eu/

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