Research on Bidding Strategies for Virtual Power Plants Based on Continuous Two-way Auctions

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Abstract: In response to the progressive depletion of fossil fuel resources and the exacerbation of climate change, the global development of renewable energy generation has accelerated. However, the extensive integration of renewable energies into the electrical grid presents significant challenges. These include not only a substantial impact on the traditional energy market's supply-demand equilibrium but also the introduction of unpredictable elements into the power market. This paper introduces a novel bidding strategy for virtual power plants, employing a continuous two-way auction mechanism. This strategy aims to leverage electricity pricing as a motivational tool for energizing both supply and demand stakeholders, thereby enhancing renewable energy consumption levels. The proposed method involves a detailed analysis of power market trading conditions, methodologies, and regulatory frameworks. This analysis facilitates the creation of a three-stage bidding function that aligns with the psychological profiles of both buyers and sellers. Additionally, the strategy encompasses user cost calculations and error mitigation strategies. Through a series of simulation tests, the efficiency of renewable energy consumption and the enhancement of social welfare in a sealed-bid auction context are compared and assessed. The results affirm that the proposed continuous two-way auction-based strategy for virtual power plants significantly contributes to the optimized utilization of renewable energy and fosters the growth of the electricity market.

Keywords: electricity market; renewable energy consumption; virtual power plant

1 Introduction

In recent years, the issue of global fossil fuel scarcity has become increasingly prominent, accompanied by growing concerns regarding the environmental impact of conventional thermal power generation. This has captured the attention of nations worldwide. In response to these global energy trends, China has been actively promoting the development of clean energy sources, such as wind and photovoltaic power [1]. However, due to the limited capacity for guaranteed power generation from these renewable energy sources, enterprises in this sector face challenges in the power market, characterized by reduced competitiveness. Consequently, the rapid growth of renewable energy has led to significant issues, including the curtailment of wind and solar power, making the consumption of renewable energy an urgent problem to address in modern power system operations. As a result, power market bidding strategies have garnered considerable interest from global energy researchers [2]. These strategies, essential for enhancing the market competitiveness of renewable energy and promoting its consumption, involve selecting various bids during the power trading process in accordance with specific

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rules. This approach is based on a thorough analysis of the current power market trading mechanisms, incorporating cost calculation and detailed analysis of specific trading regulations. Such strategies aim to safeguard the interests of power generation enterprises, substantially improve the market competitiveness of renewable energy generation, and ultimately foster increased consumption of renewable energy.

The exploration of how current renewable energy policies impact bidding strategies within the power market has garnered considerable attention from experts and scholars globally. The research documented by Zhang et al. [3] offered a comprehensive comparison and summary of medium- and long-term trading regulations within the electricity spot market across four distinct regions. This study delved into the current status of renewable energy trading in China, identified prevalent issues, and provided recommendations for the integration of renewable energy into power market bidding strategies. Additionally, Zhang and Shi [4] examined the evolution of China's power markets in response to renewable energy. They contrasted the incentives for renewable energy with various trading methods, exploring the myriad challenges that renewable energy participation in power markets may encounter. This research also aggregated and reviewed the findings from different countries in the realm of renewable energy. Chen et al. [5] integrated the guaranteed renewable energy consumption concept into the electricity market's bidding strategy framework. They proposed a strategy that was activated by the spot market in instances of energy curtailment. Meanwhile, Zhou et al. [6] developed a novel bidding strategy that includes both thermal power and wind turbines. This strategy takes into consideration the quota system and green power certificate trading policies, aiming to maximize the interests of all involved parties. The approach employs Monte Carlo simulations and neural network algorithms to address the problem, demonstrating the strategy's feasibility through empirical verification. In summary, as the variety and capacity of renewable energy sources connected to the power grid continue to grow, their share in the power market is also increasing. As active participants in power market transactions, it becomes imperative for renewable energy providers to articulate their trading intentions clearly. Therefore, to better balance the interests of both parties in market transactions, there is a pressing need for further research into bidding strategies based on renewable energy consumption, particularly in the context of bilateral transactions.

This paper focuses on the virtual power plant and the renewable energy sector, conceptualized as the buyer and seller within the power market. It examines the applicable conditions, transaction modes, and rules governing power market transactions facilitated through a continuous two-way auction. In line with the transactional psychology of the involved parties, a three-stage bidding function is proposed. This includes a detailed analysis of cost calculation methodologies and error processing techniques. The study introduces a virtual power plant bidding strategy based on the continuous two-way auction model. This strategy enables virtual power plants and the renewable energy sector to adjust their bid prices in response to market trading data. Simulation results demonstrate that this approach surpasses traditional sealed-bid auction strategies in terms of renewable energy consumption efficiency and societal welfare.

2 Transaction mechanisms in electricity markets based on continuous two-way auctions

2.1 Transactions

When deploying continuous two-way auctions in electricity market transactions, the process unfolds in distinct trading cycles. In each cycle, a specified portion of electricity is auctioned until the transaction reaches completion. The initiation and conclusion timings of these auctions are not predetermined but vary randomly. Within the same trading cycle, the buyer (virtual power plant) is able to procure a predetermined amount of electricity at a specific price; similarly, the seller (renewable energy power plant) can publicly offer a set quantity of electricity for sale at a designated price. The bids from these power trading entities are accessible to all participants in the market, ensuring uniformity in the information available to both buyers and sellers. If the bid from the buyer (virtual power plant) exceeds the asking price of the seller (renewable energy power plant), a transaction will occur. In cases where a transaction is not completed, both entities have the flexibility to modify their offers to align more closely with market trends, thereby increasing the likelihood of a successful electricity trade. Specifically, the seller (renewable energy power plant) may reduce its price, while the buyer (virtual power plant) can increase its offer before participating in the next auction cycle. The auction process concludes either when no further transactions occur or when the market's capacity limit is reached, leading to the closure of the market. Figure 1 illustrates this transaction mechanism in a continuous two-way auction-based electricity market.

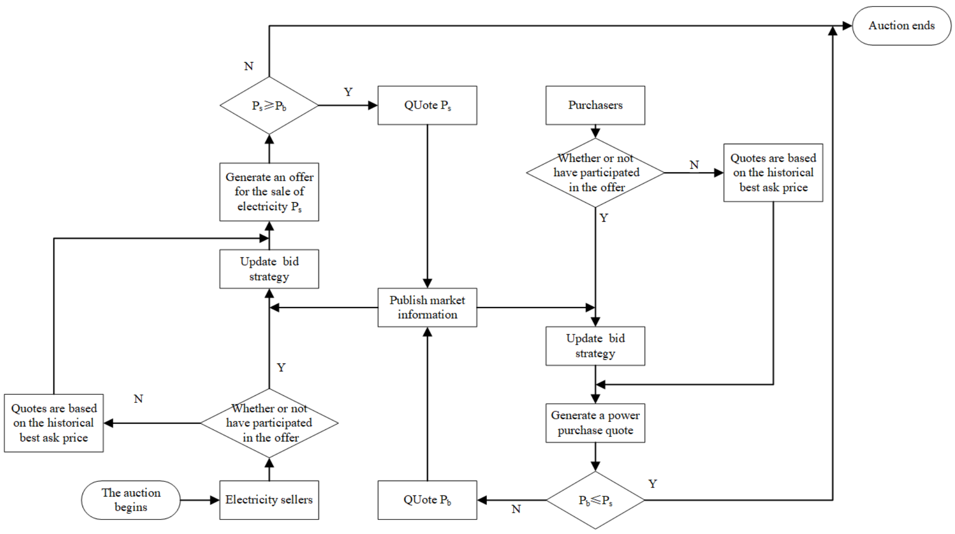

Fig. 1 Transaction diagram of the continuous two-way auction market.

Daily, within a predetermined timeframe, renewable energy power plants and virtual power plants that satisfy the market entry criteria submit their trading applications. These applications are assessed collaboratively by the power trading organization and the power dispatching organization. Subsequently, centralized bidding and trading are conducted. Both transaction parties utilize the power trading platform to declare their electricity and tariff offers. This platform is responsible for matching transactions, disclosing the identities of the involved parties, and updating transaction information in accordance with the bidding rules of the continuous two-way auction. The bidding process concludes either when one party's electricity transactions are fully executed or when the maximum number of bidding rounds is reached.

2.2 Transaction rules

The term "continuous two-way auction" refers to a trading market scenario where both buyers and sellers exist in a "many-to-many" configuration. In the power market trading cycle, buyers and sellers can submit their offers at any time. A transaction is completed once the offer aligns with the transaction rules. The transaction rules for the continuous two-way auction mechanism are illustrated in Figure 2. During the bidding process of a continuous two-way auction, the highest bid submitted by the buyer (virtual power plant) is termed the "optimal bid", while the lowest offer made by the seller (renewable energy power plant) is known as the "optimal selling price". A transaction is executed when the optimal selling price is lower than the optimal buying price, with the transaction price being the average of the two prices. Throughout the transaction process, market participants can access electricity pricing information, adjust their bidding strategies based on market data, and initiate the next round of transactions. This continues until all electricity bids are transacted or the designated transaction period concludes. Should the buyers and sellers in the electricity market fail to complete their matching by the closing time of the transaction, they will resort to purchasing or selling electricity from or to the larger power grid.

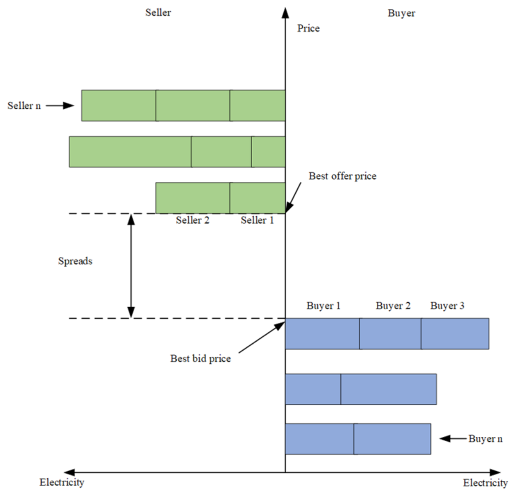

Fig. 2 Transaction rules of continuous two-way auction mechanism.

3 Quoting strategies based on continuous two-way auctions

3.1 Three-stage bidding function among transaction parties

The bid submissions by virtual power plants and renewable energy farms are segmented into three stages, reflecting the psychology of the trading parties:

(1) Stage I: Initial trading offer strategy

At the onset of the first trading round, as the parties have just entered the market, there is an absence of current offer information in the trading market. Consequently, bids must be predicated on historical optimal buying and selling prices. During this initial phase, both the virtual power plant and the renewable energy power plant are in a phase of observation, assessing market price trends. In the continuous two-way auction market's trading process, since virtual power plants and renewable energy farms deal exclusively in electricity, there is no concern regarding the varying quality of traded commodities. Hence, the pricing trend and bidding are more influenced by the psychological insights of the trading parties. This can significantly aid the adjustment process in bidding strategies. Given that the market is in its nascent stage with limited transactions, an unsuccessful deal at this point does not substantially affect either party's total revenue. Therefore, in this initial offer stage, it is feasible to adopt a riskier approach by submitting a higher bid. A successful transaction at this juncture can yield considerable profits. Conversely, if the deal does not materialize, both parties gain a clearer understanding of the prevailing market prices.

$$F_{\mathrm{VVP}i,t}=F_{\mathrm{OVPP}}+\alpha\left[\min\left\{v_i,\ \ F_{\mathrm{ODG}}\right\}-F_{\mathrm{OVPP}}\right] \tag{1}$$

$$F_{\mathrm{DG}j,t}=F_{\mathrm{ODG}}-\alpha\left[F_{\mathrm{ODG}}-\min\left\{c_j,\ \ F_{\mathrm{OVPP}}\right\}\right] \tag{2}$$

Here, t=1 signifies the first trading round. $F_{\mathrm{VPP}i,t}$ represents the bid from virtual power plant i in round t; $F_{\mathrm{DG}j,t}$ denotes the offer from distributed power source j in round t. F_{OVPP} and F_{ODG} correspond to the historical optimal buying price of the virtual power plant and the historical optimal selling price of the distributed power source, respectively. v_i the estimated commodity value of virtual power plant i, and c_j denotes the cost of distributed power source j. The parameter α represents the rate of increase in the offer, which ranges from 0 to 1.

(2) Stage 2: Quotation strategy for the principal profit phase

Following the initial round of bids, both parties involved in the transaction attain a preliminary understanding of the current market price. This stage, which is critical for revenue generation for virtual power plants and renewable energy farms, leads to the development of a revised bid proposal after analyzing the initial bid information.

In this principal profitability stage, several factors significantly influence the bidding psychology of the parties involved. These factors include the total number of completed transactions, the frequency of participation in the bidding rounds, and the volume of unsold electricity for each party. The coefficients reflecting the impact of these short-term behaviors on the virtual power plant and renewable energy power plants' bidding strategies are delineated in Equations (3) and (4):

$$IF_{\text{SVVP}i}=\begin{cases}\left(\dfrac{N_{\text{win}i}}{N_{all}}\right)^2\times K_1+N_1 & 0\le\dfrac{N_{\text{win}i}}{N_{all}}\le 0.3\\ \left(\dfrac{N_{\text{win}i}}{N_{\text{all}}}\right)^2\times K_2+N_1 & 0.3<\dfrac{N_{\text{win}i}}{N_{\text{all}}}\le 0.7\\ \left(\dfrac{N_{\text{win}i}}{N_{\text{all}}}\right)^2\times K_3+N_1 & 0.7<\dfrac{N_{\text{win}i}}{N_{\text{all}}}\le 1\end{cases} \tag{3}$$

$$IF_{\text{SDG}j}=\begin{cases}\left(\dfrac{N'_{\text{win}j}}{N_{\text{all}}}\right)^2\times K_1+N_1 & 0\le\dfrac{N'_{\text{win}j}}{N_{\text{all}}}\le 0.3\\ \left(\dfrac{N'_{\text{win}j}}{N_{\text{all}}}\right)^2\times K_2+N_1 & 0.3<\dfrac{N'_{\text{win}j}}{N_{\text{all}}}\le 0.7\\ \left(\dfrac{N'_{\text{win}j}}{N_{\text{all}}}\right)^2\times K_3+N_1 & 0.7<\dfrac{N'_{\text{win}j}}{N_{\text{all}}}\le 1\end{cases} \tag{4}$$

Here, $N_{\text{win}i}$ denotes the total number of transactions of virtual power plant i; N_{all} denotes the total number of bidding participations by virtual power plant i; $N'_{\text{win}j}$ represents the total number of transactions by renewable energy power plant j. K_1, K_2, K_3 and N_1 are constants influencing short-term behavior, where K_1, K_2, K_3 are positive integers, and $K_1 < K_2 < K_3$. Based on short-term behavior, a higher value of IF_s indicates a greater tendency for the entity to gain. Analyzing the values of K_1, K_2 and K_3 can reflect the propensity for profit.

The influence coefficients reflecting the long-term behavior of the virtual power plant and the renewable energy power plant are outlined in Equations (5) and (6):

$$IF_{\text{LVPP}i}=\begin{cases}N_2+(1-N_2)\times\left(\dfrac{W_{\text{no}i}}{W_{\text{all}}}\right)^{\delta_1} & 0\le\dfrac{W_{\text{no}i}}{W_{\text{all}}}\le 0.4\\ N_2+(1-N_2)\times\left(\dfrac{W_{\text{no}i}}{W_{\text{all}}}\right)^{\delta_2} & 0.4<\dfrac{W_{\text{no}i}}{W_{\text{all}}}\le 0.6\\ N_2+(1-N_2)\times\left(\dfrac{W_{\text{no}i}}{W_{\text{all}}}\right)^{\delta_3} & 0.6<\dfrac{W_{\text{no}i}}{W_{\text{all}}}\le 1\end{cases} \tag{5}$$

$$IF_{\mathrm{LDG}j}=\begin{cases} N_2+(1-N_2)\times\left(\frac{W'_{\mathrm{no}j}}{W_{\mathrm{all}}}\right)^{\delta_1} & 0\le\frac{W'_{\mathrm{no}j}}{W_{\mathrm{all}}}\le 0.4 \\ N_2+(1-N_2)\times\left(\frac{W'_{\mathrm{no}j}}{W_{\mathrm{all}}}\right)^{\delta_2} & 0.4<\frac{W'_{\mathrm{no}j}}{W_{\mathrm{all}}}\le 0.6 \\ N_2+(1-N_2)\times\left(\frac{W'_{\mathrm{no}j}}{W_{\mathrm{all}}}\right)^{\delta_3} & 0.6<\frac{W'_{\mathrm{no}j}}{W_{\mathrm{all}}}\le 1 \end{cases} \quad (6)$$

In these equations, $W_{\mathrm{no}\,i}$ represents the instances where the virtual power plant i did not engage in trading; W_{all} denotes the total trading participation of the virtual power plant i; $W'_{\mathrm{no}j}$ indicates the non-trading instances of the renewable energy power plant j; and N_2 represents the long-term impact constant, a value within the range of [0,1]. A higher value of IF_{L} implies that the entity has participated in fewer trading rounds, suggesting that a reduction in the bid might be necessary to enhance the probability of a successful transaction.

The values of both the short-term and long-term behavioral impact factors for the trading entities can be deduced using the aforementioned equations. By integrating these factors, we derive the following formulae to calculate the behavioral impact factors for the virtual power plant and the renewable energy power plant:

$$A_{\mathrm{VPP}i}=\frac{e^{\eta\times\left(\frac{IF_{\mathrm{SVPP}i}}{IF_{\mathrm{SVPP}i}+IF_{\mathrm{LVPP}i}}\right)}-1}{e^{\eta}-1} \quad (7)$$

$$A_{\mathrm{DG}j}=1-\frac{e^{\eta\times\left(\frac{IF_{\mathrm{SDG}j}}{IF_{\mathrm{SDG}j}+IF_{\mathrm{LDG}j}}\right)}-1}{e^{\eta}-1} \quad (8)$$

Where η denotes the influence constant. The primary objective of the entities participating in power market transactions is to maximize revenue. Given this goal, the short-term influence factor IF_{S} plays a pivotal role in determining the revenue outcomes of transactions, thus predominating in the equations above.

The bid functions for both virtual power plants and renewable energy power plants during the main profitability stages are outlined as follows:

If the virtual power plant did not trade in round t-1:

$$F_{\mathrm{vpp}i,t}=F_{\mathrm{VPP}i}(t-1)+A_{\mathrm{VPP}i}\left[V_i-F_{\mathrm{VPP}i}(t-1)\right] \quad (9)$$

If the virtual power plant traded in round t-1:

$$F_{\mathrm{VPP}i,t}=F_{\mathrm{VPP}i}(t-1)-A_{\mathrm{VPP}i}\left[V_i-F_{\mathrm{VPP}i}(t-1)\right] \quad (10)$$

If the renewable energy power plant did not trade in round t-1:

$$F_{\mathrm{DGj},t} = F_{\mathrm{DG}j}\left(t-1\right) - A_{\mathrm{DG}j}\left[F_{\mathrm{DG}j}\left(t-1\right) - c_j\right] \tag{11}$$

If the renewable energy power plant traded in round t-1:

$$F_{\mathrm{DG}\,j,t} = F_{\mathrm{DG}j}\left(t-1\right) + A_{\mathrm{DG}j}\left[F_{\mathrm{DG}j}\left(t-1\right) - c_j\right] \tag{12}$$

In the equation, $F_{\mathrm{VPP}i}$ (t-1) and $F_{\mathrm{DG}j}$ (t-1) denote the previous round (t-1) bids of the virtual power plant and the renewable energy power plant, respectively. These entities assess the power quantity traded in the current market to gauge the trading status. The higher the quantity of power traded, the less remains for subsequent transactions, thus affecting the likelihood of successful bidding. Consequently, as the available electricity quantity decreases and the number of trading rounds increases, the bid for the virtual power plant will incrementally rise, while the bid for the renewable energy power plant will correspondingly decline.

(3) Stage 3: Low-profit and high-volume sales bid strategy

In this stage, towards the end of the transaction cycle, most renewable energy power plants have covered their costs. Consequently, any remaining power becomes less critical for revenue generation, allowing these plants to consider selling at lower prices. Additionally, there is a segment of renewable energy power plants with surplus power that actively engage in transactions to capitalize on the market's low-profit, high-volume sales dynamic. In contrast, near the end of the transaction phase and yet to achieve their expected power procurement, virtual power plants might increase their bid prices to align with the psychology of securing the highest bid in the auction.

$$F_{\mathrm{VVP}i,t}=\max\left[F_{\mathrm{VPP}i}\left(t\text{-}1\right)\right]+\left\{\max\left[F_{\mathrm{VPP}i}\left(t-1\right)\right]-F_{\mathrm{OVPP}}\right\}\times\alpha \tag{13}$$

$$F_{\mathrm{DG}j,t}=\min\left[F_{\mathrm{DG}j}\left(t\text{-}1\right)\right]-\left\{F_{\mathrm{DG}j}-\min\left[F_{\mathrm{DG}j}\left(t-1\right)\right]\right\}\times\alpha \tag{14}$$

In these equations, α is a variable taking values between 0 and 0.2.

(4) Bid constraints

$$F_{\min} \le F_{\mathrm{VVP}i,t} \le \mathrm{v}_i \tag{15}$$

$$\mathrm{c}_j \le F_{\mathrm{DG}j,t} \le F_{\max} \tag{16}$$

where $F_{\min}$ and $F_{\max}$ represent the minimum and maximum electricity prices in the market, respectively.

3.2 Costing and error management

The load forecasts of virtual power plants and the output predictions of renewable energy power plants may not always align precisely with actual conditions, leading to certain prediction errors. These discrepancies can result in either surplus or deficit power, which then necessitates transactions with the larger power grid to balance the difference.

In instances where a virtual power plant purchases more power than its actual load requirement, there is no provision for refunding the excess power. Conversely, if the power procured by a virtual power plant falls short of its actual load demand, the shortfall must be compensated by acquiring additional power from the power grid. This process ensures that the virtual power plant's load requirements are consistently met, despite variations in initial forecasting accuracy.

$$C_{\mathrm{VVP}i}=\sum_{\mathrm{t}}\left(F_{\mathrm{VPP}i,t}\times W_{\mathrm{VPP}i,t}\right)-C_{\mathrm{sgr}i}\times\Delta W_{\mathrm{VPP}} \qquad \Delta W_{\mathrm{VPP}}\leq 0 \tag{17}$$

$$C_{\mathrm{VVP}i}=\sum_{t}\left(F_{\mathrm{VPP}i,t}\times W_{\mathrm{VPP}i,t}\right)+C_{\mathrm{bgr}i}\times\Delta W_{\mathrm{VPP}} \qquad \Delta W_{\mathrm{VPP}}>0 \tag{18}$$

Where $C_{\mathrm{VPP}i}$ denotes the total cost of power purchase for virtual power plant i; $W_{\mathrm{VPP}i,t}$ represents the amount of power purchased by virtual power plant i in the *t-th* trading round; $C_{\mathrm{sgr}i}$ denotes the unit price of power sold to the large grid; and $C_{\mathrm{bgr}i}$ denotes the unit price of power purchased from the large grid.

If the amount of electricity sold by a renewable energy power plant is less than its output, the excess electricity will be sold to the main grid; if the amount of electricity sold by a renewable energy power plant is more than its output, the lesser amount of electricity will be purchased from the main grid.

$$C_{\mathrm{DG}j}=\sum_{\mathrm{t}}\left(F_{\mathrm{DG}j,t}\times W_{\mathrm{DG}j,t}\right)-C_{\mathrm{sgr}i}\times\Delta W_{\mathrm{DG}} \qquad \Delta W_{\mathrm{DG}}\leq 0 \tag{19}$$

$$C_{\mathrm{DG}j}=\sum_{t}\left(F_{\mathrm{DG}j,t}\times W_{\mathrm{DG}j,t}\right)+C_{\mathrm{bgr}i}\times\Delta W_{\mathrm{DG}} \qquad \Delta W_{\mathrm{DG}}>0 \tag{20}$$

where $C_{\mathrm{DG}j}$ denotes the total power purchase cost of the renewable energy power plant j; $W_{\mathrm{DG}j,}$ denotes the power purchased by renewable energy power plant j in the *t-th* trading round.

4 Simulation analysis

In this section, we conduct a simulation experiment to analyze the continuous two-way auction in the power market. For this simulation, the sellers are comprised of two photovoltaic power stations, two pumped storage power stations, and two wind farms. On the buyer's side, three virtual power plants are selected for the analysis. Figure 3 illustrates the predicted output map for the renewable energy power field.

As depicted in Figure 3, only the two wind farms participate in the bidding during time slots 0-6 and 20-24. In the time slots of 14-20, both the wind farms and the photovoltaic power stations are involved in the bidding. For the time slots 6-14, the wind farms, photovoltaic power stations, and pumped storage power plants all engage in the bidding process. Based on the participation of various trading entities in the bidding, this study selects time slots 10 and 15 for focused simulation analysis.

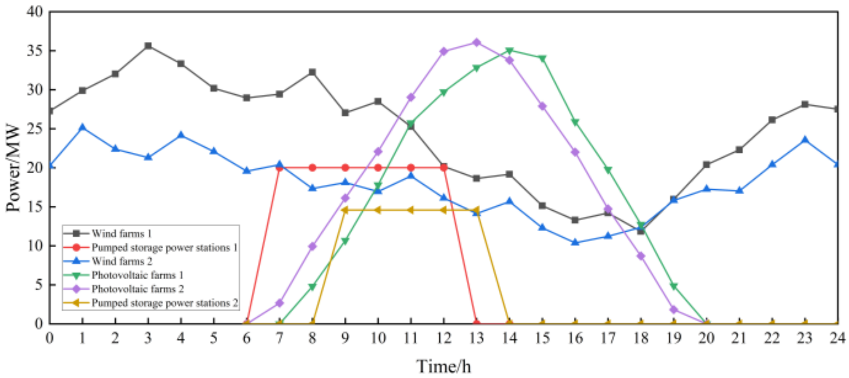

Fig. 3 Predicted output of renewable energy electric field.

Based on the aforementioned trading strategy and parameter settings, a simulation analysis was conducted using MATLAB on a computer equipped with an i5-7500 CPU and 8GB of RAM. The simulation was designed with a maximum of 15 trading rounds per session, categorized into three stages: Stage I involves the first round of trading, Stage II encompasses rounds 2 to 12, and Stage III includes rounds 13 to 15. Figures 4 and 5 display the optimal bid and ask prices, as well as the transaction prices for 15 rounds of trading during the 10:00 and 15:00 time periods, respectively.

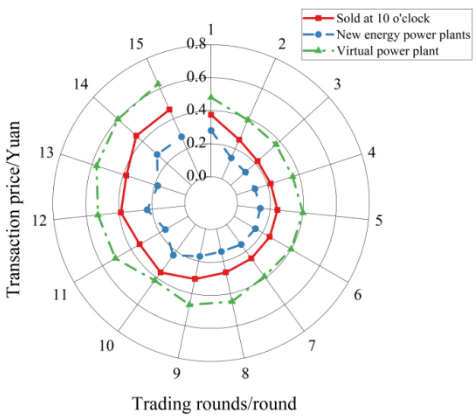

Fig. 4 Schematic diagram of the optimal purchase price, optimal selling price, and transaction price at 10:00.

The termination criterion for the continuous two-way auction is established as follows: the highest price offered by the buyer (virtual power plant) is termed the best bid, while the lowest price offered by the seller (renewable energy power plant) is designated as the best ask. If the optimal selling price falls below the optimal buying price, the transaction is executed, with the transaction price set at the average of the two prices. Adhering to these transaction rules and referring to Figures 4-6, it is evident that during the 10:00 time period, each of the 15 trading rounds successfully matched the bids of both parties. This outcome is attributed to the fact that in each round, the optimal selling price was consistently lower than the optimal buying price, indicating that the renewable energy power plant's optimal bid was always less than that of the virtual power plant. Consequently, the final transaction price is determined by averaging these two prices.

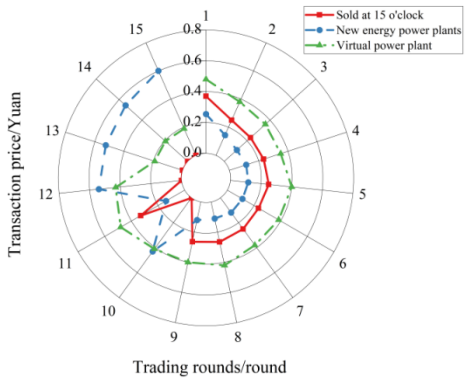

Fig. 5 Schematic diagram of the optimal purchase price, optimal selling price, and transaction price at 15:00.

As illustrated in Figure 4-5, certain transaction prices are recorded as zero. This occurs when the transaction criteria are not met, specifically when the optimal bid of the renewable energy power plant exceeds that of the virtual power plant, resulting in a failed transaction. For instance, consider the bidding scenario in the third round: the prices, arranged from lowest to highest, are represented by a red dot, green dot, and blue dot, respectively. The value of the red dot is zero because the green dot's value is less than that of the blue dot. In other words, the bid from the virtual power plant is lower than the bid from the renewable energy power plant, leading to the failure of the third-round bidding and hence no transaction price is established.

The outcomes of the individual session's continuous two-way auction bidding are depicted in Figures 6 and 7.

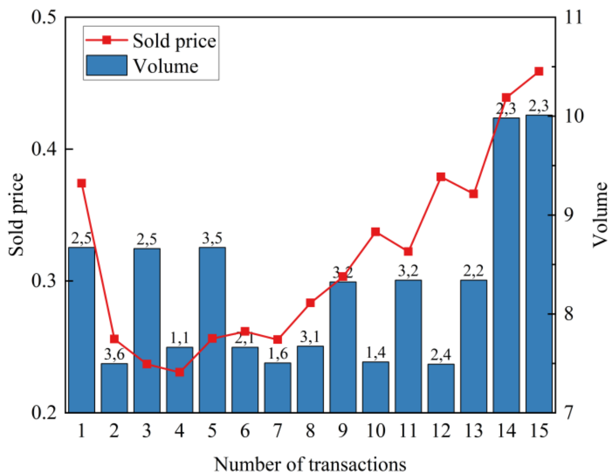

Fig. 6 Bidding results of the continuous two-way auction at 10:00.

Figure 6 presents the bidding outcomes of the continuous two-way auction at 10:00. At this time, all entities on the power-selling side participated in the bidding. Throughout the entire trading cycle, a total of 15 rounds of transactions were completed. The bar graph in the figure illustrates the transaction volume for each round, while the numbers above the bars indicate the participating entities in that particular round. The numbers before the comma represent virtual power plants 1-3, and those after the comma correspond to renewable energy power plants 1-6, which include photovoltaic 1, photovoltaic 2, pumped storage 1, pumped storage 2, wind power 1, wind power 2. Additionally, the line graph traces the transaction prices for each round. The initial round of transactions involved virtual power plant 2 and wind power 1. This was due to virtual power plant 2 placing a higher bid based on its valuation, while wind power 1, having lower operational costs, offered a more competitive price, thus facilitating a successful transaction in the first round. Pumped Storage 1, bearing the highest cost among the participants, did not manage to complete a transaction until the final two rounds.

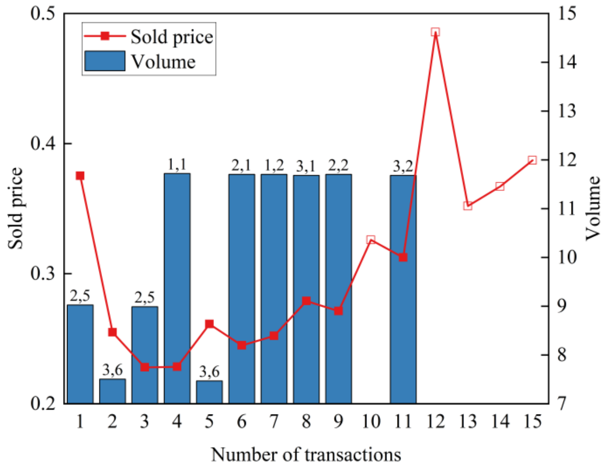

Fig. 7 Bidding results of the continuous two-way auction at 15:00.

Figure 7 displays the results of the continuous two-way auction bidding at 15:00. At this time, on the selling side, only photovoltaic 1, photovoltaic 2, wind power 1, and wind power 2 participated in market bidding. Throughout the entire trading cycle, the trading entities made a total of 15 transaction offers, out of which ten rounds concluded successfully. The pairs of participating parties in these transactions were as follows: (1,1), (1,2), (2,1), (2,2), (2,5), (3,2), and (3,6). The absence of transactions in the 10th round and the 12th to 15th rounds, marked by hollow points and zero volume, is attributed to the failure of these bidding rounds. The underlying reason for these unsuccessful bids was that the optimal bid was lower than the optimal ask price.

Subsequently, to provide a focused analysis, the bid curves of virtual power plant 2 and photovoltaic 2 during the 10:00 time period are examined as representative examples of buyers and sellers, respectively. As depicted in Figure 8, the bid curves of both the buyer and the seller are illustrated.

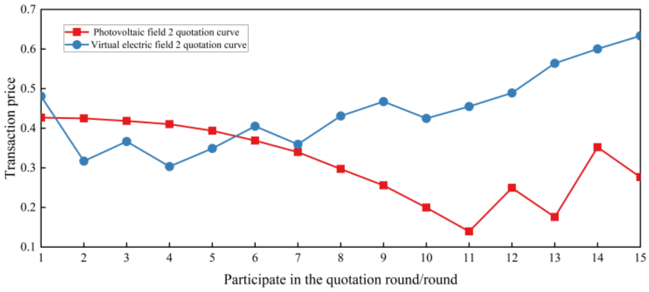

Fig. 8 Quotation curve of the buyer and the seller.

Figure 8 reveals that the bids from virtual power plant 2 exhibit a fluctuating pattern. This fluctuation can be analyzed in relation to the number of transaction rounds in which it participated, specifically rounds 1, 3, 6, 9, 12, 13, 14, and 15. In the first bidding round, virtual power plant 2 achieved a successful bid. Subsequently, to minimize the power purchase costs, the impact factor was adjusted, resulting in $A_{VVP} < 0$, thereby reducing the bid in the second round. However, due to the failure to secure a deal in the second round, the A_{VVP} was promptly adjusted to be greater than zero, leading to an increased bid in the subsequent rounds. Notably, in rounds 12 to 15, virtual power plant 2 succeeded in consecutive transactions. This success in the later stages was influenced by the plant entering the third stage of bidding, where it had not yet reached the anticipated power purchase volume, prompting an increase in the bid price. In contrast, photovoltaic 2 consistently reduced its price in the first ten rounds. The absolute value of its slope demonstrates an increasing trend, influenced by the impact factor A_{DG}. The necessity to rapidly decrease the bid for improved turnover rates demanded an increase in the absolute value of the impact factor A_{DG}.

Given that the grid's selling price exceeds the transaction price in the continuous two-way auction market, and the purchasing price from the grid is lower than the auction market's transaction price, there are financial consequences for the virtual power plant. Specifically, if the actual electricity consumption of the virtual power plant is less than the forecasted amount and this surplus cannot be refunded, this discrepancy results in effectively paying an additional cost for the electricity within the transaction process. Conversely, if the consumption exceeds the forecast, the expenditure surpasses the anticipated amount due to the grid's higher selling price compared to the auction market's transaction price. For renewable energy power plants, when actual generation falls short of the forecast, the plant must buy electricity from the grid to compensate for the production deficit. However, since the grid's selling price is higher, this leads to a decrease in revenue for the plant. In scenarios where the actual generation exceeds the forecast, the final revenue of the renewable energy power plant is still lower than expected. This is attributed to the grid's relatively low purchasing price for surplus electricity.

In practical trading scenarios, the forecasts made by virtual power plants and renewable energy power plants are inevitably subject to errors. Consider, for instance, virtual power plant 1 in the buyer's market, which engaged in three transaction rounds with respective prices of P_1 = 0.230 yuan, P_2 = 0.257 yuan, and P_3 = 0.337 yuan, leading to a total transaction amount of P = 6226 yuan. If there is a prediction error denoted as ΔP, and additional power needs to be purchased from the grid at a cost of C_{bgri}, then the resultant economic loss due to this error is calculated as $P_\delta = \Delta P * C_{bgri}$. Consequently, the actual total cost of purchased electricity becomes P_s

$=6226+P_\delta$. As illustrated in Figure 9, the magnitude of this prediction error can be analyzed to understand its impact on the expenditures and revenues of both the virtual power plant and the renewable energy power plants. This analysis aids in simulating the economic losses incurred by both the virtual power plant and the renewable energy power plants under varying degrees of prediction errors.

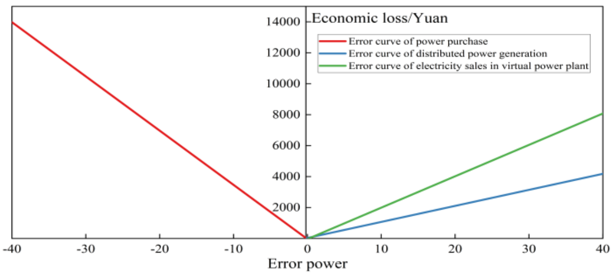

Fig. 9 Economic loss curve of virtual power plant and distributed power generation under different prediction errors.

Figure 9 demonstrates that the economic losses incurred by both the virtual power plant and the renewable energy power field are directly proportional to the absolute value of the error in power prediction. The graph depicts three linear error curves, a result of the fixed unit prices for both selling and purchasing electricity by these entities in transactions with the larger power grid. This implies that any disparity between the predicted and actual output values, regardless of magnitude, results in economic losses for the trading parties. The larger the discrepancy in this prediction, the more significant the economic loss. Hence, to safeguard their interests, it is imperative for both virtual power plants and renewable energy power plants to enhance the accuracy of their output predictions.

This section compares the merits and drawbacks of the trading strategy discussed in this chapter with the traditional sealed-bid auction strategy, as utilized in the literature [7], particularly in terms of renewable energy consumption efficiency and social welfare. The sealed-bid auction is also a form of bilateral transaction where bidders submit their bids without knowledge of others' bids. These bids are concealed until a simultaneous reveal, with the highest bid determining the winner. Assuming that the total electricity bought and sold by both the virtual power plant and the renewable energy power plant is 120 MW, and that their bids range from 0.1 to 0.5 kWh/$, 20 simulation tests are carried out using both the continuous two-way auction trading model and the sealed-bid auction trading model. These simulations aim to compare the efficiency of renewable energy consumption and the overall social welfare achieved by these two distinct auction mechanisms [8].

In this analysis, renewable energy consumption efficiency is defined as the ratio of renewable energy utilization under the two bidding strategies. Specifically, it is the proportion of electricity that the buyer (virtual power plant) purchases from the seller (renewable energy power plant) relative to the total amount of electricity bought. Social welfare, within the context of microeconomics, is conceptualized as the net change in consumer surplus and producer surplus. Consumer surplus refers to the difference between the maximum price consumers (in this case, virtual power plants) are willing to pay for a certain quantity of a commodity and its actual market price. Producer surplus, on the other hand, represents the additional revenue for producers (here, renewable energy power plants) arising from the difference between the minimum supply price of production factors and products, and the prevailing market price.

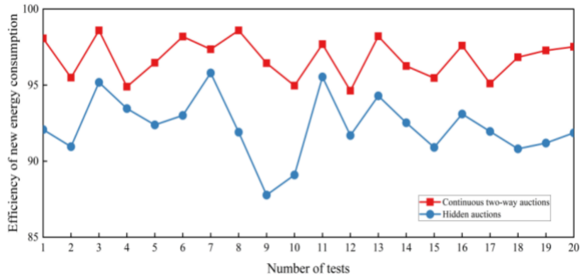

Fig. 10 Test results of new energy consumption efficiency.

Analysis of Figures 10 and 11 indicates that the bidding strategy proposed in this paper surpasses the sealed-bid auction approach in terms of both renewable energy consumption efficiency and social welfare.

When examining renewable energy consumption efficiency, it becomes evident that this efficiency is higher under the continuous two-way auction bidding strategy. The reason for this is that in a sealed-bid auction, parties are unable to adjust their bids in response to market prices, aiming instead to maximize their individual incomes. In contrast, the continuous two-way auction strategy, as introduced in this chapter, allows for bid adjustment based on estimated market prices, thereby enhancing social welfare. Additionally, the sealed-bid auction relies heavily on third-party institutions and stores transaction data on centralized servers, which lack transparency and are susceptible to tampering, with no traceability. In comparison, the continuous two-way auction more effectively aligns with the principles of open and fair market transactions.

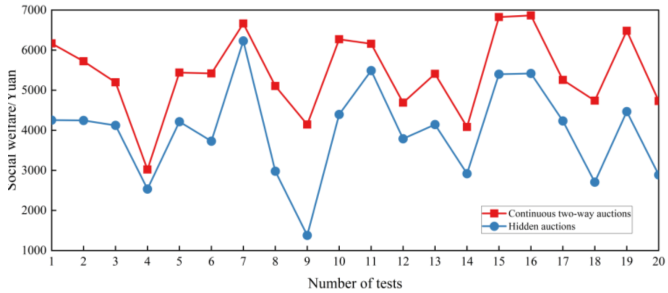

Fig. 11 Social welfare test results.

5 Conclusion

To enhance market flexibility and foster renewable energy consumption, a bidding strategy for virtual power plants based on continuous two-way auction is proposed. This strategy involves identifying virtual power plants and renewable energy farms as the buyers and sellers, respectively. It examines the power market transaction in terms of applicable conditions, transaction modes, and rules under the continuous two-way auction framework. Additionally, an in-depth analysis of the three-stage bid function and the cost calculations for both parties is conducted. Simulations demonstrate that this proposed bidding strategy enables virtual power plants and renewable energy farms to dynamically adjust their bids according to market trading information. Furthermore, the continuous two-way auction model surpasses the traditional sealed-bid auction strategy in terms of renewable energy consumption efficiency and social welfare. This approach caters to the decentralized, small-scale, and cost-effective trading needs of distributed renewable energy farms, thereby promoting renewable energy consumption. It also provides a valuable reference for establishing bilateral trading in the microgrid power market amidst ongoing electricity market reforms.

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