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The Generation Rights Trading between Self-Owned Power Plants and New Energy Enterprises under the Conditions of Price Difference and Time-of-Use Pricing Settlement

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Abstract: Currently, the proportion of enterprise self-owned power plants (SPPs) is increasing, with a significant share occupied by small coal-fired units, severely affecting the absorption of new energy and causing substantial pollution. To address this issue, developing generation rights trading between SPPs and new energy enterprises is an effective solution. At present, research on generation rights trading is mainly based on early water and thermal generation rights replacement trading. This approach, to some extent, overlooks changes in electricity market policies. Based on this, a new generation rights trading bidding strategy incorporating price differences and time-of-use pricing settlement is proposed. Firstly, the relationship between price difference settlement and generation rights trading is studied and the win–win model of generation rights trading is improved. Secondly, in the time-of-use pricing settlement mode, the single bidding strategy is optimized with the objective of maximizing the total social benefits in the win–win model. Finally, an example analysis compares different bidding strategies under time-of-use pricing settlement. Even in the most extreme cases, the time-of-use bidding strategy can improve social benefits by 5.61% and reduce wind and solar curtailment by 7.25% compared to the single bid strategy. The results show that the optimized time-of-use bidding strategy significantly improves the efficiency of generation rights trading, greatly helping to promote the absorption of new energy and alleviate wind and solar power curtailment.

Keywords: self-owned power plants; generation rights trading; price difference settlement; time-of-use electricity pricing

Citation: Li, W.; Cheng, X.; Gong, Y.; Qu, K.; Udabala; Liu, J.; Yu, X. The Generation Rights Trading between Self-Owned Power Plants and New Energy Enterprises under the Conditions of Price Difference and Time-of-Use Pricing Settlement. *Electronics* **2024**, *13*, 3908. https://doi.org/10.3390/electronics13193908

Academic Editors: Gianpaolo Vitale and Rui Castro

Received: 31 July 2024
Revised: 13 September 2024
Accepted: 14 September 2024
Published: 2 October 2024

1. Introduction

To address the issues of the inadequate adaptability of the power system to large-scale high-proportion new energy grid connection and consumption, and significant land resource constraints in new energy development and utilization [1], the National Development and Reform Commission and the National Energy Administration jointly issued the "Implementation Plan for Promoting High-Quality Development of New Energy in the New Era". The document outlines a goal to achieve a total installed capacity of wind and solar power generation of more than 1.2 billion kilowatts by 2030, accelerating the construction of a clean, low-carbon, safe, and efficient energy system. However, key wind power bases in China [2], such as Inner Mongolia, Gansu, Hebei, Jilin, and Xinjiang, face serious wind and solar power curtailment due to insufficient grid peaking capacity, lagging grid structure, and external transmission channels. For instance, the monthly highest wind curtailment rate of the west Inner Mongolia grid reached 15.2% from January to May 2023, and the solar curtailment rate was as high as 16.2%. Therefore, how to maximize the utilization of wind and solar power is an urgent issue. Self-owned power plants (SPPs) emerged in the 1950s due to power supply shortages. In recent years, these SPPs have grown significantly in scale, playing a crucial role in ensuring local power supply, attracting investment, and promoting local economic development [3,4]. The proportion of SPPs is steadily increasing, with a considerable share occupied by small coal-fired units that are high energy consumers and heavy polluters, severely impacting the absorption of new energy and causing significant pollution. Thus, it is necessary to study the promotion of new energy consumption and the improvement of air pollution by adjusting the operation mode of SPPs under the conditions of price difference and time-of-use pricing settlement.

Generation rights trading for SPPs is an effective solution to the high energy consumption and heavy pollution of these plants. This trading not only promotes the transformation of SPPs and safeguards the interests of the plants and their affiliated users but also effectively reduces wind and solar power curtailment, promotes new energy consumption, reduces carbon emissions, and improves air pollution. In the coastal areas of China and some regions in Europe [5], there are numerous offshore wind farms. For these areas experiencing wind and solar power curtailment, generation rights trading is also feasible and can encourage local governments to explore new possibilities for obtaining energy from renewable sources. There is already a considerable amount of literature on generation rights trading between new energy enterprises and SPPs. Reference [6] analyzes the benefits of power replacement between SPPs and new energy enterprises based on traditional catalog electricity pricing and designs trading rules. Reference [7], compared to [6], considers the variable and fixed costs of power generation before generation rights trading and establishes a win–win model for generation rights trading. References [8,9] establish cooperative game models aimed at maximizing the net benefits of both parties in generation rights trading. The former finds that the Shapley value distribution strategy can achieve balanced interests and multi-party win–win, while the latter develops a multi-factor improved Shapley value profit distribution model to enhance the fairness of profit distribution. Reference [10] establishes a wind power curtailment assessment probability model using reduced wind power curtailment from generation rights trading as the main evaluation indicator, aiming to strengthen the mitigation effect of generation rights trading on wind and solar power curtailment. Reference [11] proposes a multi-spatial coordination and substitution optimization model for clean energy and SPPs, addressing issues such as comprehensive benefits, the impact of pre-trading network losses on trading orders, and trading space limited to within the province in the current generation rights trading. Reference [12] analyzes the current situation, potential issues, and risks of interregional generation rights trading and proposes corresponding research solutions. Reference [13] constructs a wind–thermal generation rights trading model aimed at minimizing trading risks by drawing on financial market risk control theories and principal–agent principles, addressing trading risks caused by random changes in external environmental costs. These studies, from different perspectives, build corresponding trading models for generation rights trading. However, the above studies do not consider the impact of generation rights trading on difference settlement when calculating the benefits of rights trading. When considering long-term generation rights trading, the relationship between mid-to-long-term electricity and spot electricity of market participants might change, and it is necessary to study the win–win model of generation rights trading under the context of price difference settlement.

Reference [14] establishes a generation rights trading model for SPPs participating in wind power consumption based on short time scales. Reference [15] introduces the regulatory role of market mechanisms and establishes a generation rights regulation market based on hydro-thermal power replacement on the contract market, monthly market, and day-ahead market. Reference [16] points out the deviations in traditional generation rights trading in actual implementation due to the instability of new energy generation power and factors like coal conditions and the unplanned outages of coal-fired SPPs, proposing an intra-day trading mode for generation rights as a supplement. Reference [17] considers the complex characteristics of cascade hydropower and focuses on the coupling relationship between unit maintenance and generation rights trading. It proposes a bi-level planning model for the maintenance of hydro and thermal power units under a yearly time scale, considering generation rights trading for provincial power grids. Reference [18] constructs a contribution model of different market mechanisms to new energy consumption for generation rights trading, reserve auxiliary service trading, and time-of-use pricing trading. Reference [19] analyzes five trading strategies from the perspective of maximizing the profits of coal-fired power generators and studies how generators choose strategies to achieve maximum profits. Reference [20] constructs a bi-level model for selecting trading counterparts and assessing risk in generation rights trading that considers both large and small hydropower under a bilateral negotiation trading model. Reference [21] proposes an optimized generation rights trading model for renewable energy systems that takes into account carbon trading. These studies design different generation rights trading mechanisms for various market mechanisms or trading strategies, but they do not fully consider the operational characteristics of SPP units, the output of new energy, and the impact of time-of-use pricing and wind and solar power curtailment. These factors may lead to deviations in actual trading volume and profits, making it necessary to further study generation rights trading by incorporating indicators such as time-of-use pricing and wind and solar power curtailment.

In summary, the current generation rights trading between SPPs and new energy enterprises under the price difference settlement mode has the following shortcomings: (1) The existing generation rights trading is often based on early catalog electricity pricing settlement or considers only contract electricity price settlement, whereas current electricity price settlement generally adopts mid-to-long-term spot price differences. After rights trading, the trading participants need to trade electricity from the spot market, which will affect price difference settlement and change the benefits of rights trading. (2) Under the settlement context of peak–flat–valley electricity prices, traditional mid-to-long-term bidding strategies cannot maximize the total social benefits of electricity trading across different time periods. In extreme cases, they may only satisfy a win–win model for a single time period, which severely affects the integration of renewable energy.

Based on the existing research on SPP generation rights trading mechanisms and China's latest power market policies, this paper studies the feasibility of rights trading between SPPs and new energy enterprises under the price difference and time-of-use settlement mode. Firstly, generation rights trading and price difference settlement are combined to calculate three possible impacts of rights trading on price difference settlement. Based on this, a win–win model for generation rights trading under the price difference settlement mode is established by integrating the existing generation rights trading models and the method for setting upper limits on rights trading. Secondly, based on the established win–win model and the differences in the wind and solar power curtailment of new energy enterprises in different periods under time-of-use pricing, a time-of-use bidding strategy is proposed. Finally, an example analysis is conducted to verify the feasibility of the win–win model and the rationality of the mid-to-long-term strategy.

2. Framework for Generation Rights Trading under New Electricity Market Rules

Considering the impact of generation rights trading on spot electricity volumes, this study analyzes the effects of mid-to-long spot price difference settlements on generation rights trading and improves the existing win–win model. Under the time-of-use price settlement background, in the context of time-of-use pricing, a strategy for separate time period bidding is proposed. Compared to a single bidding strategy, this approach can maximize both social benefits and new energy consumption. The overall framework of generation rights trading is illustrated in Figure 1, with the details as follows:

(1) Relationship between price difference settlement and generation rights trading: After generation rights trading, the spot electricity volume for both trading participants increases, altering the relationship between spot and mid-to-long-term electricity volumes. By calculating the price difference in power purchase costs in the spot

market before and after trading for SPPs, the unit price of the traded generation rights volume is obtained.

(2) Establishment of a win–win model under price difference settlement: The benefits for SPPs participating in generation rights trading include trading fees and savings from reduced variable generation costs. The expenditures include power purchase costs from the spot market, transmission and distribution fees, government funds, environmental premiums paid to new energy enterprises, and rights trading costs. New energy enterprises' benefits include additional power sales revenue in the spot market and environmental premiums paid by SPPs, and their expenditures include additional variable generation costs, payments for generation rights, and trading costs. The win–win model constraints include ensuring positive net benefits for both SPPs and new energy enterprises, maintaining normal grid operation with the total traded generation rights volume, and centralized matching trading constraints, aiming to maximize social welfare.

(3) Bidding strategy under time-of-use price settlement: Under time-of-use price settlement conditions, the significant differences in spot market prices during the peak, flat, and valley periods make it difficult for traditional bidding strategies to maximize both social welfare and new energy utilization, severely affecting the efficiency of generation rights trading. Therefore, a time-of-use bidding strategy is proposed. This strategy calculates the proportion of wind and solar power curtailment during different time periods based on the new energy enterprises' generation and output curves, and then calculates the social benefits and renewable energy consumption of generation rights trading based on the obtained results and the win–win model. Finally, we compare the time-of-use bidding strategy with the traditional bidding strategy.

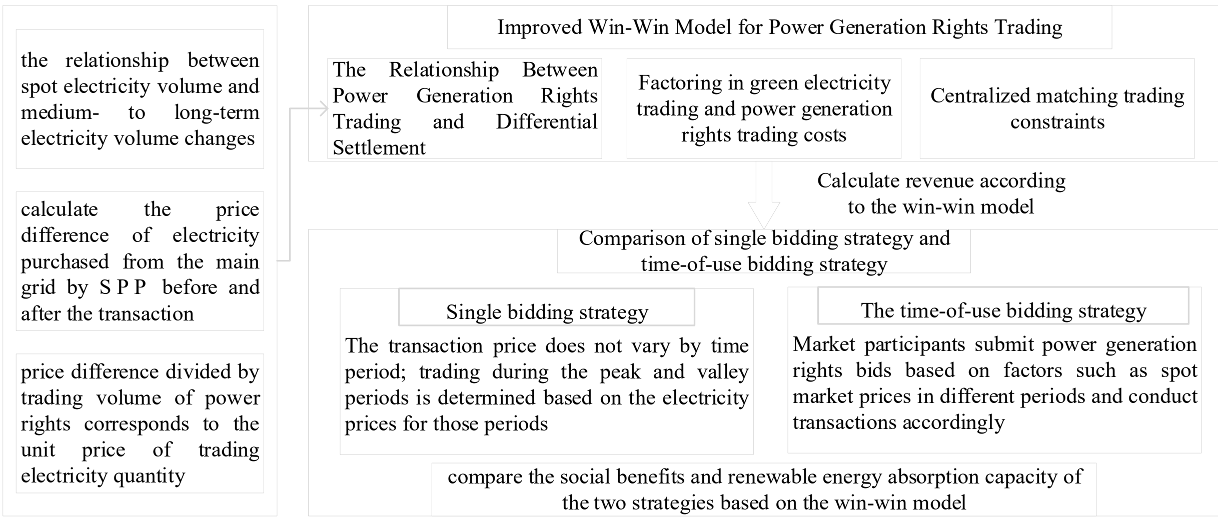

Figure 1. The establishment of the win–win model and the framework for generation rights trading under time-of-use pricing.

3. The Relationship between Price Difference Settlement and Electricity Generation Rights Trading

3.1. Introduction to Settlement Rules

In a certain period, users sign medium-to-long-term contracts with power generation companies for corresponding electricity volumes. The actual electricity usage by users during this period corresponds to spot electricity. When the contract electricity volume exceeds the spot volume, the surplus is settled based on the difference between the contract and spot prices, with the remainder settled at the contract price. When the contract volume is lower than the spot volume, the surplus spot market electricity is settled at the spot price, with the remainder settled at the contract price. See Figure 2 for details.

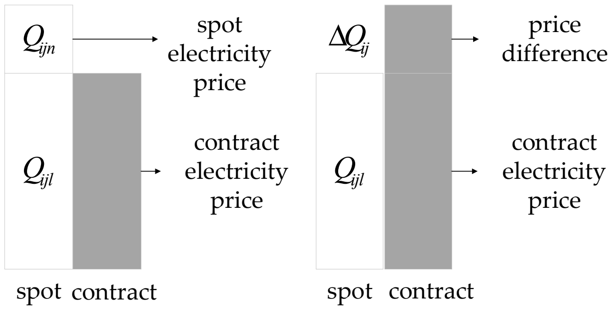

Figure 2. Medium-to-long-term spot financial difference settlement.

3.2. The Impact of Difference Settlement on Electricity Trading Rights

After conducting generation rights trading with new energy enterprises, SPPs need to purchase this part of the electricity from the spot market. In this scenario, the SPP acts as a consumer. Prior to the generation rights trading, the electricity settlement rules are as shown in Figure 1. Following the trading, with an increase in spot electricity volume for the SPPs, difference settlement may occur under the following three conditions:

(1) The Relative Magnitude between Spot Volume and Contract Volume Changes

As shown in Figure 3, the excess electricity volume used due to the rights trading is settled at the spot electricity price, and the others are settled at the contract electricity price.

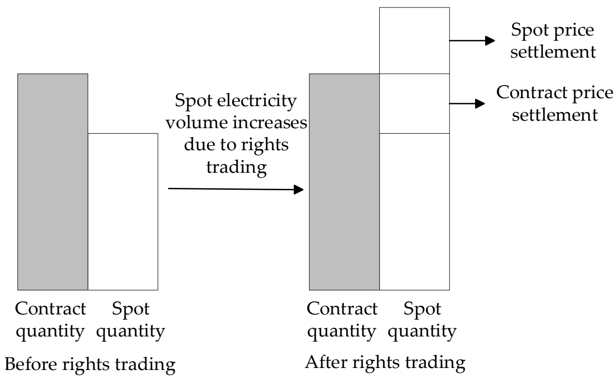

Figure 3. Change in the relationship between spot and contract electricity volumes before and after the trading.

Before the trading, the electricity purchase cost for SPPs from the spot market is as follows:

$$Q_{i\_n} \times P_{i\_l} - (Q_{i\_l} - Q_{i\_n}) \times (P_{i\_l} - P_{i\_n}) \quad (1)$$

where P_{i_n} is the spot electricity price, P_{i_l} is the contract electricity price, Q_{i_n} is the spot electricity volume before the trading, and Q_{i_l} is the contract electricity volume before the trading.

After the trading, the electricity purchase cost for SPPs from the spot market is as follows:

$$Q_{i\_l} \times P_{i\_l} + (Q^*_{i\_n} - Q_{i\_l}) \times P_{i\_n} \quad (2)$$

where $Q^*_{i\_n}$ is the spot electricity volume after rights trading.

The change in electricity purchase costs from the spot market for SPPs before and after the trading is as follows:

$$\begin{aligned} &\left[Q_{i\_l} \times P_{i\_l} + (Q^*_{i\_n} - Q_{i\_l}) \times P_{i\_n}\right] - [Q_{i\_n} \times P_{i\_l} - (Q_{i\_l} - Q_{i\_n}) \times (P_{i\_l} - P_{i\_n})] \\ &= (Q^*_{i\_n} - Q_{i\_n}) \times P_{i\_n} \\ &= Q_{ij} \times P_{i\_n} \end{aligned} \quad (3)$$

where Q_{ij} is the rights trading volume of the *i*-th SPP and the *j*-th renewable energy enterprise.

At this time, the unit electricity price corresponding to the rights trading volume is as follows:

$$P_{i\_B1} = P_{i\_n} \times Q_{ij}/Q_{ij} = P_{i\_n} \tag{4}$$

(2) Before and after the trading, the spot volume is less than the contract volume

As shown in Figure 4, in this case, after the rights trading, the spot volume remains lower than the contract volume. The portion where the spot volume is still lower than the contract volume is settled using the price difference settlement, and the others are settled at the contract electricity price.

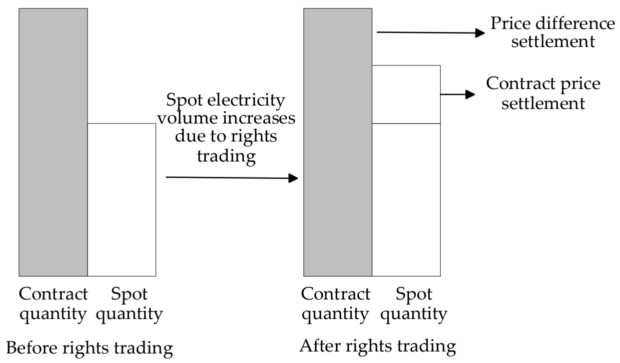

Figure 4. Spot volume before and after the trading is less than the contract volume.

Before the trading, the electricity purchase cost for SPPs from the spot market is shown in Formula (1). After the trading, the electricity purchase cost for SPPs from the spot market is as follows:

$$Q^{*}_{i\_n} \times P_{i\_l} + (Q_{i\_l} - Q_{i\_n1}) \times (P_{i\_l} - P_{i\_n}) \tag{5}$$

The change in electricity purchase costs from the spot market for SPPs before and after the trading is as follows:

$$\begin{aligned} &\left[Q^{*}_{i\_n} \times P_{i\_l} + (Q_{i\_l} - Q_{i\_n1}) \times (P_{i\_l} - P_{i\_n})\right] - [Q_{i\_n} \times P_{i\_l} - (Q_{i\_l} - Q_{i\_n}) \times (P_{i\_l} - P_{i\_n})] \\ &= (Q^{*}_{i\_n} - Q_{i\_n}) \times P_{i\_n} \\ &= Q_{ij} \times P_{i\_n} \end{aligned} \tag{6}$$

At this time, the unit electricity price corresponding to the rights trading volume is as follows:

$$P_{i\_B2} = P_{i\_n} \times Q_{ij}/Q_{ij} = P_{i\_n} \tag{7}$$

(3) Before and after the trading, the spot volume is more than the contract volume

As shown in Figure 5, the additional electricity used due to the rights trading is settled at the spot electricity price.

Before the trading, the electricity purchase cost for SPPs from the spot market is as follows:

$$Q_{i\_l} \times P_{i\_l} - (Q_{i\_n} - Q_{i\_l}) \times P_{i\_n} \tag{8}$$

After the trading, the electricity purchase cost for SPPs from the spot market is as follows:

$$Q_{i\_l} \times P_{i\_l} - (Q^{*}_{i\_n} - Q_{i\_l}) \times P_{i\_n} \tag{9}$$

The change in electricity purchase costs from the spot market for SPPs before and after the trading is as follows:

$$\begin{aligned} &\left[Q_{i\_l} \times P_{i\_l} - (Q^{*}_{i\_n} - Q_{i\_l}) \times P_{i\_n}\right] - [Q_{i\_l} \times P_{i\_l} - (Q_{i\_n} - Q_{i\_l}) \times P_{i\_n}] \\ &= (Q^{*}_{i\_n} - Q_{i\_n}) \times P_{i\_n} \\ &= Q_{ij} \times P_{i\_n} \end{aligned} \tag{10}$$

At this time, the unit electricity price corresponding to the generation rights trading volume is as follows:

$$P_{i\_B3} = P_{i\_n} \times Q_{ij}/Q_{ij} = P_{i\_n} \quad (11)$$

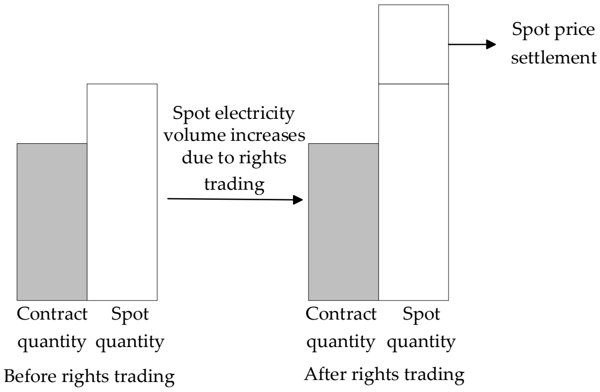

Figure 5. Spot volume before and after the trading is more than the contract volume.

The situation for new energy generation enterprises after the trading is the same as that for SPPs, except that the electricity consumption becomes electricity generation, and the electricity price changes from the user side to the generation side. Based on the three scenarios described above, it can be observed that for SPPs, the additional electricity cost incurred due to generation rights trading equals the spot electricity price when purchasing from the grid, regardless of the contract price or the volumes of spot and contract. The same applies to new energy generation enterprises.

4. Win–Win Model for Power

4.1. The Starting Conditions for Generation Rights Trading by SPPs

When SPPs participate in generation rights trading, their income comes from the trading fee paid by new energy generation enterprises, denoted as P_{ij}, and the savings in electricity corresponding to the variable generation cost, denoted as C_i. Their expenditures stem from entering into contracts with new energy generation enterprises, incurring additional electricity purchase expenditures from the spot market. Additionally, purchasing electricity from the spot market also entails paying government funds P_{i_g} and transmission and distribution charges P_{i_t}.

To simplify the calculation formula, since the spot electricity price, government funds, and transmission and distribution charges correspond to the same portion of electricity in the calculation, we merge them and denote them as the unit electricity cost:

$$P_{i\_N} = P_{i\_n} + P_{i\_g} + P_{i\_t} \quad (12)$$

After SPPs and new energy generation enterprises participate in generation rights trading, the electricity traded by new energy generation enterprises in the spot market cannot be considered as green electricity trading, as the current green electricity trading framework in China is based on contract trading [22]. To compensate new energy generation enterprises, SPPs should additionally pay a portion of the environmental premium P^e_{ij}. At the same time, it is assumed that SPPs receive green certificates [23].

For SPPs to profit, their income must exceed their expenditures. This can be expressed as follows:

$$P_{ij} + C_i > P_{i\_N} + P^e_{ij} \quad (13)$$

When considering trading costs, the above inequality is amended to the following:

$$P_{ij} + C_i > P_{i\_N} + P^e_{ij} + C_{ij} \quad (14)$$

The profit obtained by SPPs in generation rights trading is as follows:

$$S_j = P_{j\_n} \times \sum_{i=1}^{n} Q_{ij} + \sum_{i=1}^{n} (Q_{ij} \times P_{ij}^e) - \sum_{i=1}^{n} (Q_{ij} \times P_{ij}) - C_j \times \sum_{i=1}^{n} Q_{ij} - \sum_{i=1}^{n} (Q_{ij} \times C_{ij}) \quad (15)$$

4.2. The Starting Conditions for Generation Rights Trading by New Energy Generation Enterprises

When new energy generation enterprises participate in generation rights trading, their income comes from the profit obtained in the spot market due to the excess electricity generation from generation rights trading, denoted as P_{j_n}, and the environmental premium, denoted as P_{ij}^e. Their expenditures include paying the generation rights trading price to SPPs, denoted as P_{ij}, and the variable generation cost, denoted as C_j.

For new energy generation enterprises to profit, their expenditures must be less than their income. This can be expressed as follows:

$$P_{ij} + C_j < P_{j\_n} + P_{ij}^e \quad (16)$$

When considering trading costs C_{ij}, the above inequality is amended to the following:

$$P_{ij} + C_j + C_{ij} < P_{j\_n} + P_{ij}^e \quad (17)$$

The profit obtained by new energy generation enterprises in generation rights trading is as follows:

$$S_j = P_{j\_n} \times \sum_{i=1}^{n} Q_{ij} + \sum_{i=1}^{n} (Q_{ij} \times P_{ij}^e) - \sum_{i=1}^{n} (Q_{ij} \times P_{ij}) - C_j \times \sum_{i=1}^{n} Q_{ij} - \sum_{i=1}^{n} (Q_{ij} \times C_{ij}) \quad (18)$$

The total social benefit of generation rights trading is as follows:

$$S_{\mathrm{p}} = \sum_{i=1}^{n} S_i + \sum_{j=1}^{m} S_j = \sum_{i=1}^{n} \sum_{j=1}^{m} (P_{j\_n} - P_{i\_N} + C_i - C_j) Q_{ij} \quad (19)$$

4.3. Win–Win Model

The goal of the win–win model for generation rights trading is to ensure that all the market participants gain benefits. On this basis, the objective is to maximize the total benefit for all the members of society, i.e., to maximize the total social benefit.

The objective function is as follows:

$$\max\left(\sum_{i=1}^{n} S_i + \sum_{j=1}^{m} S_j\right) \quad (20)$$

The constraints are as follows:

$$P_i < P_j \quad (21)$$

$$P_{ij} = \frac{P_i + P_j}{2} \quad (22)$$

$$P_{ij} > P_{i\_N} + P_{ij}^e + C_{ij} - C_i \quad (23)$$

$$P_{ij} < P_{j\_n} + P_{ij}^e - C_{ij} - C_j \quad (24)$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} Q_{ij} \le Q_{\max} \quad (25)$$

Formulas (21) and (22) represent the constraints for centralized bidding [24]. Formulas (23) and (24) represent the profitability conditions for SPPs and new energy generation enterprises. Formula (25) represents the upper limit constraint on the generation rights volume, where $Q_{\max}$ is the maximum amount of generation rights trading that can be absorbed by the system while ensuring safety (inertia and stability).

5. Bidding and Trading Model under Time-of-Use Pricing

5.1. Single Bidding Settlement

Time-of-use pricing is generally categorized into four types:

(1) Static Time-of-Use Pricing: This divides a day into several broad time periods, using simple day/night divisions to reflect peak and off-peak times.
(2) Dynamic Time-of-Use Pricing: Also known as real-time time-of-use pricing, this approach calculates prices based on electricity usage measured hourly or with greater precision, such as every 15 min. The real-time time-of-use price is then determined based on the wholesale market price of electricity plus the retailer's profit margin.
(3) Variable Peak Time-of-Use Pricing: A hybrid of static and dynamic time-of-use pricing, where different price segments are predefined, and peak prices vary according to market conditions.
(4) Critical Peak Time-of-Use Pricing: This involves significant price increases on a few days each year, typically when wholesale prices are at their highest.

In most regions of China, the electricity price in a day is divided into three time periods: peak, flat, and valley. Due to the high spot electricity prices during peak periods, the amount of wind and solar power curtailment is essentially zero. Therefore, there is no need for new energy consumption or generation rights trading during these times. In contrast, it is more reasonable to focus on trading during the valley and flat periods.

In order to compare the bidding strategies during the valley and flat periods, it is necessary to compare the benefits and overall social welfare of the same user adopting different bidding strategies. The significant difference in spot prices between the valley and flat periods can lead to the following situations for a user's single bid in different periods:

(1) For SPPs, a bid targeting the valley period may result in the following situations during the flat period:

$$P_{ijv} + C_i < P_{i\_Nf} + P_{ij}^{e} + C_{ij} \tag{26}$$

where P_{ijv} is the generation rights trading price during the valley period, and P_{ijv} is the spot price during the flat period on the user side, including transmission and distribution charges and government funds. At this point, the SPPs cannot profit, and the trading during the flat period cannot be completed.

(2) For new energy enterprises, the quotation for the flat period during the valley period may result in the following situation:

$$P_{ijf} + C_j + C_{ij} > P_{j\_nv} + P_{ij}^{e} \tag{27}$$

where P_{ijf} is the trading price during the flat period, and P_{j_nv} is the spot price during the valley period on the generation side. At this time, the new energy enterprises cannot profit.

The difference between the spot prices in the flat and valley periods causes the bidding space to either not overlap or overlap only slightly when trying to meet the win–win conditions in these two periods. A single bidding strategy does not fully utilize the generation rights to absorb new energy. The time-of-use bidding strategy, based on the spot prices and the curtailment of wind and solar energy in different periods of the day, can maximize the reduction in wind and solar curtailment for new energy enterprises.

5.2. Revenue Calculation

Based on the forecasted generation output and the forecasted grid input quantity, calculate the total amount of wind and solar power curtailment S, and the amount of wind and solar power curtailment for the peak, flat, and valley periods, denoted as S_P, S_f, S_v. Then, calculate the proportion of curtailment in each period to represent the share of the generation rights trading in each period. Combine this with the improved win–win model to calculate the generation rights trading revenue for each new energy enterprise and each SPP.

$$S = (P_{output} - P_{on-grid}) \times \sum_{P_{output} - P_{on-grid} > 0} T \tag{28}$$

$$\begin{cases} S_p = (P_{output.p} - P_{on-grid.p}) \times \sum\limits_{P_{output.p} > P_{on-grid.p}} T \\ S_f = (P_{output.f} - P_{on-grid.f}) \times \sum\limits_{P_{output.f} > P_{on-grid.f}} T \\ S_v = (P_{output.v} - P_{on-grid.v}) \times \sum\limits_{P_{output.v} > P_{on-grid.v}} T \end{cases} \tag{29}$$

where P_{output} and $P_{on-grid}$ represent the forecasted output and forecasted grid input of the new energy enterprise, and p, f, and v denote the peak, flat, and valley periods, respectively, with T representing the total generation time of the day.

The time-of-use pricing in China, and the day/night time-of-use pricing commonly used in Europe, both fall under the category of static time-of-use pricing. This aligns closely with the time-segmented bidding strategy proposed in this paper. However, for other types of time-of-use pricing mechanisms, further refinement of the bidding process is necessary.

The process for calculating profits is shown in Figure 6. The simulation example was conducted in MATLAB (R2017a) using a centralized matching strategy to calculate the profits [25].

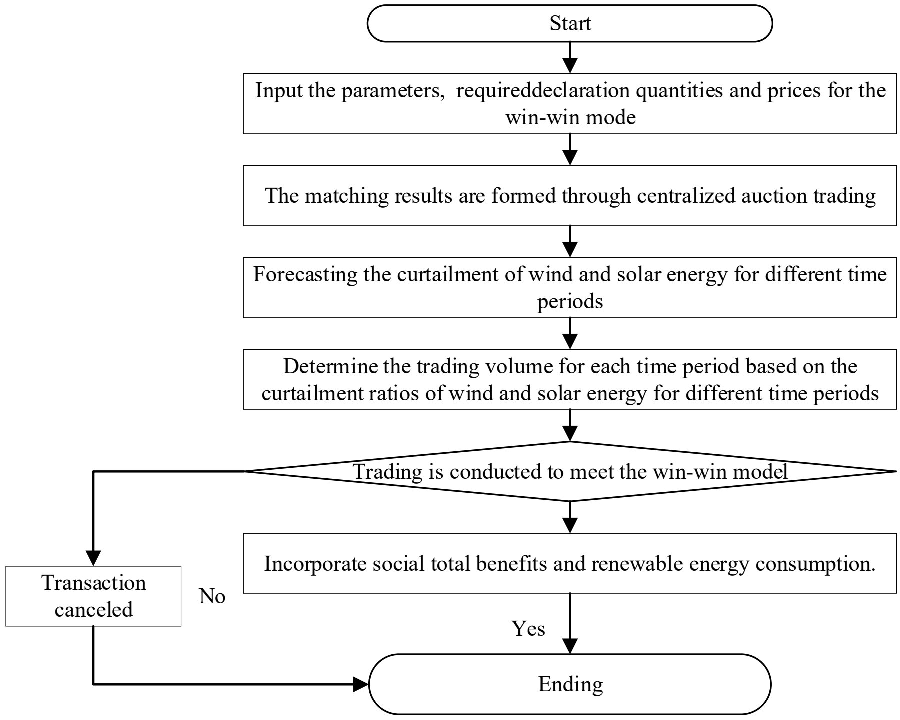

Figure 6. Flowchart of profit calculation.

6. Example Analysis

6.1. Parameter Settings

In the example, five SPPs and five new energy enterprises participate in generation rights trading. The trading model is centralized bidding using high and low quotes for matching and clearing. Some parameters required for the calculation are shown in Table 1.

Table 1. Parameters required for the case study.

Parameters(¥·kWh^{-1})	Value
transmission and distribution tariff	0.0455
government levy	0.001
operating costs for new energy generation enterprises	0.1
green energy environmental premium	0.03

SPPs mainly use coal-fired units for power generation. Table 2 shows the characteristic parameters of these plants, including installed capacity, maximum output, minimum output, ramping rate, and variable generation cost.

Table 2. Variable generation costs for SPPs.

SPP	1	2	3	4	5
Installed capacity (MW)	30	35	40	25	20
Maximum output (MW)	27	31.5	36	22.5	18
Minimum output (MW)	0	0	0	0	0
Ramping rate (MW·min^{-1})	0.9	1.1	1.2	0.75	0.6
Variable cost (¥·kWh^{-1})	0.32	0.36	0.3	0.4	0.38

To calculate the win–win conditions for generation rights and the profits of market participants in different time periods, we need the time-of-use electricity prices for the peak, flat, and valley periods during the windy season, as shown in Table 3.

Table 3. Time-of-use electricity prices during windy season.

Time Period		Variable Cost (¥·kWh^{-1})
Valley	00:00~04:00 11:00~16:00	0.232
Flat	04:00~06:00 08:00~11:00 22:00~24:00	0.388
Peak	06:00~08:00 16:00~22:00	0.592

As shown in Figures 7 and 8, the output forecasts and scheduled grid input for wind and solar power enterprises are illustrated. The gaps in the figure represent the curtailed wind and solar power. The proportion of generation rights trading volume for each period is determined based on the proportion of curtailed wind and solar power for the corresponding period.

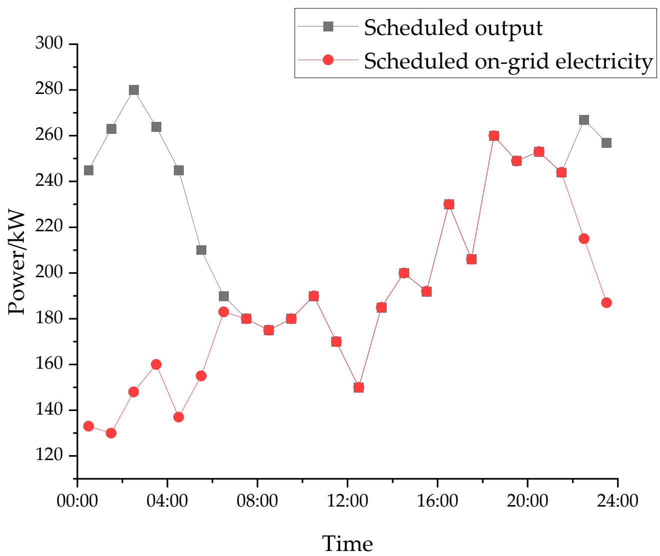

Figure 7. Day-ahead wind power output forecasting and scheduled grid-connected electricity.

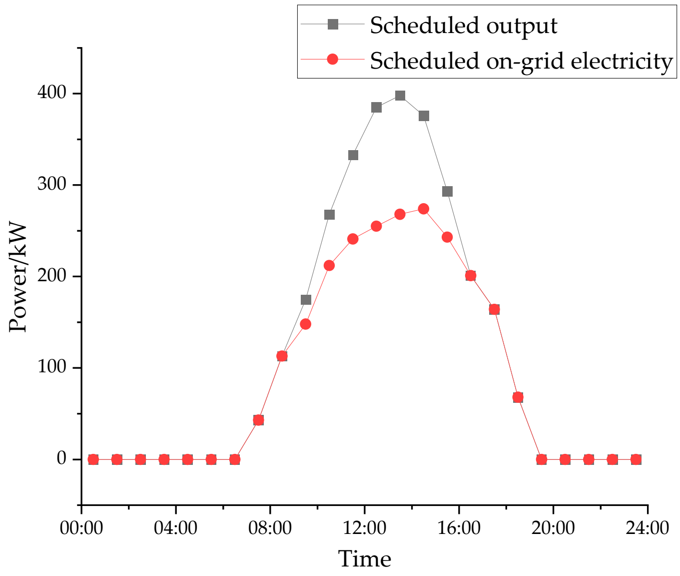

Figure 8. Day-ahead solar power output forecasting and scheduled grid-connected electricity.

6.2. Profit Margin

For SPPs, to meet their bid requirements $P_i > P_{i\_N} + P_{ij}^e - C_i$, the minimum profitable bids for the five SPPs at different times are shown in Figure 9.

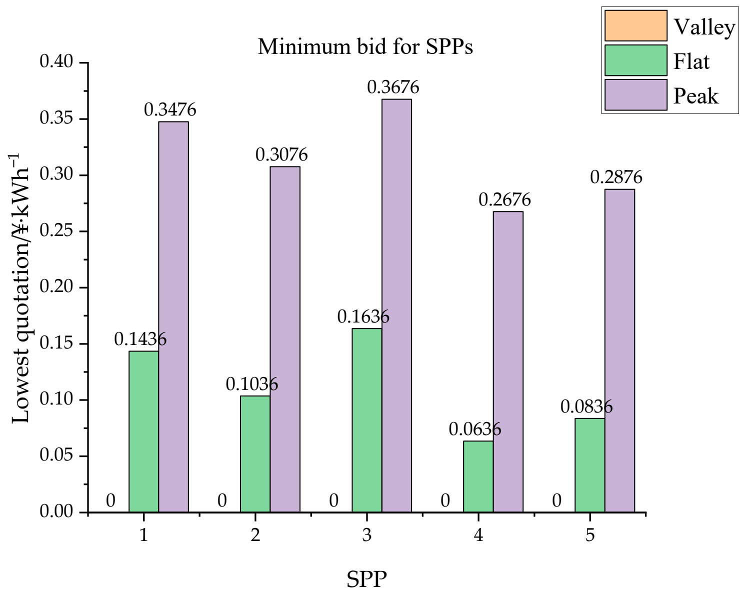

Figure 9. Lowest quotation for SPPs during the windy season.

For new energy generation enterprises, to meet their bid requirements $P_j < P_{j\_n} + P_{ij}^e - C_j$, the maximum profitable bids for the new energy generation enterprises at different times are shown in Table 4.

Table 4. The highest quotations for new energy in the windy season.

The Highest Offer in the Windy Season (¥·kWh^{-1})		
Valley	Flat	Peak
0.162	0.318	0.522

6.3. Comparison of Bidding Strategies

6.3.1. Single Bidding Strategy

Keeping the bid quantity of SPPs and new energy enterprises constant while changing their bid prices, use centralized matching trading for pairing. Calculate the total social benefits and the new energy consumption based on the win–win model and the proportion of wind and solar power curtailment in different periods.

The bidding situations of SPPs and new energy enterprises are shown in Tables 5 and 6.

Table 5. Bidding for SPPs by single bidding strategy.

SPP	1	2	3	4	5
Quotation (¥·kWh^{-1})	0.04	0.03	0.05	0.01	0.02
	0.06	0.05	0.07	0.03	0.04
	0.08	0.07	0.09	0.05	0.06
	0.1	0.09	0.11	0.07	0.08
	0.12	0.11	0.13	0.09	0.1
Volume (MWh)	80	90	100	70	40

Table 6. Bidding of new energy generation enterprises by single bidding strategy.

New Energy	1	2	3	4	5
Quotation (¥·kWh^{-1})	0.17	0.19	0.18	0.21	0.2
	0.19	0.21	0.2	0.23	0.22
	0.21	0.23	0.22	0.25	0.24
	0.23	0.25	0.24	0.27	0.26
	0.25	0.27	0.26	0.29	0.28
Volume (MWh)	90	70	60	100	50

Five SPPs and five new energy generation enterprises each have five sets of bids. Matching these bids results in 25 different trading outcomes. There are nine distinct trading results, differentiated by trading price, as shown in Table 7.

Table 7. Trading price.

Trading Price (¥·kWh^{-1})				
0.195/0.190	0.185/0.180	0.175/0.170	0.165/0.160	0.155/0.150
0.145/0.140	0.135/0.130	0.125/0.120	0.115/0.110	

The number 1 represents a trading price of 0.110/0.115, the number 2 represents a trading price of 0.120/0.125, and so on. The total social benefit and new energy consumption corresponding to these trading prices are shown in Figure 10.

When the trading price is 0.150/0.155 CNY·kWh^{-1}, both the total social benefit and new energy consumption reach their maximum values. At this point, the total social benefit is CNY 70,379, and the new energy consumption is 345 MWh. When the price exceeds 0.162 CNY·kWh^{-1}, new energy generation enterprises cannot make a profit during the valley period, resulting in a significant reduction in both the total social benefit and new energy consumption.

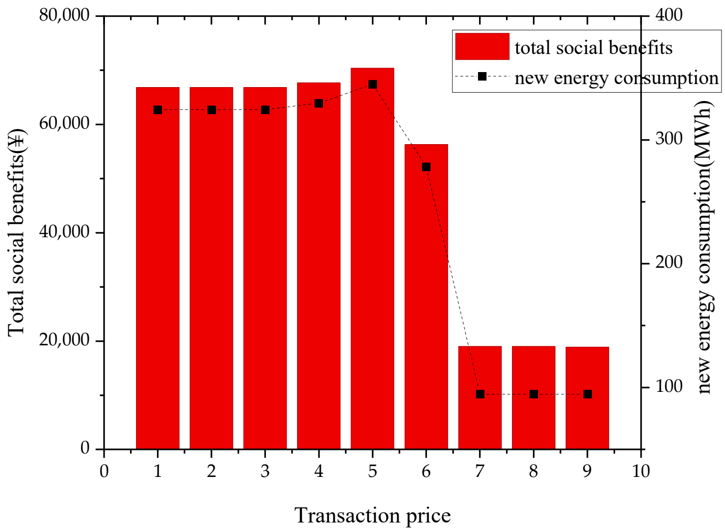

Figure 10. Total social benefits and new energy consumption.

6.3.2. Time-of-Use Bidding Strategy

These SPPs and new energy enterprises bid separately for the valley and flat periods. The bid quantities for each period are determined by the proportion of wind and solar power curtailment in each period.

The bidding situations of SPPs and new energy enterprises are shown in Tables 8 and 9.

Table 8. Bidding for SPPs by time-of-use bidding strategy.

Number	**1**	**2**	**3**	**4**	**5**
Time period			Valley		
Quotation (¥·kWh^{-1})	0.04	0.03	0.05	0.01	0.02
Volume (MWh)	59	67	74	52	30
Time period			Flat		
Quotation (¥·kWh^{-1})	0.17	0.16	0.18	0.14	0.15
Volume (MWh)	21	23	26	18	10

Table 9. Bidding of new energy generation enterprises by time-of-use bidding strategy.

Number	**1**	**2**	**3**	**4**	**5**
Time period			Valley		
Quotation (¥·kWh^{-1})	0.11	0.13	0.12	0.15	0.14
Volume (MWh)	67	52	45	74	37
Time period			Flat		
Quotation (¥·kWh^{-1})	0.24	0.26	0.25	0.28	0.27
Volume (MWh)	23	17	15	26	13

The total social benefit of the time-of-use bidding strategy is CNY 74,328, with the new energy consumption of 370 MWh.

The time-of-use bidding method achieves a 5.61% higher total social benefit and a 7.25% higher new energy consumption compared to the optimal scenario of single bidding. Additionally, single bidding is more likely to face the issue where the trading price cannot simultaneously meet the win–win conditions for the flat and valley periods, resulting in a significant decrease in the actual trading volume. Therefore, time-of-use bidding can be considered a superior power rights bidding strategy under the time-of-use electricity pricing context.

7. Conclusions

This paper explores the relationship between price difference settlement and generation rights trading, improves the win–win model for generation rights trading, and proposes a time-of-use bidding strategy for generation rights trading under time-of-use pricing. The example analysis calculates the total social benefit and new energy consumption of generation rights trading using the win–win model. By comparing the time-of-use bidding strategy with the single bidding strategy, the following conclusions are drawn:

After participating in generation rights trading, the relationship between the contract electricity volume and spot electricity volume changes. However, the unit price of additional electricity purchased from the spot market by the SPP due to generation rights trading remains the same as the spot price, unaffected by other factors. Similarly, the selling price for new energy follows the same principle.

(1) When the single bidding strategy can simultaneously satisfy the win–win conditions for both the peak and valley periods, the time-of-use bidding strategy achieves 5–12% higher total social benefits and 7–14% less wind and solar curtailment compared to the single-period strategy. In cases where the single-period bidding strategy cannot simultaneously meet the win–win conditions for the peak and valley periods, the time-of-use bidding strategy can achieve up to three times the total social benefits and renewable energy consumption compared to the single strategy.

(2) Under the background of price difference and time-of-use electricity pricing, even when considering factors such as green electricity and transmission and distribution costs, there remains room for a win–win situation in generation rights trading. This indicates that generation rights trading can effectively facilitate the transformation of SPPs, contributing to energy conservation, emission reduction, and environmental protection. Additionally, since static time-of-use pricing mechanisms are widely adopted in parts of Europe and the United States, the time-of-use bidding strategy also holds significant potential for application in these regions.

(3) This paper proposes a new generation rights transaction declaration strategy for the peak–flat–valley settlement mechanism of static time-of-use pricing, which is difficult to cope with more complex variable peak and dynamic time-of-use pricing, and has certain limitations. The next research focus is to further subdivide the time-of-use bidding strategy proposed in this paper so that it can be promoted in more countries and regions. Additionally, research methods for generation rights trading still need further exploration. For instance, the robust optimization method [26] and the stochastic optimization method [27] can be used for rights trading.

Author Contributions: Conceptualization, W.L. and X.C.; methodology, Y.G.; software, K.Q.; validation, U.; formal analysis, X.C.; investigation, W.L.; resources, X.C.; data curation, J.L.; writing—original draft preparation, X.Y.; writing—review and editing, J.L.; visualization, W.L.; supervision, W.L.; project administration, W.L.; funding acquisition, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Inner Mongolia Power Economic and Technological Research Institute by Science and Technology Project "Research on Demand-side response trading and new energy substitution mechanisms for captive power plants"(NO.HJ-YBHT-2023-JHTYB-1302-0067).

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank the Inner Mongolia Power Economic and Technological Research Institute for financial support. (Project NO. HJ-YBHT-2023-JHTYB-1302-0067).

Conflicts of Interest: The author Xiaolei Cheng was employed by the company Inner Mongolia Daqingshan Laboratory Co., Ltd. The author Yuying Gong was employed by the company Inner Mongolia Power (GROUP) Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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