

Article

Multi-Market Joint Trading of Distributed Resource Aggregators Considering a Carbon–Green Certificate Linkage Mechanism

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Abstract

To address the coupling among bidding decisions, resource allocation, and coordinated utilization of environmental rights for distributed resource aggregators in multiple markets, including the energy market, peak regulation ancillary service market, carbon trading market, and tradable green certificate market, this paper proposes a bi-level optimization model for multi-market joint trading considering a limited carbon–green certificate linkage mechanism. First, a quantitative mapping relationship between the emission reduction attribute of surplus green certificates and carbon emission reduction is established, and an upper limit constraint on the offset ratio is introduced to describe the limited conversion of green certificate environmental attributes into carbon emission reduction value. Second, an upper-level bidding model for the distributed resource aggregator is constructed, aiming at profit maximization while considering revenues from the energy, peak regulation ancillary service, carbon trading, and green certificate markets, as well as the operational constraints of gas turbines, energy storage, and flexible loads. This model characterizes the aggregator's joint bidding strategy and internal resource coordination. Then, a lower-level unified market clearing model is developed to minimize system operating cost and simulate the segmented bidding and unified clearing process of the aggregator, wind power, and thermal power units in the energy and peak regulation ancillary service markets. Finally, the bi-level model is transformed into a solvable single-level model using the Karush–Kuhn–Tucker (KKT) conditions and the Big-M method, and case studies are conducted to verify its effectiveness. The numerical results show that under the complete multi-market mechanism, the distributed resource aggregator (DRA) obtains a net profit of 2245.03 yuan, which is higher than 1450.33 yuan in the scenario without the carbon–green certificate mechanism and 773.48 yuan in the energy-only scenario. The wind curtailment rate decreases from 8.53% in the energy-only scenario to 2.71%, and the carbon emissions accounted for within the DRA boundary are reduced to 2865.40 kg. Although the price-taker scenario obtains a slightly higher net profit of 2300.20 yuan, its average regulation price reaches 455.20 yuan/MWh, compared with 412.50 yuan/MWh under the proposed model, indicating that the proposed strategy achieves a better balance between aggregator revenue and system-side regulation cost.

Keywords: distributed resource aggregator; multi-market trading; peak regulation ancillary service; carbon trading; tradable green certificate trading; bi-level optimization



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1. Introduction

With the continuous development of new power systems and the deepening of electricity market-oriented reform, the regulatory value of distributed resources, such as distributed generation, energy storage, electric vehicles, and flexible loads, has been increasingly enhanced. As important entities connecting distributed resources with power systems and various markets, virtual power plants and distributed resource aggregators can transform small-capacity and dispersed resources into observable, dispatchable, and tradable market resources through aggregation management [1]. Meanwhile, tradable green certificates, carbon emission trading, and related coordination mechanisms have been continuously improved. The external price signals faced by power market participants have gradually expanded from traditional electric energy prices to ancillary service prices, carbon prices, and green environmental attribute prices [2–6]. Under the background of coordinated electricity–carbon–green certificate multi-market operation, aggregators need not only to optimize the operation of internal resources but also to coordinate their bidding behavior, resource allocation, and revenue structure in the electric energy market, regulation ancillary-service market, carbon trading market, and green certificate market. Therefore, it is of great research significance to construct a joint trading mechanism for aggregators that takes into account economic benefits, low-carbon constraints, environmental attribute values, and system regulation requirements.

1.1. Literature Review

This subsection reviews the literature most closely related to the present study from three perspectives: the market participation of virtual power plants and distributed resource aggregators, joint energy–ancillary service trading, and the coordination of carbon and green certificate markets. Existing studies on the market-oriented operation of virtual power plants and distributed resource aggregators have mainly focused on resource aggregation, optimal dispatch, and market participation. Reference [7] pointed out that virtual power plants can improve the visibility and controllability of distributed resources for system operators and market participants through aggregation. Reference [8] systematically reviewed virtual power plant models and their participation modes in electricity markets. Reference [9] further summarized the configurations of virtual power plants and their interactions with electricity, carbon, and flexibility markets. These studies provide a theoretical basis for aggregators to participate in market transactions. However, most of them focus on the concept of virtual power plants, resource organization forms, and general market participation frameworks. Further research is still needed on joint bidding, unified clearing, and revenue coordination mechanisms of aggregators under multiple market price signals.

In terms of electric energy market trading, existing studies mainly focus on day-ahead trading, joint energy–reserve bidding, and price-maker bidding strategies. Reference [10] studied the mid-term dispatch optimization of virtual power plants and revealed the relationship between cross-period dispatch and market participation. References [11,12] established bidding models for virtual power plants participating in energy and spinning reserve markets, and analyzed the coupling relationship between bidding behavior and internal resource constraints in joint markets. Reference [13] developed a bi-level optimization model for a price-maker virtual power plant participating in energy and reserve markets, showing that when a virtual power plant reaches a certain resource scale, its bidding behavior can influence market clearing results. Reference [14] further investigated the bidding strategy of virtual power plants in energy and reserve markets. In general, existing studies on electric energy trading have sufficiently considered the interaction between aggregator bidding decisions and market clearing. However, most of them focus

on energy, reserve, or regulation service markets, while research on joint electric energy–peak-regulation ancillary service trading for renewable energy accommodation is still relatively insufficient.

With the increasing penetration of renewable energy, net load fluctuation and low-load regulation pressure have become more significant. The peak-regulation ancillary service has gradually become an important market product for reflecting the value of distributed flexible resources. Reference [15] constructed an optimization model for the joint electric energy–peak-regulation market of virtual power plants considering differentiated quotations of power supply equipment, demonstrating that virtual power plant participation in joint trading can improve resource utilization efficiency. Reference [16] verified the role of demand-side flexible resources in enhancing system regulation capability from the perspective of large-scale electric vehicles participating in regional power grid deep peak regulation. Reference [17] indicated that the regulation of the ancillary-service market can guide flexible resources to participate in system regulation through price mechanisms, thereby promoting renewable energy accommodation. Reference [18] showed from the perspective of deep peak-regulation control strategies of thermal power units that flexible operation of thermal power units is an important support for improving renewable energy accommodation capability. These studies provide useful references for aggregators participating in peak-regulation ancillary services. However, two deficiencies remain. First, the coordinated allocation of multiple resources, such as gas turbines, energy storage, reducible loads, and time-shiftable loads, among the electric energy market, upward peak-regulation service, and downward peak-regulation service has not been sufficiently characterized. Second, the coupling relationship between peak-regulation trading and environmental attribute markets, such as carbon trading and green certificate trading, has not been fully explored, making it difficult to comprehensively reflect the decision-making characteristics of aggregators under multiple value signals.

In terms of low-carbon mechanisms and environmental attribute markets, carbon trading and green certificate trading have gradually become important external constraints affecting aggregator operation strategies. Reference [19] constructed an optimal scheduling model for virtual power plants combining carbon trading and green certificate trading, and verified the role of low-carbon mechanisms in improving virtual power plant revenue and promoting renewable energy accommodation. Reference [20] studied the day-ahead operation strategy of virtual power plants in a coupled market environment, considering green certificate classification. Reference [21] analyzed the sequential decision-making optimization process of virtual power plants under electricity–carbon–certificate multi-market conditions. Reference [22] summarized the coordination relationship between electricity markets and low-carbon markets from the perspective of electricity–carbon–quota coupling transactions. Reference [23] investigated the two-stage optimal operation strategy of large energy bases under electricity–carbon–green certificate joint market trading. Reference [24] further extended the research boundary of urban virtual power plants participating in joint electricity and carbon trading. Existing studies show that carbon trading and green certificate trading can change the operation strategies of aggregators through cost constraints, revenue compensation, and compliance responsibilities. However, most studies still treat carbon trading costs and green certificate revenues as independent cost or revenue items. Further research is needed on how the green power environmental attributes carried by green certificates can be quantitatively mapped into low-carbon accounting or model-based offset mechanisms, and how boundary constraints can be introduced to avoid double counting and excessive offsetting of environmental attributes. Energy Communities (ECs) have recently attracted increasing attention because they aggregate distributed generation, energy storage, and flexible demand and enable their members to participate

actively in electricity markets. In this respect, ECs share several operational characteristics with distributed resource aggregators. Van den Berghe and Wieczorek [25] analyzed how electricity-market organization affects the participation of Energy Communities and identified institutional and market barriers to their active participation. Algarvio [26] developed a strategic bidding approach for active Citizen Energy Communities participating in spot electricity markets, demonstrating that improved forecasting and short-term bidding can reduce imbalance exposure and electricity costs. Cruz-De-Jesús et al. [27] reviewed practical strategies for Energy Communities participating in electricity and ancillary-service markets, either directly or through aggregators and other market intermediaries. These studies demonstrate that the aggregation of distributed generation, storage, and flexible demand can facilitate the participation of small-scale resources in electricity markets. However, Energy Communities generally emphasize community governance and benefits for their members, whereas the distributed resource aggregator considered in this study is modeled as a market-oriented entity that coordinates heterogeneous resources and jointly participates in energy, upward and downward regulation, carbon, and green certificate markets.

In summary, existing studies have carried out extensive exploration from the perspectives of aggregator and Energy Community participation in electricity markets, joint electric energy–ancillary service optimization, and carbon trading and green certificate trading mechanisms. Nevertheless, the following deficiencies remain. First, studies on aggregator multi-market trading mostly focus on energy, reserve, or regulation service markets, while insufficient attention has been paid to the coordinated allocation of multiple resources in joint electric energy–peak-regulation ancillary service trading, especially the characterization of its interaction with unified market clearing prices. Second, carbon trading and green certificate trading are mostly introduced as independent cost or revenue items, while the quantitative mapping between the environmental attributes of surplus green certificates and carbon emission reductions, as well as the boundary of their limited coordination, has not been adequately modeled. Third, few studies analyze the interaction among aggregators, wind power, and thermal power units under the electricity–peak-regulation–carbon–green certificate multi-market mechanism from the perspective of unified clearing, making it difficult to reveal the impact of aggregator trading behavior on thermal power deep peak regulation and renewable energy accommodation. These research gaps motivate the development of a unified framework that integrates aggregator bidding, internal resource coordination, market clearing, and limited carbon–green certificate linkage.

1.2. System and Regulatory Background

The power system considered in this study comprises a market operator, wind power producers, thermal power units, and a DRA. The DRA coordinates distributed photovoltaic generation, wind power, micro gas turbines, energy storage, reducible loads, and time-shiftable loads. It submits bids to the electric energy market and the upward and downward regulation markets and allocates the cleared quantities among its internal resources. The market operator performs unified clearing of the electric energy and regulation markets based on the bids submitted by the DRA, wind power producers, and thermal power units. Carbon trading and tradable green certificate trading are incorporated into the upper-level decision-making of the DRA as external environmental-market signals rather than being jointly cleared by the electricity-market operator.

In the Chinese regulatory context, virtual power plant policies define the market role and market-access requirements of aggregation entities [1]. Tradable green certificate policies specify the issuance, trading, and consumption accounting of the environmental attributes of renewable electricity [2,4,6], while carbon emission trading regulations define the corresponding carbon-accounting and trading boundaries [3,5]. Accordingly, the

DRA in this study is modeled as a market participant and resource-coordination entity. It does not operate the electricity market; instead, it coordinates its internal resources, submits market bids, and bears the corresponding costs and revenues within the defined modeling boundary.

1.3. Research Objectives and Contributions

To address the research gaps identified above, the objective of this study is to develop a unified multi-market decision-making framework for a distributed resource aggregator participating in the electric energy market, upward and downward regulation markets, carbon trading market, and tradable green certificate market. A bi-level optimization model for multi-market joint trading considering a limited carbon–green certificate coordination mechanism is constructed. Specifically, the upper level describes the aggregator’s bidding and internal resource allocation decisions, while the lower level represents the market operator’s unified clearing process. The model is transformed through KKT conditions and the Big-M method, and its effectiveness is verified through scenario comparison. The main contributions of this paper are as follows. It should be noted that the contribution lies in embedding a limited CET–TGC linkage mechanism into the multi-market joint trading framework of a DRA, while explicitly considering its strategic bidding, internal source–storage–load coordination, unified energy–regulation market clearing, and interactions with wind power and thermal power units.

(1) A limited carbon–green certificate coordination mechanism is incorporated into the DRA multi-market trading model to describe the quantitative mapping between surplus green certificates and deductible carbon emission reductions. Based on the accounting method for emission reductions from renewable energy generation [28], the theoretical emission reductions corresponding to surplus green certificates are quantified. An upper limit constraint on the offset ratio is introduced to characterize the limited coordination relationship through which the environmental attributes of green certificates are transformed into carbon emission reduction value under the model scenario, thereby avoiding double counting and excessive offsetting of environmental attributes.

(2) An upper-level multi-market bidding model for distributed resource aggregators is constructed. With the objective of maximizing aggregator profit, the model comprehensively considers the revenues from the electric energy market, regulation ancillary-service market, carbon trading market, and green certificate market, as well as the operation constraints of resources such as gas turbines, energy storage, and flexible loads. The joint bidding behavior and internal resource coordination of aggregators in multiple markets are characterized.

(3) A lower-level unified clearing model for the market operator is constructed. With the objective of minimizing system operating cost, a unified clearing model including aggregators, wind power, and thermal power units is established. The segmented bidding and clearing process of multiple market participants in the electric energy market and the regulation ancillary-service market is simulated, and the impacts of aggregator strategic bidding on market prices, system regulation, and renewable energy accommodation are analyzed.

(4) A scenario-comparison analysis framework is established based on the transformed bi-level market-interaction model. The optimality conditions of the lower-level unified clearing model are transformed into KKT conditions, and the complementarity constraints are linearized using the Big-M method. By comparing different market participation scenarios, the aggregator revenue structure, the effect of limited carbon–green certificate coordination, internal resource allocation, thermal power deep peak regulation, and wind power accommodation are analyzed to verify the effectiveness of the proposed mechanism.

2. Carbon-Green Certificate Linkage Mechanism for Environmental Rights Coordination

Under China's carbon peaking and carbon neutrality goals and renewable energy consumption responsibility mechanism, Carbon Emissions Trading (CET) and Tradable Green Certificates (TGCs) jointly affect the operating costs, environmental benefits, and market bidding strategies of distributed resource aggregators. The aggregator bears carbon-related costs associated with micro gas turbine output and grid electricity purchases, while obtaining TGC revenue and fulfilling renewable energy consumption obligations through renewable generation such as wind power and photovoltaic output. If CET and TGC trading are modeled only as independent cost or revenue items, the emission-reduction value embedded in surplus green certificates and the coordination relationship between different environmental rights cannot be fully represented.

Accordingly, this study develops a limited CET-TGC linkage mechanism based on the existing CET and TGC frameworks. The mechanism first calculates the surplus TGCs after the aggregator satisfies its Renewable Portfolio Standard (RPS) requirement and then converts the associated environmental attributes of renewable generation into theoretical deductible carbon emission reductions. To avoid double counting and excessive offsetting, an upper-limit constraint is introduced to restrict the proportion of actual carbon emissions that can be offset by surplus TGCs. This mechanism establishes a limited model-level linkage between CET and TGC trading and supports the joint optimization of the DRA in the energy, regulation, ancillary-service, carbon, and green certificate markets.

2.1. CET Mechanism

Under the CET framework, the carbon emission quota rights obtained by distributed resource aggregators can be expressed as:

$$E_{CO_2}^* = \chi_{mt} P_{mt} + \chi_{buy} P_{buy} \eta_{fire} \quad (1)$$

In the formula, $E_{CO_2}^*$ is the total amount of carbon emissions quota; χ_{mt} and χ_{buy} are the carbon quota coefficients of micro gas turbines and power grid purchase, respectively; P_{mt} is the power output of the micro gas turbine; P_{buy} is the electricity purchased from the grid; η_{fire} is the proportion of grid-purchased electricity supplied by thermal power generation.

It should be noted that the quota associated with grid-purchased electricity is introduced from the perspective of the DRA's indirect carbon responsibility. The DRA is not regarded as the physical producer of grid electricity. Instead, the grid-purchase term is used to establish an indirect, consumption-based carbon-accounting boundary for the DRA and to determine its carbon-market position. By contrast, the physical emissions associated with thermal power generation remain direct emissions of the corresponding generating units. The generator-side direct emissions and the DRA-side indirect emissions therefore belong to different accounting scopes and are reported separately. They are not added together when evaluating total physical emissions at the system level.

The actual carbon emissions generated by the aggregator can be expressed as:

$$E_{CO_2}^{real} = e_{mt} P_{mt} + e_{grid} P_{buy} \eta_{fire} \quad (2)$$

In the formula, $E_{CO_2}^{real}$ is the actual carbon emissions generated by the DRA, and e_{mt} and e_{grid} are the carbon emission coefficients of the micro gas turbine and the power grid respectively. Accordingly, $E_{CO_2}^{real}$ represents the emissions accounted for within the DRA's decision-making boundary rather than the total physical carbon emissions of the entire power system. The grid-purchase-related component is used only for the DRA's indirect carbon accounting and carbon-trading decision. Therefore, the DRA-side emissions in

Equation (2) are not summed with the generator-side direct emissions in Equation (32) to calculate total system emissions.

Based on the above relationship between quotas and emissions, the carbon emission trading volume of distributed resource aggregators in the CET market can be calculated by the ladder carbon price model:

$$E_{CO_2}^{dif} = E_{CO_2}^{real} - E_{CO_2}^* \quad (3)$$

$$C_{CET} = \begin{cases} \lambda_{CO_2} E_{CO_2}^{dif} & E_{CO_2}^{dif} \leq l \\ \lambda_{CO_2} (1 + \alpha) (E_{CO_2}^{dif} - l) + \lambda_{CO_2} l & l < E_{CO_2}^{dif} \leq 2l \\ \lambda_{CO_2} (1 + 2\alpha) (E_{CO_2}^{dif} - 2l) + \lambda_{CO_2} (2 + \alpha) l & 2l < E_{CO_2}^{dif} \leq 3l \\ \lambda_{CO_2} (1 + 3\alpha) (E_{CO_2}^{dif} - 3l) + \lambda_{CO_2} (3 + 3\alpha) l & 3l < E_{CO_2}^{dif} \leq 4l \\ \lambda_{CO_2} (1 + 4\alpha) (E_{CO_2}^{dif} - 4l) + \lambda_{CO_2} (4 + 6\alpha) l & 4l < E_{CO_2}^{dif} \leq 5l \\ \lambda_{CO_2} (1 + 5\alpha) (E_{CO_2}^{dif} - 5l) + \lambda_{CO_2} (5 + 10\alpha) l & E_{CO_2}^{dif} > 5l \end{cases} \quad (4)$$

In the formula, C_{CET} denotes the net carbon transaction cost of the DRA, and $E_{CO_2}^{dif}$ is the carbon allowance deficit after accounting for the allocated quota and the eligible green-certificate offset, λ_{CO_2} is the benchmark price of carbon trading, α is the price growth rate, and l is the length of the carbon emission interval. In the case study, $\lambda_{CO_2} = 0.27$ yuan/kg, $\alpha = 0.10$, and $l = 10$ kg. A positive C_{CET} represents the cost of purchasing carbon allowances, whereas a negative value represents revenue from selling surplus allowances.

2.2. TGC Trading Mechanism

TGC is used to characterize the environmental attributes corresponding to renewable energy power generation, and its unit usually corresponds to a certain amount of renewable energy power generation. Through the TGC trading mechanism, the market-oriented allocation of the environmental value of renewable energy can be realized, and a quantitative basis for the coordinated operation of multiple markets can be provided.

The green certificate performance requirements that distributed resource aggregators need to complete can be expressed as:

$$N_{Green}^* = \psi_{Green} (P_{cut} + P_{shift} + P_{trans}) \quad (5)$$

In the formula, N_{Green}^* is the number of TGC required for performance; ψ_{Green} is the green certificate compliance coefficient, which is used to reflect the minimum renewable energy consumption requirements. P_{cut} and P_{shift} denote the electricity consumption associated with the reducible load and shiftable load, respectively.

The number of TGC obtained by distributed resource aggregators through configured renewable energy units is:

$$N_{Green}^{real} = \tau_{pv} P_{pv} + \tau_{wind} P_{wind} \quad (6)$$

In the formula, N_{Green}^{real} is the actual number of TGC held; τ_{pv} and τ_{wind} are the green certificate conversion coefficients of photovoltaic and wind power respectively.

When $N_{Green}^{real} < N_{Green}^*$, it is necessary to purchase the balance part through the TGC market; when $N_{Green}^{real} > N_{Green}^*$, the excess TGC can obtain benefits through market transactions, and the transaction cost or benefit is expressed as:

$$C_{TGC} = \lambda_{TGC} \times (N_{Green}^* - N_{Green}^{real}) \quad (7)$$

In the formula, C_{TGC} is the transaction cost (or income) of green certificate; λ_{TGC} is the trading price of green certificate.

2.3. CET-TGC Linkage Mechanism Considering Surplus Green Certificate Deduction

To coordinate the Renewable Portfolio Standard (RPS) with Carbon Emissions Trading (CET), this study quantifies the emission-reduction attributes of surplus TGCs after RPS compliance and converts them into eligible carbon emission reductions within the defined accounting boundary. The key to the proposed linkage mechanism is to establish a quantitative conversion relationship between surplus TGCs and carbon emission reductions, while imposing an offset upper limit to avoid double counting and excessive weakening of the carbon-price signal.

According to the first edition of the integrated baseline methodology for renewable energy power generation grid-connected projects (CM-001-V01) issued by the National Development and Reform Commission of China [28], the carbon emission reduction corresponding to renewable energy power generation can be calculated by the regional grid baseline emission factor. For wind power and photovoltaic power generation projects, the weights of the marginal emission factor of electricity and the marginal emission factor of capacity are 0.75 and 0.25, respectively, and the carbon emission reduction conversion coefficient corresponding to the unit TGC can be obtained:

$$\chi_{TGC} = 0.75 \times \chi_{OM} + 0.25 \times \chi_{BM} \quad (8)$$

After completing the TGC performance requirements, the number of surplus green certificates held by distributed resource aggregators is N_{Green}^{sur} , and the corresponding theoretical deductible carbon emission reduction $E_{CO_2}^{sur}$ can be expressed as:

$$\begin{cases} N_{Green}^{sur} = \max\{0, N_{Green}^{real} - N_{Green}^*\} \\ E_{CO_2}^{sur} = \chi_{TGC} \times N_{Green}^{sur} \end{cases} \quad (9)$$

Because the accounting boundaries of TGC environmental attributes and carbon emission reductions may differ, an offset upper-limit constraint is introduced to avoid repeated declaration of emission reductions and excessive interference with the CET price signal. The eligible carbon offset from surplus TGCs is constrained not to exceed a specified proportion of the actual carbon emissions:

$$E_{CO_2}^{TGC} = \min(E_{CO_2}^{sur}, \eta_{CO_2}^{TGC} E_{CO_2}^*) \quad (10)$$

where $\eta_{CO_2}^{TGC}$ is the maximum proportion of actual carbon emissions that can be offset using the emission-reduction attributes of surplus green certificates. Because the current regulatory framework does not prescribe a uniform conversion ratio between TGCs and carbon allowances, $\eta_{CO_2}^{TGC}$ is introduced as a scenario parameter rather than a statutory coefficient. In this study, it is conservatively set to 0.08 to limit the offset to a small proportion of actual emissions, thereby preventing double counting and avoiding excessive weakening of the carbon-price signal.

Then the carbon trading volume $E_{CO_2}^{dif}$ after the introduction of green certificate deduction is revised to

$$E_{CO_2}^{dif} = E_{CO_2}^{real} - E_{CO_2}^* - E_{CO_2}^{TGC} \quad (11)$$

The proposed linkage mechanism enables the DRA to convert the emission-reduction value represented by surplus TGCs into eligible carbon offsets after satisfying the green certificate compliance requirement. In this way, the environmental attributes of green certificates and carbon allowances can be coordinated within a limited accounting boundary.

This mechanism improves the utilization of green certificate environmental attributes and reduces carbon-trading costs through controlled market linkage, thereby providing economic incentives for low-carbon scheduling and integrated energy management.

3. Aggregator Upper Bidding Model

3.1. Upper Objective Function

The distributed resource aggregator establishes the objective function with the maximum total profit:

$$\max F_{DRA} = R_{DRA}^E + R_{DRA}^{PR} + R_{DRA}^{CET} + R_{DRA}^{TGC} - C_{DRA}^{op} \quad (12)$$

In the formula, F_{DRA} represents the total profit of the distributed resource aggregator, R_{DRA}^E is the electric energy market revenue of the distributed resource aggregator, R_{DRA}^{PR} is the peak-regulation auxiliary service market revenue, R_{DRA}^{CET} is the carbon market revenue, R_{DRA}^{TGC} is the green certificate market revenue, and C_{DRA}^{op} is the operating cost of the aggregator.

(1) The benefits of distributed resource aggregators participating in the energy market R^E is:

$$R_{DRA}^E = \lambda_E P_{DRA}^E \quad (13)$$

$$P_{DRA}^E = P_{DRA}^{sell} - P_{DRA}^{buy} \quad (14)$$

In the formula, λ_E is the clearing price of the electric energy market, and P_{DRA}^E is the cleared energy quantity of the DRA, P_{DRA}^{sell} and P_{DRA}^{buy} denote the electricity sold to and purchased from the energy market by the DRA, respectively. Therefore, $P_{DRA}^E > 0$ represents a net electricity sale, whereas $P_{DRA}^E < 0$ represents a net electricity purchase.

(2) The benefits of distributed resource aggregators participating in the peak-regulation market R^{PR} is:

$$R_{DRA}^{PR} = \lambda_{PR+} P_{DRA}^{PR+} + \lambda_{PR-} P_{DRA}^{PR-} \quad (15)$$

$$\begin{cases} P_{DRA}^{PR+} = P_{mt}^{PR+} + P_{es}^{PR+} + P_{cl}^{PR+} + P_{tl}^{PR+} \\ P_{DRA}^{PR-} = P_{mt}^{PR-} + P_{es}^{PR-} + P_{tl}^{PR-} \end{cases} \quad (16)$$

In the formula, λ_{PR+} and λ_{PR-} are the upward peak-regulation clearing price and the downward peak-regulation clearing price respectively, P_{DRA}^{PR+} and P_{DRA}^{PR-} are the upward regulation quantity and the downward regulation quantity of the distributed resource aggregator respectively. P_{mt}^{PR+} , P_{es}^{PR+} , P_{cl}^{PR+} and P_{tl}^{PR+} are the upward regulation power of gas turbine, energy storage, load reduction and time-shifting load in the aggregator, respectively; P_{mt}^{PR-} , P_{es}^{PR-} and P_{tl}^{PR-} are the downward regulation power of gas turbine, energy storage, and time-shifting load, respectively.

(3) The carbon market revenue of distributed resource aggregators R_{DRA}^{CET} is

$$R_{DRA}^{CET} = -C_{CET} \quad (17)$$

In the formula, C_{CET} is the signed net carbon transaction cost calculated using the ladder carbon-pricing model in Equation (4).

(4) The green certificate market revenue of distributed resource aggregators R_{DRA}^{TGC} is

$$R_{DRA}^{TGC} = \lambda_{TGC} N_{Green,DRA}^{sur} \quad (18)$$

In the formula, λ_{TGC} is the clearing price of the green certificate market, and $N_{Green,DRA}^{sur}$ is the number of green certificate transactions of the distributed resource aggregator.

(5) The operation cost of distributed resource aggregator C_{DRA}^{op} is

$$C_{DRA}^{op} = c_{pv}P_{pv} + c_{wind}P_{wind} + c_{es}(P_{es}^{cha} + P_{es}^{dis}) + (c_{cl}\Delta P_{cl} + c_{tl}\Delta P_{tl}) + C_{mt} \quad (19)$$

In the formula, C_{mt} denotes the total operating cost of the DRA. In the present model, the DRA's operating cost mainly includes the operating and compensation costs of its internal resources. Grid usage costs, including distribution network charges, wheeling charges, congestion-related charges, and network-loss-related charges, are not explicitly modeled because the present study does not represent the detailed distribution network topology or location-dependent network tariffs. Consequently, the potential reduction in grid usage costs resulting from local coordination of distributed generation and demand is not captured in the calculated DRA profit. Accordingly, the profit objective represents pre-grid market-trading profit before distribution network charges, wheeling costs, congestion-related costs, and network-loss-related costs are considered.

3.2. Aggregate Resource Operation and Bidding Constraints

Aggregator power balance constraint:

$$\begin{aligned} P_{es}^{E,cha} + P_{cl}^E + P_{tl}^E + P_{DRA}^E &= P_{pv}^E + P_{wind}^E + P_{mt}^E + P_{es}^{E,dis} \\ 0 \leq P_{buy,t} &\leq M^{trade} u_t^{trade} \\ 0 \leq P_{sell,t} &\leq M^{trade} (1 - u_t^{trade}) \\ u_t^{trade} &\in \{0, 1\} \end{aligned} \quad (20)$$

In the formula, P_{pv}^E , P_{wind}^E and P_{mt}^E are the power of photovoltaic, wind power and gas turbine in the electric energy market of the aggregator, $P_{es}^{E,cha}$ and $P_{es}^{E,dis}$ are the charging and discharging power of the energy storage system in the electric energy market, P_{cl}^E and P_{tl}^E are the power of the load that can be reduced and time-shifted in the electric energy market.

To prevent simultaneous electricity purchasing and selling, the binary variable u_t^{trade} is introduced. When $u_t^{trade} = 1$, the DRA can purchase electricity but cannot sell electricity; when $u_t^{trade} = 0$, it can sell electricity but cannot purchase electricity. In the case study, M^{trade} is set to 2000 kW.

Distributed resource modeling within aggregators:

(1) Gas turbine:

$$P_{mt} = P_{mt}^E + P_{mt}^{PR+} - P_{mt}^{PR-} \quad (21)$$

$$\begin{cases} P_{mt}^{MIN} \leq P_{mt} \leq P_{mt}^{MAX} \\ -P_{mt}^{DOWN} \leq P_{mt}(t) - P_{mt}(t-1) \leq P_{mt}^{UP} \\ 0 \leq P_{mt}^{PR+} \leq P_{mt}^{PR+,MAX} \\ 0 \leq P_{mt}^{PR-} \leq P_{mt}^{PR-,MAX} \end{cases} \quad (22)$$

In the formula, P_{mt} is the power of the micro gas turbine, P_{mt}^{MAX} and P_{mt}^{MIN} are the upper and lower limits of the output of the micro gas turbine, P_{mt}^{UP} and P_{mt}^{DOWN} are the ramp-up and ramp-down limits of the micro gas turbine. P_{mt}^{PR+} and P_{mt}^{PR-} are the upward and downward regulation outputs of the micro gas turbine, $P_{mt}^{PR+,MAX}$ and $P_{mt}^{PR-,MAX}$ are the maximum outputs of the gas turbine.

(2) Energy storage:

$$\begin{cases} 0 \leq P_{es}^{cha}(t) \leq Y_{es}^{cha} P_{es}^{MAX} \\ 0 \leq P_{es}^{dis}(t) \leq Y_{es}^{dis} P_{es}^{MAX} \\ 0 \leq Y_{es}^{cha} + Y_{es}^{dis} \leq 1 \end{cases} \quad (23)$$

In the formula, Y_{es}^{cha} and Y_{es}^{dis} represent the charging and discharging operation state of energy storage, P_{es}^{cha} and P_{es}^{dis} are the charging and discharging power of energy storage, and P_{es}^{MAX} is the upper limit of energy storage power.

$$\begin{cases} 0 \leq P_{es}^{PR+}(t) \leq Y_{es}^{PR+} P_{es}^{PR+,MAX} \\ 0 \leq P_{es}^{PR-}(t) \leq Y_{es}^{PR-} P_{es}^{PR-,MAX} \\ 0 \leq Y_{es}^{PR+} + Y_{es}^{PR-} \leq 1 \end{cases} \quad (24)$$

In the formula, $P_{es}^{PR+,MAX}$ and $P_{es}^{PR-,MAX}$ are the maximum output of the energy storage, Y_{es}^{PR+} and Y_{es}^{PR-} are the binary charging and discharging state variables.

$$\begin{cases} SOC_{es}^{MIN} \leq SOC_{es}(t) \leq SOC_{es}^{MAX} \\ SOC_{es}(0) = SOC_{es}(T) \\ SOC_{es}(t) = SOC_{es}(t-1) + \mu_{es}^{cha} P_{es}^{cha}(t) - P_{es}^{dis}(t) / \mu_{es}^{dis} \end{cases} \quad (25)$$

In the formula, SOC_{es}^{MIN} and SOC_{es}^{MAX} are the minimum and maximum state of charge of energy storage, μ_{es}^{cha} and μ_{es}^{dis} are the charging and discharging efficiency of energy storage.

(3) Reduced load:

$$\begin{cases} P_{cl}^{E,MIN} \leq P_{cl}^E \leq P_{cl}^{E,MAX} \\ 0 \leq P_{cl}^{PR+} \leq P_{cl}^{PR+,MAX} \end{cases} \quad (26)$$

In the formula, P_{cl}^E denotes the reducible-load power participating in the energy market, P_{cl}^{PR+} is the regulation output, and $P_{cl}^{PR+,MAX}$ is the maximum output of the load that can be reduced.

(4) Time-shiftable load:

$$\sum_{t=t_{tl-}}^{t=t_+} P_{tl}^{out} = \sum_{t=t_{tl-}}^{t=t_+} P_{tl}^{in} \quad (27)$$

In the formula, P_{tl}^{out} and P_{tl}^{in} are the transfer-out and transfer-in power.

$$\begin{cases} 0 \leq P_{tl}^{out} \leq Y_{tl} \beta_{tl} P_{tl}^0 \\ 0 \leq P_{tl}^{PR+} \leq P_{tl}^{PR+,MAX} \\ 0 \leq P_{tl}^{PR-} \leq P_{tl}^{PR-,MAX} \end{cases} \quad (28)$$

In the formula, P_{tl}^0 is the baseline time-shiftable load power, Y_{tl} represents the state of internal time shift, β_{tl} is the proportion of time-shiftable load, $P_{tl}^{PR+,MAX}$ and $P_{tl}^{PR-,MAX}$ are the maximum power of time-shiftable load up and down peak regulation.

4. The Unified Clearing Model of the Lower Level of the Market Operator

The upper model depicts the distributed resource aggregator's bidding strategy and internal scheduling logic oriented to maximize its total profit. However, the final winning amount and actual market return of the aggregator depend not only on its own declaration strategy but also on the unified clearing mechanism operated by the market operator. In the bi-level model framework, the market operator is the follower, and its core goal is to minimize the comprehensive operating cost of the whole system while satisfying system power balance and operational constraints. To this end, this section will build a unified clearing model at the lower level of the market operator and simulate the multi-agent "segmented bidding and unified clearing" process, including aggregators, wind power, and traditional thermal power units, in detail.

4.1. The Lower Objective Function

$$\min F_{sys} = C_{DRA} + C_W + \sum_{gen \in G} C_{gen} \quad (29)$$

(1) The cost of distributed resource aggregator C_{DRA} is:

$$C_{DRA} = b_{DRA}^E P_{DRA}^E + (b_{DRA}^{PR+} P_{DRA}^{PR+} + b_{DRA}^{PR-} P_{DRA}^{PR-}) \quad (30)$$

In the formula, b_{DRA}^E , b_{DRA}^{PR+} and b_{DRA}^{PR-} are the electric energy, upward regulation and downward regulation market quotations of the distributed resource aggregator, respectively.

(2) Wind power cost C_W is:

$$C_W = b_W^E P_W^E + b_W^{PR-} P_W^{PR-} - c_W^{cur} P_W^{PR-} - R_W^{TGC} \quad (31)$$

In the formula, b_W^E , b_W^{PR-} and c_W^{cur} are the operation and maintenance cost, downward-regulation cost, and wind-curtailment cost of wind power, P_W^E and P_W^{PR-} are the power of wind power in the electric energy market and downward regulation market. R_W^{TGC} is the income of wind power in the green certificate market.

(3) The thermal power cost C_{gen} is:

$$C_{gen} = b_{gen}^E P_{gen}^E + (b_{gen}^{PR+} P_{gen}^{PR+} + b_{gen}^{PR-} P_{gen}^{PR-}) - C_{gen}^{DP} + C_{gen}^{CET} \quad (32)$$

In the formula, b_{gen}^E , b_{gen}^{PR+} and b_{gen}^{PR-} are the electric energy of thermal power, the upward regulation and downward regulation market quotations, respectively, and C_{gen}^{DP} is the deep peak-regulation cost of thermal power. C_{gen}^{CET} is the carbon transaction cost of thermal power. This term represents the generator-side carbon cost associated with the direct emissions of thermal power generation. It belongs to the direct-emission accounting boundary of the generating unit and is not combined with the DRA emissions in Equation (2), which belong to the DRA's indirect consumption-based accounting boundary. These two emission-accounting terms are used separately for their respective market decisions and are never summed to compute total system emissions.

In this paper, subsidies for thermal power participation in deep peak regulation are considered.

$$\begin{cases} C_{gen}^{DP} = C_{gen}^{DP,1} + C_{gen}^{DP,2} \\ C_{gen}^{DP,1} = c_{gen}^{DP,1} P_{gen}^{DP,1}, 0.3P_{gen}^{MAX} \leq P_{gen}^{DP,1} \leq 0.5P_{gen}^{MAX} \\ C_{gen}^{DP,2} = c_{gen}^{DP,2} P_{gen}^{DP,2}, P_{gen}^{MIN} \leq P_{gen}^{DP,2} \leq 0.3P_{gen}^{MAX} \end{cases} \quad (33)$$

In the formula, $c_{gen}^{DP,k}$ is the subsidy price of the k -stage deep peak regulation, and $P_{gen}^{DP,k}$ is the winning bid power of the k -stage deep peak regulation price.

4.2. Lower Constraint Conditions

The Big-M method is a linearization modeling method commonly used to deal with logical constraints, which is suitable for mixed integer linear programming models. This method transforms the original nonlinear logical relationship into linear inequality constraints by introducing a sufficiently large positive number M and a 0–1 decision variable Y , so as to facilitate the solution.

4.2.1. System Electric Energy Balance Constraints

The system electric energy balance constraint ensures that the total cleared electricity supplied by the DRA, wind power, and thermal units is equal to the system electricity demand in each period, as follows:

$$P_{DRA}^E + P_W^E + \sum_{gen \in G} P_{gen}^E = D^E \quad (34)$$

4.2.2. System Upward and Downward Regulation Balance Constraints

$$\begin{cases} P_{DRA}^{PR+} + \sum_{gen \in G} P_{gen}^{PR+} = D_{sys}^{PR+} \\ P_{DRA}^{PR-} + P_W^{PR-} + \sum_{gen \in G} P_{gen}^{PR-} = D_{sys}^{PR-} \end{cases} \quad (35)$$

Wind turbine safety constraints:

$$\begin{cases} P_W = P_W^E + P_W^{PR-} \\ 0 \leq P_W^{PR-} \leq P_W^{PR-,MAX} \\ P_W^{MIN} \leq P_W \leq P_W^{MAX} \end{cases} \quad (36)$$

In the formula, P_W is the wind power output, P_W^E is the standard power in the electric energy market, P_W^{PR-} is the downward regulation power, $P_W^{PR-,MAX}$ is the upper limit of the downward regulation of wind power, P_W^{MAX} and P_W^{MIN} are the maximum and minimum output of wind power.

Safety constraints of thermal power units:

$$P_{gen} = P_{gen}^E + P_{gen}^{PR+} - P_{gen}^{PR-} \quad (37)$$

$$\begin{cases} P_{gen}^{MIN} \leq P_{gen} \leq P_{gen}^{MAX} \\ -P_{gen}^{DOWN} \leq P_{gen}(t) - P_{gen}(t-1) \leq P_{gen}^{UP} \end{cases} \quad (38)$$

In the formula, P_{gen} is the output of thermal power unit, P_{gen}^{MAX} and P_{gen}^{MIN} are the upper and lower limits of thermal power, P_{gen}^{UP} and P_{gen}^{DOWN} are the upper and lower limits of climbing power.

$$\begin{cases} 0 \leq P_{gen}^{PR+} \leq P_{gen}^{PR+,MAX} \\ 0 \leq P_{gen}^{PR-} \leq P_{gen}^{PR-,MAX} \end{cases} \quad (39)$$

In the formula, P_{gen}^{PR+} and P_{gen}^{PR-} are the upper and lower peaking power of thermal power, $P_{gen}^{PR+,MAX}$ and $P_{gen}^{PR-,MAX}$ are the upper and lower peaking power limits respectively.

4.2.3. Market Clearing Constraints

In order to describe the ‘segmented quotation-unified clearing’ mechanism, the quotation segmentation variable is introduced. i represents market participants, including the distributed resource aggregator (DRA), wind power producer (W), and thermal power unit (Gen); j is the segment number; $P_{i,j}^{(\cdot)}$ is the winning power of the j th segment; $\Delta P_{i,j}^{(\cdot)}$ is the quoteable capacity of paragraph j ; $b_{i,j}^{(\cdot)}$ quote for paragraph j ; the Formulas (40)–(42) is the power decomposition and capacity boundary under the segmented quotation, which ensures that the clearing follows the segmented supply logic of ‘low price first and high price later’; the Formula (43) is a quotation compliance constraint, and the upper and lower limits can be set according to market rules.

Electricity market segmentation quotation and clearing constraints:

$$\begin{cases} P_i^E = \sum_{j=1}^J P_{i,j}^E \\ 0 \leq P_{i,j}^E \leq \Delta P_{i,j}^E \\ b_{i,1}^E \leq b_{i,2}^E \leq \dots \leq b_{i,J}^E, \forall i \end{cases} \quad (40)$$

In the formula, $\Delta P_{i,j}^E$ is the quotable capacity of subject i in the j th section of the electric energy market; $b_{i,j}^E$ is the corresponding segment quotation; $P_{i,j}^E$ is the winning power of the corresponding segment. Here, j denotes the segment index, and J denotes the total number of quotation segments.

Upward regulation market segmentation quotation and clearing constraints:

$$\begin{cases} P_i^{PR+} = \sum_{j=1}^J P_{i,j}^{PR+} \\ 0 \leq P_{i,j}^{PR+} \leq \Delta P_{i,j}^{PR+} \\ b_{i,1}^{PR+} \leq b_{i,2}^{PR+} \leq \dots \leq b_{i,J}^{PR+}, \forall i \in \{DRA\} \cup G \end{cases} \quad (41)$$

Downgrade regulation market segmentation quotation and clearing constraints:

$$\begin{cases} P_i^{PR-} = \sum_{j=1}^J P_{i,j}^{PR-} \\ 0 \leq P_{i,j}^{PR-} \leq \Delta P_{i,j}^{PR-} \\ b_{i,1}^{PR-} \leq b_{i,2}^{PR-} \leq \dots \leq b_{i,J}^{PR-}, \forall i \in \{DRA\} \cup G \cup W \end{cases} \quad (42)$$

The upper and lower limits of quotation and compliance constraints:

$$\begin{cases} b_i^{E,MIN} \leq b_{i,j}^E \leq b_i^{E,MAX} \\ b_i^{PR+,MIN} \leq b_{i,j}^{PR+} \leq b_i^{PR+,MAX} \\ b_i^{PR-,MIN} \leq b_{i,j}^{PR-} \leq b_i^{PR-,MAX} \end{cases} \quad (43)$$

5. Solution of the Bi-Level Model Based on the KKT Condition

The proposed joint market trading model is a bi-level optimization problem, where the upper level describes the profit maximization problem of the distributed resource aggregator, and the lower level represents the unified market clearing model operated by the market operator. Since the lower-level clearing model is a linear convex optimization problem, its optimal solution can be equivalently characterized by the KKT conditions. Therefore, the lower-level model is transformed into constraints of the upper-level problem using the KKT conditions, thereby enabling the bi-level model to be reformulated as a single-level problem.

The lower-level clearing model can be expressed in a general form as:

$$\begin{aligned} \min_y \quad & c(b)^T y \\ \text{s.t.} \quad & Ay = d \\ & Gy \leq h \end{aligned} \quad (44)$$

where y denotes the lower-level decision variable vector; $c(b)$ represents the cost coefficient determined by market bids; $Ay = d$ denotes equality constraints such as power balance and peak-regulation balance; and $Gy \leq h$ denotes inequality constraints such as output limits, ramping constraints, and segmented capacity constraints.

By introducing the dual variable λ for equality constraints and the dual variable μ for inequality constraints, the KKT conditions of the lower-level model can be written as:

$$\begin{aligned} Ay &= d, Gy \leq h \\ \mu &\geq 0 \\ c(b) + A^T \lambda + G^T \mu &= 0 \\ 0 &\leq \mu \perp h - Gy \leq 0 \end{aligned} \quad (45)$$

where the dual variables corresponding to the system balance constraints represent the clearing prices of the corresponding markets. By combining the above KKT conditions with the upper-level bidding decision model of the aggregator, a single-level mathematical program with equilibrium constraints (MPEC) can be obtained.

To facilitate the model solution, the Big-M method is adopted to linearize the complementarity slackness conditions. For a general complementarity relation:

$$0 \leq a \perp b \geq 0 \quad (46)$$

A binary variable Y and a sufficiently large constant M are introduced, and the relation can be linearized as:

$$\begin{aligned} 0 &\leq a \leq MY \\ 0 &\leq b \leq M(1 - Y) \end{aligned} \quad (47)$$

In the proposed model, this transformation is applied to the mutually exclusive electricity purchasing and selling states, the activation of the green-certificate offset mechanism, and the positive–negative decomposition of the carbon-trading quantity. The lower-level optimality conditions are imposed separately through primal feasibility, dual feasibility, stationarity, and strong duality.

In the numerical implementation, $M^{trade} = 2000$ kW, is used for the electricity purchasing and selling constraints, $M^{CET} = 10^4$ kg, is used for the green-certificate offset and carbon-trading quantity decomposition, and $M^{dual} = 10^4$ is imposed as a numerical bound on the market price and dual variables. These values exceed the corresponding feasible physical or numerical ranges and were chosen to avoid unnecessarily large bounds that could impair numerical stability.

6. Example Analysis

In order to verify the validity of the constructed model and analyze the trading behavior characteristics of distributed resource aggregators in a multi-market environment, this section conducts an example analysis. Firstly, by setting different scenarios, the operation results of aggregators under different market participation conditions are compared to illustrate the correctness of the model proposed in this paper in terms of economy, environmental benefits, and system regulation. On this basis, the market operation characteristics are further analyzed around the model proposed in this paper.

The case study is conducted over a 24-h scheduling horizon with a time resolution of 1 h. The considered system comprises five thermal power units, two wind power producers, and one DRA. The DRA coordinates an 800-kW photovoltaic unit, an 800-kW wind turbine, a 300-kW micro gas turbine, a battery energy storage system, a reducible load, and a time-shiftable load. This configuration represents a high-renewable-capacity case, where the installed renewable capacity is 1600 kW, and the renewable-to-gas-turbine capacity ratio is 5.33. Therefore, the results should be interpreted as reflecting the performance of the proposed mechanism under a high-renewable-penetration and relatively limited controllable-generation setting. To ensure transparency and reproducibility, the complete system scale, resource capacities, operating-cost parameters, market parameters, and 24-h load and renewable-generation profiles are provided in Appendix A. All four scenarios use the same physical system and input profiles; only the market-participation settings described below are changed.

6.1. Analysis of Market Trading Behavior of Aggregators Under Different Scenarios

In order to compare the impact of different market participation methods on the transaction results of aggregators, this paper sets up four typical scenarios and makes

a comparative analysis from the aspects of economic benefits, environmental benefits, market prices, and system adjustment through Table 1, so as to reveal the differences in the operation characteristics of aggregators under the multi-market coordination mechanism.

Table 1. Comparison of aggregator results under different trading scenarios.

Evaluation Dimension	Indicator	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Economic benefits	DRA pre-grid market-trading profit (yuan)	2245.03	1450.33	773.48	2300.2
	Electric energy market Earnings (yuan)	2294.68	2276.13	2299.43	−82.9
	Regulation market total revenue (yuan)	1473.91	1318.6	0	1436.14
	Total operating cost (yuan)	2137.92	2144.41	2139.55	212.42
Environmental benefits	Carbon trading/green certificate net income (yuan)	614.36	0	613.6	1159.39
	Total wind power curtailment rate (%)	2.71	2.73	8.53	2.81
	DRA-accounted carbon emissions (kg)	2865.4	2880	2880	2872.15
Market price	The average electricity price (yuan/MWh)	333.15	227.65	232.4	325.1
	The average peak regulation price (yuan/MWh)	412.5	315.8	0	455.2
System regulation	The total amount of deep peak regulation of thermal power (kW)	568.5	575.48	577	566.5

Scene settings:

Scenario 1: The model proposed in this paper;

Scenario 2: do not consider the carbon trading + green certificate mechanism;

Scenario 3: Distributed resource aggregators only participate in the electricity market;

Scenario 4: Distributed resource aggregators participate in the market as price receivers.

Table 1 compares the economic, environmental, market-price, and system-regulation results under the four market-participation scenarios. In Scenario 1, the DRA obtains a pre-grid market-trading profit of 2245.03 yuan, which is higher than that in Scenarios 2 and 3. This indicates that joint participation in the energy, regulation, ancillary-service, carbon, and green certificate markets can broaden the DRA's revenue sources. Scenario 4 is used as a price-taker benchmark rather than the proposed strategic-bidding mechanism. Although Scenario 4 achieves a slightly higher pre-grid market-trading profit of 2300.20 yuan, this is mainly due to its low operating cost of 212.42 yuan because the micro gas turbine is not dispatched. By contrast, Scenario 1 considers the DRA's strategic bidding behavior in the unified clearing process and achieves a comparable profit while maintaining a lower average regulation price. Therefore, the reported profits in Table 1 should be interpreted as pre-grid market-trading profits rather than final net profits. Distribution network charges, wheeling costs, congestion-related costs, and network-loss-related costs are not included in the current model. If these grid usage costs were considered, the actual net profits of all scenarios would be lower, and the profit ranking, especially between Scenarios 1 and 4, could change.

In terms of environmental performance and system regulation, Scenario 1 achieves the lowest DRA-boundary carbon emissions, at 2865.40 kg, and reduces the wind curtailment rate to 2.71%. In contrast, when the DRA participates only in the energy market in Scenario 3, the wind curtailment rate increases to 8.53% because regulation-market flexibility is not fully utilized. The total deep-regulation output of thermal power also reaches 577 kW, indicating higher system regulation pressure.

Overall, the multi-market coordination mechanism improves both the DRA's revenue structure and system regulation performance. Although Scenario 4 has a slight advantage in terms of individual DRA profit, Scenario 1 provides a more balanced performance when system regulation cost and market-operation efficiency are considered.

As shown in Figure 1, under the complete multi-market mechanism, the aggregator can obtain the benefits of the electric energy market, the regulation ancillary-service market and the environmental equity market at the same time, so the comprehensive net profit is higher. In contrast, without participating in the carbon-green certificate transaction, the DRA loses the corresponding environmental-market income. When the DRA does not participate in the regulation ancillary-service market, the flexibility value of energy storage and flexible loads cannot be fully monetized, leading to a significant decrease in economic performance.

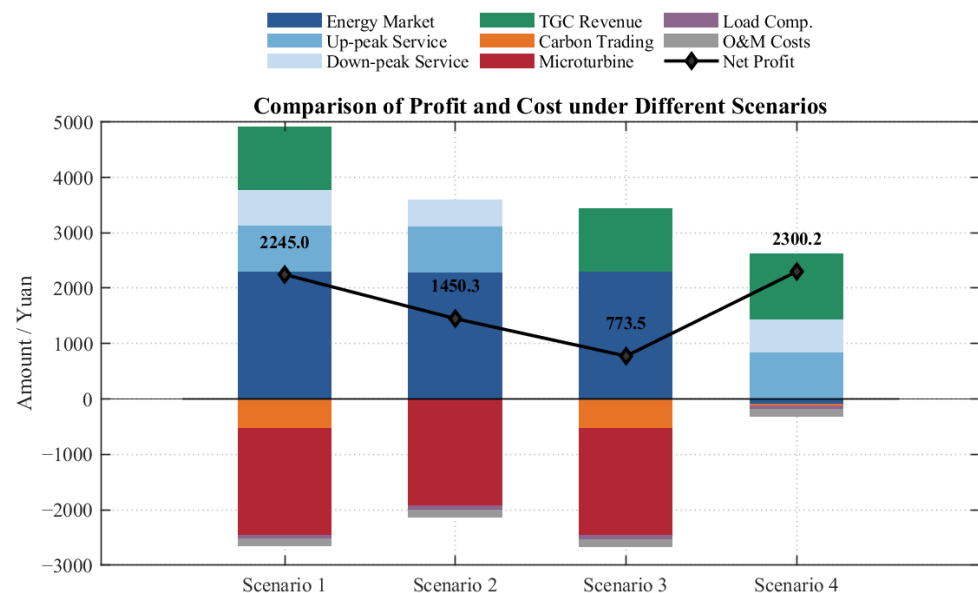


Figure 1. Comparison of aggregators' earnings under different market participation scenarios.

It should be noted that in scenario 4, when the aggregator participates in the market as a price taker, although its net profit is higher than that in scenario 1, it corresponds to a higher average regulation price. This shows that the increase in the individual income of the aggregator in this scenario is partly due to the higher regulation cost on the system side. Therefore, from the perspective of the overall operating efficiency of the system and the market-operation efficiency, scenario 1 still has better comprehensive performance. The multi-market mechanism integrating electric energy, ancillary services and environmental values helps to more fully reflect the economic value and environmental value of distributed flexible resources.

6.2. Analysis of Joint Market Trading Results Under the Carbon-Green Certificate Mechanism

Figure 2 shows that the clearing prices of the system electric energy market and the regulation auxiliary service market exhibit clear temporal variations. When the load is low at night and the wind power output is high, the clearing price of the electric energy market

is relatively low, while the downward regulation price is relatively high. During the peak period of daytime load, the price of electric energy and the price of upward regulation have increased. This indicates that market prices can reflect time-varying energy supply-demand conditions and regulation requirements.

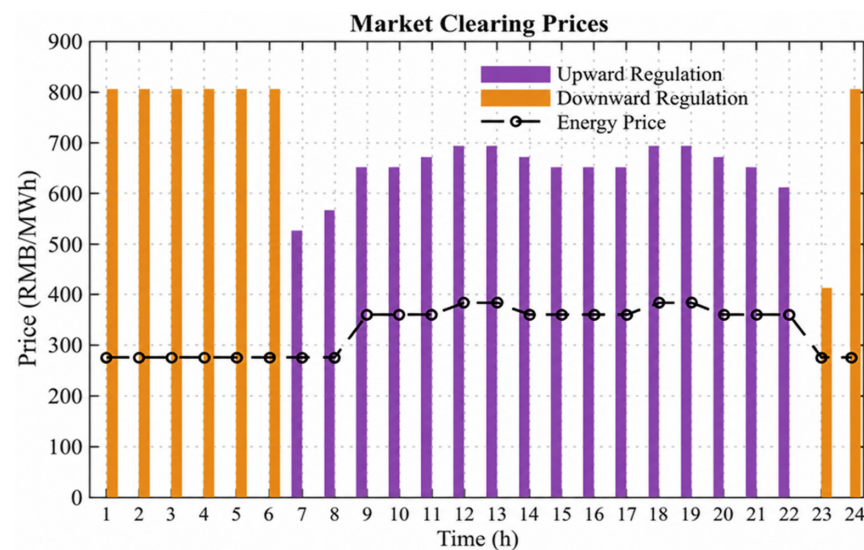


Figure 2. Joint market clearing results.

As shown in Figure 3, there are significant differences in the energy supply and regulation functions of different market participants across different periods. Thermal power units mainly provide base-load supply and provides peak regulation support when necessary. Wind power contributes to system supply during high-output periods and participates in clearing through downward regulation. The DRA participates in the energy market or the regulation ancillary-service market at different time periods according to market prices and internal resource constraints. When the net load at night is low, the wind power output increases, and the DRA provides more downward regulation; when the demand for electricity increases during the day, the aggregator provides electricity and regulation support through energy storage, flexible load, and gas turbine. The results show that under the joint market clearing, the joint clearing process forms a time-varying coordination pattern among market participants, improving system regulation capability and wind-power accommodation.

Figure 4 depicts the evolution of strategic bidding behavior of the DRA as a price-maker in the electric energy and regulation ancillary-service market. In the electric energy market, the declared price of the aggregator shows significant time-series adaptive characteristics. During periods with high renewable generation, the DRA adopts a low-price strategy to secure cleared quantities and actively lowers the quotation to close to the lower cost limit to increase the probability that surplus clean energy is cleared; in the morning and evening peak periods of electricity consumption, its quotation rises rapidly and closes to the market clearing price to maximize the marginal revenue. In addition, in the regulation ancillary-service market, based on the global optimization of the bi-level model, the aggregator tends to reduce its quotation to improve the probability of winning the bid during periods with high renewable output; during the peak load period, the quotation is relatively increased to obtain higher marginal revenue. The simulation results show that the proposed model can provide some reference for the collaborative bidding of aggregators in a multi-market environment.

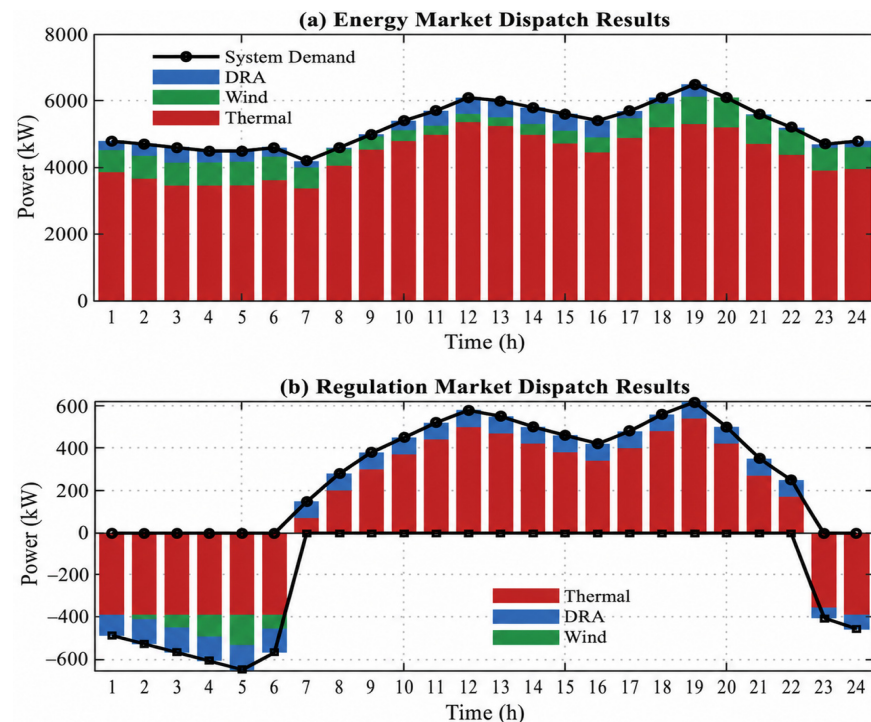


Figure 3. Joint market bid-winning power results.

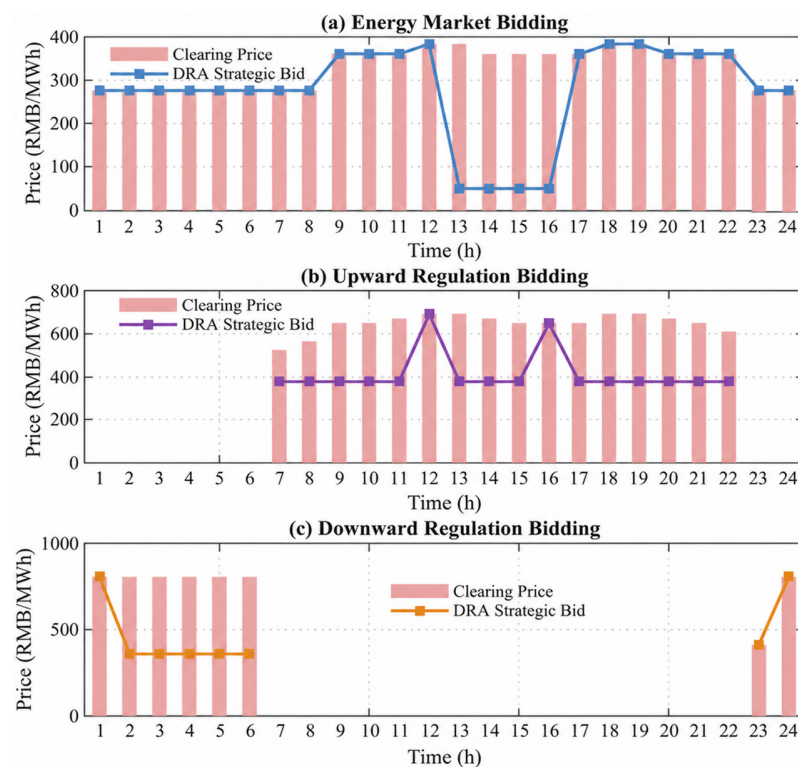


Figure 4. Aggregators' joint market quotation.

Figure 5 presents the output decomposition of the internal source-storage-load resources of the aggregator under multi-market price signals. During the period of high daytime electricity price and peak regulation price, the aggregator mainly provides regulation capacity through energy storage discharge, reducible load response, and micro gas turbine output; at night, when downward regulation demand is high and wind power output is high, it relies more on energy storage charging and time-shifting load transfer to

participate in downward regulation service. It can be seen that different resources have different functions in different markets and periods: gas turbines are more suitable for providing stable support, energy storage is more suitable for rapid two-way regulation, and flexible loads provide demand-side shifting and curtailment capability. The results show that the DRA can dispatch internal resources differently according to price signals and resource characteristics.

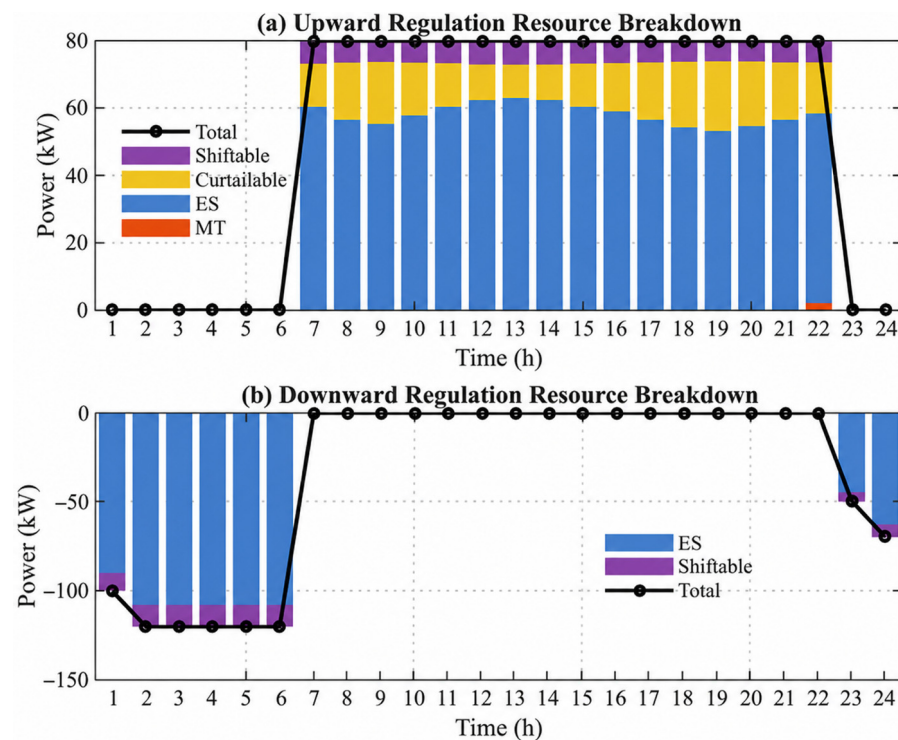


Figure 5. Aggregator regulation market output decomposition diagram.

Figure 6 shows the temporal operation status of distributed resource aggregators under the coupling mechanism of carbon allowances and green certificates. Figure 6a shows that during the peak period of photovoltaic generation at noon, the number of green certificates actually generated by the aggregator far exceeds the consumption demand of the internal load, forming a significant green certificate surplus. This surplus provides a sufficient margin for aggregators to participate in market transactions and carry out internal carbon emission deductions. Figure 6b further verifies the effectiveness of the green certificate offset constraint: although the potential green certificate deduction of the system exhibits a pronounced negative peak under high renewable generation, the actual eligible offset is restricted within the prescribed offset boundary by the actual carbon-emission level and the maximum offset ratio. This shows that the proposed bi-level optimization model can effectively curb the excessive offsetting by the DRA and maintain the accounting consistency of low-carbon operation while exploiting the economic potential of distributed resources.

Figure 7 reveals the operational characteristics of thermal power units participating in deep peak regulation under extreme load conditions. During the very low load period at night, when the conventional regulation resources are exhausted, or regulation limits are reached, the system must call on the deep peak regulation capacity of the thermal power unit to maintain the power balance. The operation results show that some thermal power units operate in the first and second deep-regulation segments during several low-load periods. Combined with the segmented peak regulation compensation mechanism introduced in the lower-level clearing model, the operation cost of thermal power participating

in deep regulation is compensated, which not only ensures the safe operation of the system but also provides more accommodation space for wind power integration. Since wind power is the renewable resource directly involved in the unified market clearing model, the wind-curtailed rate is used as the main indicator of renewable energy accommodation in this study.

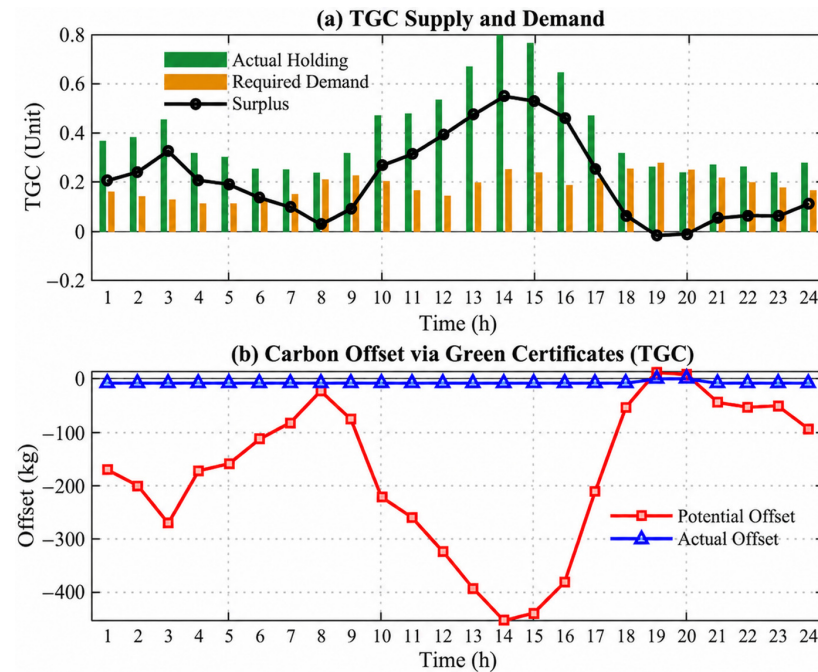


Figure 6. Results of the carbon-green certificate linkage mechanism.

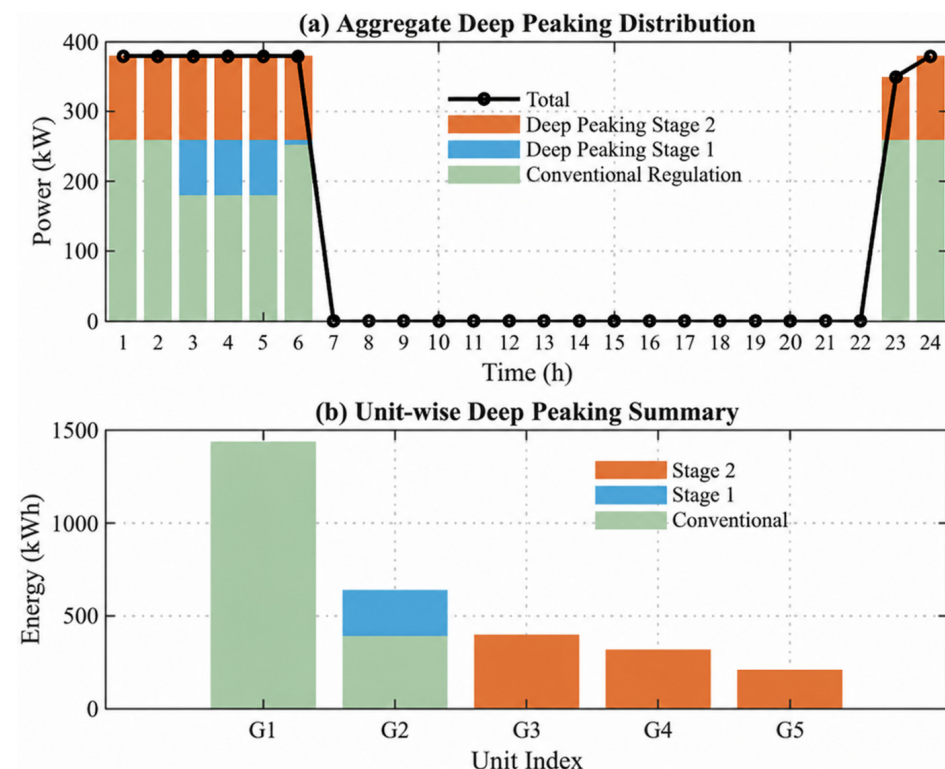


Figure 7. Deep peaking results.

6.3. Sensitivity, Robustness, and Model Validation Analysis

To further examine the robustness of the proposed model, a sensitivity analysis was conducted by varying key environmental-market and resource-availability parameters around the baseline case. Specifically, the benchmark carbon price, TGC price, renewable generation availability, and flexible-resource availability were varied by $\pm 20\%$, while the remaining parameters were kept unchanged. The proposed model was then solved under each parameter setting, and the changes in the DRA's net profit, carbon-market revenue, TGC-market revenue, and regulation-market revenue were compared with the baseline results.

Table 2 reports the sensitivity analysis results. The results show that the proposed model remains feasible under all tested parameter variations. An increase in the benchmark carbon price strengthens the low-carbon dispatch incentive and increases the economic value of the CET–TGC linkage mechanism, whereas a decrease in the carbon price weakens this incentive. Similarly, a higher TGC price improves the revenue contribution of renewable generation and surplus green certificates, while a lower TGC price reduces the environmental-market income. When renewable generation availability increases, the DRA obtains more green certificates and relies less on high-emission resources. In contrast, lower renewable availability reduces green-certificate income and increases the dependence on controllable resources. In addition, reducing flexible-resource availability weakens the DRA's ability to participate in regulation markets, leading to lower regulation-market revenue.

Table 2. Sensitivity analysis of key market and resource parameters.

Parameter Variation	Main Effect on Results	Robustness Implication
Carbon price $-20\%/+20\%$	Carbon-market revenue and low-carbon dispatch incentive decrease/increase	Main conclusions remain unchanged
TGC price $-20\%/+20\%$	TGC-market revenue decreases/increases with the TGC price	Main conclusions remain unchanged
Renewable generation availability $-20\%/+20\%$	Green-certificate income and renewable accommodation decrease/increase	Model remains feasible
Flexible-resource availability $-20\%/+20\%$	Regulation-market revenue decreases/increases with available flexibility	Model remains feasible

Overall, although the absolute values of the revenues vary with market prices and resource availability, the main conclusions of the case study remain unchanged. The proposed multi-market trading strategy can coordinate energy-market trading, regulation-market participation, and environmental-market mechanisms, and the limited CET–TGC linkage mechanism continues to improve the DRA's low-carbon operation and revenue structure under different parameter settings.

In addition to the sensitivity analysis, the model was further validated from the perspectives of constraint feasibility and mechanism consistency. The obtained solutions satisfy the main operational constraints, including energy balance, upward and downward regulation balance, micro gas turbine output limits, energy-storage charging/discharging limits, SOC bounds, flexible-load adjustment limits, and the constraint preventing simultaneous electricity purchasing and selling. Moreover, the scenario comparison verifies the consistency of the modeled market mechanisms. The DRA's net profit decreases from 2245.03 yuan under the complete multi-market mechanism to 1450.33 yuan without the carbon–green certificate mechanism and to 773.48 yuan in the energy-only scenario, which

is consistent with the modeling logic that multi-market participation and environmental-market coordination expand the DRA's revenue sources. Therefore, the proposed model is validated in terms of feasibility, mechanism consistency, and robustness.

7. Conclusions

This paper constructs a bi-level optimization model for multi-market joint trading of a distributed resource aggregator participating in the energy market, regulation ancillary-service market, carbon trading market, and tradable green certificate market. A limited carbon–green certificate linkage mechanism is incorporated, and the model is transformed and solved using KKT conditions and the Big-M method. The main conclusions are as follows. The main numerical findings are also summarized in the following conclusions to clarify the economic, environmental, and system-operation effects of the proposed model.

(1) The proposed limited carbon–green certificate linkage mechanism can describe the conversion relationship between the environmental attributes of surplus green certificates and carbon emission reduction value. By introducing an upper limit constraint on the offset ratio, repeated accounting of environmental rights and excessive offsets can be avoided, enabling a limited and controllable linkage between carbon trading and green certificate trading. Case results show that the aggregator's pre-grid market-trading profit reaches 2245.03 yuan under the complete multi-market mechanism, which is higher than 1450.33 yuan in the scenario without the carbon–green certificate mechanism and 773.48 yuan in the scenario where the aggregator only participates in the energy market.

(2) The upper-level bidding model can reflect the aggregator's joint bidding behavior and internal resource coordination under multiple market price signals. The aggregator can coordinate decisions among energy trading, upward regulation, downward regulation, carbon trading, and green certificate trading according to market prices and resource operating characteristics in different periods, thereby fully utilizing the differentiated regulation capabilities of gas turbines, energy storage, and flexible loads.

(3) The lower-level unified clearing model can characterize the market interactions among the aggregator, wind power, and thermal power units. Under the complete multi-market mechanism, the aggregator's participation in regulation of ancillary services coordinates with wind power downward regulation and thermal power deep peak regulation. As a result, the wind curtailment rate decreases from 8.53% in the energy-only scenario to 2.71%, indicating improved wind-power accommodation under the considered market-clearing framework, and the carbon emissions accounted for within the DRA boundary are reduced to 2865.40 kg.

(4) The proposed bi-level optimization model achieves a balanced performance between aggregator revenue and system operation. Although the aggregator's pre-grid market-trading profit in the price-taker scenario is 2300.20 yuan, slightly higher than 2245.03 yuan under the proposed model, the average regulation price in the price-taker scenario is 455.20 yuan/MWh, higher than 412.50 yuan/MWh under the proposed model. This indicates that the proposed model can maintain relatively high aggregator revenue while helping reduce system-side peak regulation cost.

Overall, the proposed model provides a decision-making reference for distributed resource aggregators participating in energy, regulation, ancillary service, and environmental markets. It should be emphasized that the profits reported in this study are pre-grid market-trading profits. Actual net profits would be lower after considering distribution network charges, wheeling costs, congestion-related costs, and network-loss-related costs, and the ranking of different scenarios may change. In addition, the case study adopts a high-renewable-capacity configuration, and the quantitative results may depend on this optimistic resource-capacity assumption. Future work will test the proposed mechanism

under different renewable-to-controllable capacity ratios to evaluate its scalability and applicability to systems with more diverse resource portfolios. Future research will incorporate distribution network topology, power-flow constraints, and scenario-dependent grid usage costs, including distribution network charges, wheeling charges, congestion-related charges, and network-loss-related charges, to evaluate more comprehensively the economic benefits of distributed resource aggregation.

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Appendix A

Table A1. Main system and resource parameters.

Category	Parameter	Value
Simulation	Scheduling horizon/time interval(h)	24/1
System scale	Thermal units/wind producers/DRA	5/2/1
Thermal units	Maximum output (kW)	[1800, 2000, 1500, 1200, 800]
	Minimum output (kW)	[400, 500, 350, 250, 150]
	Energy cost (yuan/kWh)	[0.20, 0.26, 0.34, 0.42, 0.52]
	Upward regulation cost (yuan/kWh)	[0.45, 0.55, 0.65, 0.80, 0.95]
	Downward regulation cost (yuan/kWh)	[0.42, 0.52, 0.62, 0.78, 0.92]
DRA renewable resources	PV/wind turbine capacity (kW)	800/800
High-renewable-capacity case setting	Installed renewable capacity in the DRA(kW)	1600
	Renewable-to-gas-turbine capacity ratio	5.33
Micro gas turbine	Minimum/maximum output (kW)	60/300
	Upward/downward ramp limit (kW/h)	150/150
Energy storage	Maximum charging/discharging power(kW)	500/500
	SOC minimum/maximum(kWh)	200/1000
	Initial SOC(kWh)	600
	Charging/discharging efficiency	0.95/0.95

Table A1. Cont.

Category	Parameter	Value
Flexible loads	Maximum reducible-load proportion	15% of the baseline load
	Reducible-load compensation cost(yuan/kWh)	0.05
	Maximum time-shiftable-load power(kW)	28.8
	Time-shiftable-load compensation cost(yuan/kWh)	0.005
DRA market limits	Energy transaction range(kW)	[−500, 500]
	Maximum upward/downward regulation capacity(kW)	80/120
Carbon parameters	Benchmark carbon price(yuan/kg)	0.27
	Carbon-price growth rate	0.10
	Carbon-emission interval length(kg)	10
	Thermal-generation share of grid purchases	0.85
	Micro gas turbine/grid emission factors(kg/kWh)	0.40/0.91
TGC parameters	TGC trading price(yuan/certificate)	225
	Maximum carbon-offset ratio	0.08
	PV/wind TGC conversion coefficients	0.001/0.001

References

1. National Development and Reform Commission; National Energy Administration. *Guiding Opinions on Accelerating the Development of Virtual Power Plants*; NDRC Energy [2025] No. 357; National Development and Reform Commission: Beijing, China, 2025.
2. National Development and Reform Commission; Ministry of Finance; National Energy Administration. *Notice on Promoting Full Coverage of Renewable Energy Green Electricity Certificates and Promoting Renewable Energy Electricity Consumption*; NDRC Energy [2023] No. 1044; National Development and Reform Commission: Beijing, China, 2023.
3. State Council of the People's Republic of China. *Interim Regulations on the Administration of Carbon Emission Trading*; Decree No. 775 of the State Council of the People's Republic of China; State Council of the People's Republic of China: Beijing, China, 2024.
4. National Development and Reform Commission; National Energy Administration; Ministry of Industry and Information Technology; Ministry of Commerce; National Data Administration. *Opinions on Promoting the High-Quality Development of the Renewable Energy Green Electricity Certificate Market*; NDRC Energy [2025] No. 262; National Development and Reform Commission: Beijing, China, 2025.
5. General Department of the National Energy Administration; General Office of the Ministry of Ecology and Environment. *Notice on Promoting the Connection Between Renewable Energy Green Electricity Certificates and the Voluntary Emission Reduction Market*; NEA General New Energy [2024] No. 124; General Department of the National Energy Administration: Beijing, China, 2024.
6. National Energy Administration. *Questions and Answers on China's Renewable Energy Green Electricity Certificates: 2025 Edition*; National Energy Administration: Beijing, China, 2025.
7. Pudjianto, D.; Ramsay, C.; Strbac, G. Virtual power plant and system integration of distributed energy resources. *IET Renew. Power Gener.* **2007**, *1*, 10–16. [\[CrossRef\]](#)
8. Naval, N.; Yusta, J.M. Virtual power plant models and electricity markets—A review. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111393. [\[CrossRef\]](#)
9. Zare, A.; Shafie-khah, M.; Siano, P.; Lazaroiu, G.C. A systematic review of virtual power plant configurations and their interaction with electricity, carbon, and flexibility markets. *Renew. Sustain. Energy Rev.* **2026**, *226*, 116448. [\[CrossRef\]](#)
10. Pandžić, H.; Kuzle, I.; Capuder, T. Virtual power plant mid-term dispatch optimization. *Appl. Energy* **2013**, *101*, 134–141. [\[CrossRef\]](#)
11. Mashhour, E.; Moghaddas-Tafreshi, S.M. Bidding strategy of virtual power plant for participating in energy and spinning reserve markets—Part I: Problem formulation. *IEEE Trans. Power Syst.* **2011**, *26*, 949–956. [\[CrossRef\]](#)

12. Mashhour, E.; Moghaddas-Tafreshi, S.M. Bidding strategy of virtual power plant for participating in energy and spinning reserve markets—Part II: Numerical analysis. *IEEE Trans. Power Syst.* **2011**, *26*, 957–964. [\[CrossRef\]](#)
13. Baringo, L.; Freire, M.; García-Bertrand, R.; Rahimiyan, M. Offering strategy of a price-maker virtual power plant in energy and reserve markets. *Sustain. Energy Grids Netw.* **2021**, *28*, 100558. [\[CrossRef\]](#)
14. Nguyen-Duc, H.; Nguyen-Hong, N. A study on the bidding strategy of the virtual power plant in energy and reserve market. *Energy Rep.* **2020**, *6*, 622–626. [\[CrossRef\]](#)
15. Shen, Y.; Cen, W.; Zhou, B. Optimization strategy for the joint electricity energy–peak shaving market of virtual power plants considering differentiated quotations of power supply equipment. *Electr. Power* **2025**, *58*, 115–127.
16. Mao, M.; Lin, C.; Wang, J. Hierarchical transactive energy control strategies for deep peak regulation in regional power grid with large-scale electrical vehicles. *Proc. CSEE* **2025**, *45*, 4187–4201.
17. Xi'an Jiaotong University. *Research on the Peak-Shaving Ancillary Service Market Mechanism for Promoting Renewable Energy Consumption and Ningxia Market Analysis*; World Bank: Washington, DC, USA, 2019.
18. Li, L.; Liu, X. Control strategy optimization for thermal power unit adapted to deep peak shaving for large-scale new energy source integration. *Electr. Power* **2020**, *53*, 155–161.
19. Guo, X.; Wang, L.; Ren, D. Optimal scheduling model for virtual power plant combining carbon trading and green certificate trading. *Energy* **2025**, *318*, 134750. [\[CrossRef\]](#)
20. Tian, Y.; Qin, Z.; Huang, Z. Day-ahead operation strategy of virtual power plants in coupled markets considering green certificate classification. *Electr. Power Constr.* **2025**, *46*, 14–26.
21. Xu, Y.; Liao, Y.; Kuang, S.; Ma, J.; Wen, T. Virtual power plant optimization process under the electricity–carbon–certificate multi-market: A case study in Southern China. *Processes* **2025**, *13*, 2148. [\[CrossRef\]](#)
22. Jiang, Y.W.; Chen, W. Review and prospect of coupled electricity-carbon-renewable portfolios trading. *Electr. Power Constr.* **2023**, *44*, 1–13. [\[CrossRef\]](#)
23. Jiang, W.; Xiao, Y.; Yi, H.; Zhao, L.; Wang, X.; Xin, C.; Hu, Z.; Xie, H.; Zhang, X. Two-stage optimal operation strategy for large-scale energy bases under the joint market trading of electricity, carbon, and green certificates. *Electr. Power Constr.* **2025**, *46*, 150–162.
24. Zhou, K.; Ma, C.; Chu, Y. Peer-to-peer joint electricity and carbon trading model for urban virtual power plants considering the cooperative behavior of prosumers. *Renew. Energy* **2025**, *255*, 123806. [\[CrossRef\]](#)
25. Van den Berghe, L.H.G.J.; Wiecek, A.J. Community participation in electricity markets: The impact of market organisation. *Environ. Innov. Soc. Transit.* **2022**, *45*, 302–317. [\[CrossRef\]](#)
26. Algarvio, H. Strategic participation of active Citizen Energy Communities in spot electricity markets using hybrid forecast methodologies. *Eng* **2023**, *4*, 1–14.
27. Cruz-De-Jesús, E.; Marano-Marcolini, A.; Martínez-Ramos, J.L. Participation of Energy Communities in electricity markets and ancillary services: An overview of successful strategies. *Energies* **2024**, *17*, 4631. [\[CrossRef\]](#)
28. China Climate Change Info-Net. *CM-001-V01 Integrated Baseline Methodology for Grid-Connected Renewable Energy Generation Projects: Version 1*; China Climate Change Info-Net: Beijing, China, 2013. Available online: <https://www.kailaimei.com/article/detail/664.html> (accessed on 17 July 2026).

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