Wind-Solar-Thermal Power Coupling System in The Power Market Environment Benefit Distribution Studies

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Abstract

With the continuous increase in the proportion of new energy, China's power system will further increase the capacity and flexibility of new energy consumption capacity and flexibility in the future. The combined operation of renewable energy and thermal power can improve the utilization rate of renewable energy and the economy of thermal power operation to a certain extent, and is one of the effective ways to solve the problem of curtailment of wind and solar power. Based on the combing of the market mode of wind-solar-thermal coupling system, this paper discusses the game relationship between wind power, photovoltaic power and thermal power, and proposes the operation strategy of wind-solar-thermal power coupling system under the spot market; Then, with the goal of maximizing economic benefits, a two-stage stochastic optimization model was constructed in the coupled operation mode and the independent operation mode, respectively, and the contribution

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of the alliance members in the day-ahead market, flexibility contribution and environmental cost contribution was weighed, and the revenue distribution method between renewable energy and thermal power was proposed by introducing the market contribution index; Finally, based on the simulation and verification of a local power grid in Liaoning Province, the results show that the proposed joint operation strategy effectively improves the overall revenue level, and proposes a gain cooperative revenue distribution strategy with computational efficiency, which fully considers the contribution of each entity to the alliance for fair distribution, and is conducive to guiding the coordinated development of new energy and thermal power.

Keywords: New energy consumption, coupling system, spot market, cooperative game, profit distribution.

1 Introduction

With the acceleration of energy transformation and change, China's renewable energy will continue to maintain the growth trend, from supplementary power source to the main power source. According to relevant forecasts, China's installed capacity of photovoltaic and wind power will realize 5.1 billion kilowatts by 2050, with a combined generating capacity of 9.66 trillion kilowatt-hours, accounting for 64% of the country's total generating capacity, and becoming the main source of green power supply in the future. However, China's power grid is currently for renewable energy consumption capacity is obviously insufficient, 2021 national abandoned wind abandoned light electricity amounted to 20.61 billion kWh, 6.78 billion kWh, resulting in great economic loss. The reason for this is that the insufficiency of the marketization system and the backwardness of the energy system system are one of the important factors affecting the utilization rate of renewable energy in China [1–3]. For this reason, China has issued the Notice on Accelerating the Recommended Construction of Electricity Spot Market since 2022, which will promote the spot market trading of renewable energy, and actively promote the formation of a Chinese domestic modern electricity market system, promote the optimal allocation of electricity resources by market-oriented means, and then enhance the integration capacity of the whole chain of "source-network-load-storage", as well as explore the system value space in-depth, and further explore the potential space of the system. system value space, and further explore the potential space of the system. In this context, renewable energy enterprises will realize systematic changes in their future living space, operation mode, profitability and other underlying logic.

The spot market is mainly divided into the day-ahead market and the real-time balancing market according to the trading cycle, and the day-ahead market is responsible for determining the next day's clearing tariffs as well as the next day's generation plans of each power generation company, while the real-time balancing market eliminates the imbalance by adjusting the level of power supply and load electricity consumption [4]. Renewable energy sources participating in spot market trading will face the risk of imbalance penalties due to the volatility and stochasticity of their own output, which may weaken their market competitiveness. In order to avoid imbalance penalties, there are two main countermeasures, one is to improve the accuracy of output forecast to reduce the degree of deviation, and the other is to form an alliance with the flexibility of regulating power sources to make up for the instability of their output through joint operation. In recent years, the National Development and Reform Commission (NDRC) has proposed to carry out the construction of “wind, fire and storage integration” to coordinate the coordinated development and scientific allocation of multiple resources [5]. Among them, when the combination of renewable energy and thermal power as a whole to participate in the market, both can improve the rate of wind consumption, but also to improve the flexibility of the grid, thus enhancing the overall control performance of the system, improve economic efficiency, China to achieve the "double carbon" goal and green development is of great significance. Therefore, how to formulate the strategy of wind-fire coupling system and establish a fair and reasonable alliance revenue distribution method under the spot market environment has become the focus of research [6].

2 The Participation Model of Wind-Solar-Thermal Power Coupling System In The Market

In the current electricity market in China, there is a trading model in which each trading entity independently participates in market bidding. There is a competitive relationship between renewable energy enterprises represented by wind power and photovoltaic power, and traditional energy enterprises represented by thermal power. Bidding games are conducted based on the goal of achieving optimal comprehensive income, and each enterprise is not willing to compromise with each other. However, the output instability

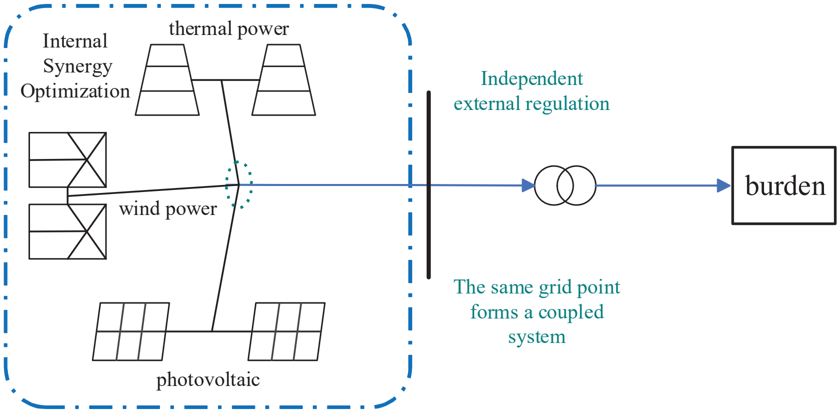

Figure 1 The wind-solar-thermal power coupling system participates in the running mode of spot market.

and volatility of renewable energy companies result in their actual output deviating from expected data, which will increase real-time balancing costs and reduce their competitive advantage in the spot market, leading to resource waste such as wind and solar power [7].

Based on this, this article constructs a new market trading model – the wind-solar-thermal power coupling system participating in the market. Intended to use market-oriented means to adjust the interests of participants and promote the consumption of renewable energy, by forming cooperative and win-win alliances with different characteristic resources to participate in market transactions and achieve maximum alliance benefits. Among them, thermal power, as a flexible resource, can provide flexible adjustment contributions in the real-time balanced market to reduce the unbalanced costs caused by the output characteristics of renewable energy enterprises. Renewable energy companies generate electricity at lower marginal costs and earn higher profits. That is to say, by setting appropriate coupling operation modes of wind, solar, and fire, fully utilizing the complementary effects between various characteristic entities, improving the system's ability to absorb renewable energy and the economic efficiency of operation [8].

2.1 Operation Analysis of Wind-Solar-Thermal Power Coupling System

The wind-solar-thermal power coupling system is an integrated technology that integrates multiple power sources such as wind power, photovoltaic power, and thermal power, achieving complementary advantages and providing high-quality, economical, environmentally friendly, and renewable electricity for the power grid. Among them, thermal power operates smoothly and reliably, with low requirements for geographical environment, but its operating cost is high and it pollutes the environment seriously; Renewable energy generation, such as wind and solar power, has weaknesses such as large fluctuations, randomness, and discreteness. However, its operating costs are low, resources are abundant, and renewable. Renewable energy and thermal power have natural complementarity in terms of resources, operation, and investment.

From a long-term perspective, the policy direction of “low-carbon” and “zero emissions” has clearly indicated the future trend: clean renewable resources such as solar and wind power will play a crucial role in promoting global energy structure adjustment and reducing greenhouse gas emissions [9]. If renewable energy and thermal power cooperate, thermal power can use its own flexible regulation ability to provide flexible services to compensate for the regional and seasonal limitations of wind power, as well as the limitations of photovoltaic power generation in terms of day and night and power generation capacity; The safety and economic benefits of renewable energy can also become the driving force for thermal power to seek transformation under carbon reduction policies.

Based on cooperative game theory, combined with the background of power system reform and the generation characteristics of renewable energy and thermal power, a wind-solar-thermal power coupling system operation mode is designed as shown in Figure 2.

The wind-solar-thermal power coupling system participates in the running mode of spot marketThe wind-solar-thermal power coupling system refers to the integration and coupling of multiple renewable energy enterprises and multiple thermal power enterprises to form an electric energy production body on the principle of voluntary mutual benefit, and participate in the power market trading in the form of cooperative alliance. In the process of cooperation, considering the uncertainty of renewable energy output, thermal power enterprises need to play a flexible adjustment role as much as possible on the basis of ensuring their own minimum output, giving power generation space to renewable energy enterprises, and ensuring that wind power and photovoltaic participate in market scheduling with a larger share. At the same time, the increase in the output of renewable energy enterprises, because its marginal cost is lower than that of thermal power, will bring additional economic profits to the alliance, and this part of the

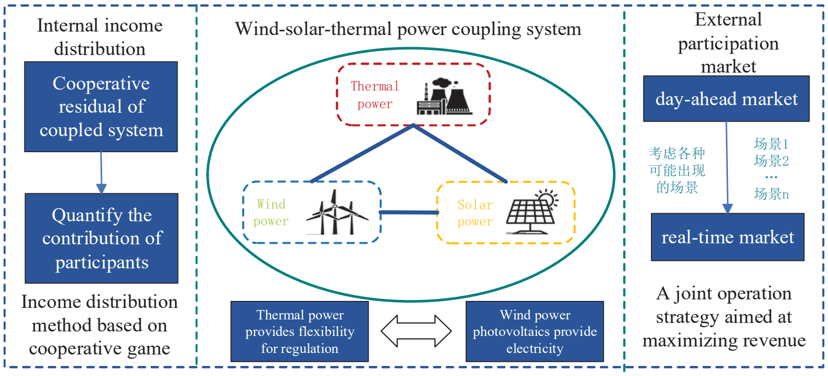

Figure 2 The wind-solar-thermal power coupling system participates in the running mode of spot market.

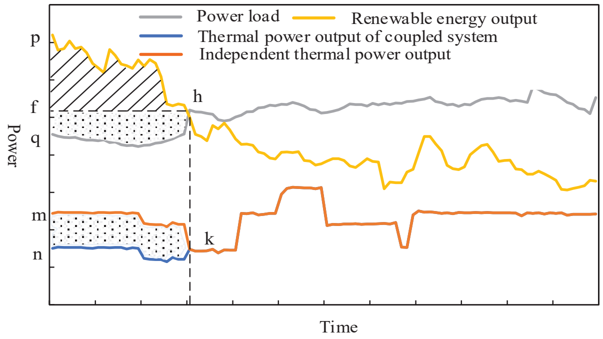

Figure 3 Power generation space transferred by thermal power for renewable energy.

income should be part of the compensation for thermal power generation space. The thermal power transfer space diagram of the wind-solar-thermal power coupling system participating in the market is shown in Figure 3.

Figure 2 shows the substitution relationship between the amount of electricity consumed by renewable energy and the flexibility adjustment ability of thermal power under the premise of meeting the load demand of the power grid. Among them, the gray curve represents the daily load curve of the power system, the yellow curve represents the output curve of renewable energy, the orange curve represents the output curve of thermal power independent participation in the market, and the blue curve represents the output curve of thermal power after the joint operation of renewable energy and thermal power (after point k, the blue curve and the orange curve coincide). The shaded part fhq indicates the abandonment of wind and light power; The shaded mnk indicates the space that thermal power gives way to renewable energy. In Figure 2, the area of pqh is equal to the area of mnk, that is, the potential flexibility adjustment capacity of thermal power units is equal to the power generation avoided by renewable energy enterprises. In the mode of joint operation, the actual amount of renewable energy abandoned by wind and light is the area of shadow pfh.

2.2 Two-Stage Electricity Market Process

The research in this paper takes into account both the day-ahead markets and real-time equilibrium markets,and the designed the wind-solar-thermal power coupling system participating in the two markets is shown in Figure 3.

A day-ahead market ensures that market participants settle day-ahead market trades electricity at day-ahead prices, and the difference between real-time output and day-ahead declaration is included in the real-time market.

In the day-ahead market stage, the alliance will submit the next-day power curve before 12:00 noon according to the forecast of wind power, photovoltaic output and electricity price, combined with the operation characteristics of thermal power units. This declaration curve is actually based on the day-ahead market time point, taking into account the actual output of renewable energy that may exist on the operation day and the flexibility adjustment ability of thermal power under the corresponding working conditions. The mechanism of the interaction between the day-ahead market and the real-time equilibrium market is taken into account in the operational decision-making of the day-ahead market, so that the power generators can obtain greater benefits. During the operation day, due to the forecast error, the real output of the power generator may be different from the previous day's plan, and the coupling system needs to adjust the operation mode of the thermal power unit in the coupling system according to the actual wind power, photovoltaic output and electricity price after the real-time balance market is started in each period, and complete the unbalanced power settlement after the event. Generating companies will receive additional compensation income based on the positive-sum imbalance electricity settlement price.

In addition, this paper discusses the pricing mechanism of electricity through the implementation of the two-price method in the case of the imbalance of positive and negative electricity prices. There is no possibility of arbitrage in this way, and it has a positive impact on promoting the enthusiasm of market participants [10, 11].

3 Construction of Mathematical Model

3.1 Operation Model of Wind-Solar-Thermal Power Coupling System

The operation strategy of wind-solar-fire coupling system participating in the market aims at maximizing the comprehensive income of the cooperation alliance. The objective function includes the income in the day-ahead market, the expected income in the real-time balanced market, the power generation cost of thermal power and the annual average fixed cost of renewable energy:

$$\begin{aligned}\max U_{DWS} = & \sum_{t=1}^{24}\sum_{h=1}^{N}\lambda_h \rho_{h,t}^{da}\cdot P_{DWS,h,t}^{da} - \rho_W P_{W,h,t}^{rt} - \rho_S P_{S,h,t}^{rt} \\ & + \sum_{t=1}^{24}\sum_{h=1}^{N}\gamma_h(\rho_{h,t}^{\mathrm{rt}+}\cdot P_{DWS,h,t}^{rt+} - \rho_{h,t}^{\mathrm{rt}-}\cdot P_{DWS,h,t}^{rt-} - C_{DWS,t}^{da})\end{aligned} \tag{1}$$

Where U_{DWS} defines the combined gain of the wind-scenery-fire coupled system at moment t, $\rho_{h,t}^{da}$ difines the day-ahead market clearing price of electricity at time t,$\rho_{h,t}^{\mathrm{rt}+}$, $\rho_{h,t}^{\mathrm{rt}-}$ define the positive and negative imbalance power settlement prices in the real-time balancing market at moment t in scenario h, respectively, $P_{DWS,h,t}^{da}$, $P_{DWS,h,t}^{rt+}$, $P_{DWS,h,t}^{rt-}$ define the declared power of the coupled system in the day-ahead market and the positive and negative unbalanced power in the real-time balancing market, respectively, γ_h defines the scenario probability, ρ_W, ρ_S defines the cost of kWh of wind and PV in the coupled system, $P_{W,h,t}^{rt}$, $P_{S,h,t}^{rt}$ define the actual output of wind power and photovoltaics, $C_{DWS,h,t}^{da}$ defines operating costs for thermal units in the day-ahead market, real-time balancing market, for moment t.

The positive and negative imbalance power settlement prices in the real-time balancing market can be expressed as:

$$\rho^{rt+} = \theta_{up}\cdot\rho_t^{da} \tag{2}$$

$$\rho^{rt-} = \theta_{down}\cdot\rho_t^{da} \tag{3}$$

Where θ_{up}, θ_{down} denotes the penalty coefficients corresponding to positive and negative imbalance power, respectively.

The operating cost of thermal units in the day-ahead market, real-time balancing market can be expressed as:

$$C_{DWS,t}^{da} = \rho_r \sum_{j=1}^{N} [a_j \cdot (P_{D-j}^{rt})^2 + b_j \cdot P_{D-j}^{rt} + c_j] \tag{4}$$

Where ρ_r defines the coal price, P_{D-j}^{rt} defines the actual power generated by thermal power, a_j, b_j, c_j define the parameters of the consumption characteristics of unit j.

The cost of kWh of wind and PV units can be expressed as [12]:

$$\rho_W = \frac{C_{Wi} + OMC_W + C_{W\,fim}}{Q_W} - C_{Wv} \tag{5}$$

$$\rho_S = \frac{C_{Si} + OMC_S + C_{S\,fim}}{Q_S} - C_{Sv} \tag{6}$$

Where C_{Wi}, C_{Si} define the total investment cost for wind and PV units, OMC_W, OMC_S denote the operation and maintenance costs of wind power and photovoltaic units, $C_{W\,fim}$, $C_{S\,fim}$ denote financial interest costs for wind and photovoltaic units, C_{Wv}, C_{Sv} denote the cost of government subsidies for wind and photovoltaic units, Q_W, Q_S denote the total life-cycle electricity generation from wind and photovoltaic units.

$$Q_W = \sum_{t=1}^{T_W} \frac{C_W \times H_W \times (1 - PCR_W)}{(1 + r_W)^t} \tag{7}$$

$$Q_S = \sum_{t=1}^{T_S} \frac{C_S \times H_S \times (1 - PCR_S)}{(1 + r_S)^t} \tag{8}$$

Where C_W, C_S define the installed capacity of photovoltaic and wind turbines, H_W, H_S define the average annual power generation hours of photovoltaic and wind turbines, PCR_W, PCR_S define the electricity usage rates for photovoltaic and wind turbines, r_W, r_S denote the discount rate for photovoltaic and wind turbines, T_S, T_W denote the life cycle of photovoltaic and wind turbines.

The constraints that need to be satisfied for a coupled system to participate in the market are as follows:

(1) Power balance constraints

$$P_{DWS,h,t}^{rt} - P_{DWS,h,t}^{da} = P_{DWS,h,t}^{rt+} - P_{DWS,h,t}^{rt-} \tag{9}$$

$$0 \leq P_{\mathrm{DWS},h,t}^{rt+} \leq M_1 \cdot (1 - \nu_t) \tag{10}$$

$$0 \leq P_{\mathrm{DWS},h,t}^{rt-} \leq M_2 \cdot \nu_t \tag{11}$$

Where $P_{DWS,h,t}^{rt}$ defines Actual output of the coupled system.

(2) Overall coalition output constraints

$$P_D^{\min} \leq P_{DWS,h,t}^{da} \leq P_W^{\max} + P_S^{\max} + P_D^{\max} \tag{12}$$

where $P_W^{\max}$, $P_S^{\max}$, $P_D^{\max}$ denote the maximum output capacity of wind power subjects, photovoltaic subjects and thermal power subjects. $P_D^{\min}$ defines the minimum output limits for thermal power.

(3) Climbing rate constraint

$$P_{D-j,t}^{rt} - P_{D-j,t-1}^{rt} \leq P_{D-j}^{up} \cdot \Delta T \tag{13}$$

$$P_{D-j,t}^{rt} - P_{D-j,t-1}^{rt} \leq P_{D-j}^{down} \cdot \Delta T \tag{14}$$

where $P_{D-j,t}^{rt}$, $P_{D-j,t-1}^{rt}$ define the actual thermal power output at the moment t/t-1, P_{D-j}^{up}, P_{D-j}^{down} denote the maximum upward and downward creep rates for thermal unit j. take 15 minutes as a statistical period

3.2 Modeling The Independent Operation of Renewable Energy and Thermal Power Generation

3.2.1 Wind power independent operation model

The operation strategy for independent participation of wind power in the market is based on the objective of maximizing the comprehensive return of wind power, and a two-stage stochastic optimization model is established by considering the day-ahead market and real-time balancing market, and the objective function is shown as follows:

$$\begin{aligned} \max U_W^i = {} & \sum_{t=1}^{T} \rho_t^{da} \cdot P_{\mathrm{W,t}}^{da} - \rho_W P_W + \sum_{t=1}^{T} \sum_{h=1}^{N} \gamma_h \\ & \times (\rho_{h,t}^{\mathrm{rt+}} \cdot P_{\mathrm{W,h,t}}^{\mathrm{rt+}} - \rho_{\mathrm{h,t}}^{\mathrm{rt-}} \cdot P_{\mathrm{W},h,\mathrm{t}}^{\mathrm{rt-}}) \end{aligned} \tag{15}$$

Where $P_{\mathrm{W,h,t}}^{\mathrm{rt+}}$, $P_{\mathrm{W},h,\mathrm{t}}^{\mathrm{rt-}}$ denote positive and negative unbalanced power of the wind subject in the real-time balancing market at moment t for scenario h. The constraints for independent operation are mostly similar to those of the coupled system and will not be repeated here.

3.2.2 Solar power independent operation model

Similar to wind power, the operational strategy for PV's independent participation in the market is aimed at maximizing the PV's overall return, with the objective function shown below:

$$\max U_S = \sum_{t=1}^{T} \rho_t^{da} \cdot P_{\mathrm{S,t}}^{da} - \rho_S P_S + \sum_{h=1}^{N} \gamma_{\mathrm{h}} (\rho_{h,t}^{\mathrm{rt+}} \cdot P_{\mathrm{S,h,t}}^{\mathrm{rt+}} - \rho_{\mathrm{h,t}}^{\mathrm{rt-}} \cdot P_{\mathrm{S},h,\mathrm{t}}^{\mathrm{rt-}}) \tag{16}$$

Where $P_{\mathrm{S,h,t}}^{\mathrm{rt+}}$, $P_{\mathrm{S},h,\mathrm{t}}^{\mathrm{rt-}}$ denote the positive and negative unbalanced power of PV subjects in the real-time balancing market at moment t in scenario h.

$$\max U_D = \rho_t^{da} \cdot P_{\mathrm{D,t}}^{da} - C_{\mathrm{D,t}}^{\mathrm{da}} \tag{17}$$

4 Income Distribution Mechanism Based on the Shapley Value Approach

The most commonly used method for benefit allocation in cooperative games is the shapley value method, which is based on the marginal effect of individuals in the coupled system, but this method increases the computational volume greatly when the number of individuals in the coupled system is large, and the computational efficiency is low.

This study aims to deal with the revenue allocation challenge that arises when the number of individuals in the coupled system is large, based on which we propose an improved Shapley value method for revenue allocation. Firstly, the same type of coupled subjects in the wind-fire coupled system are divided into wind-power coupled subjects, photovoltaic coupled subjects, and thermal-power coupled subjects respectively, in order to reduce the size of the coalition and to optimize, schedule, and solve all the combination cases consisting of coupled subjects. Then, according to the results of the scheduling calculation, the Shapley value algorithm is used as the base allocation method, so as to derive the base allocation results of the incremental gains between coupled subjects of the same type; secondly, within the subject of interest, the contribution degree of each member in the coupled subject is quantified from three perspectives of the power volume, flexibility, and the environmental cost, and the contribution index of the cooperative gains is constructed; after that, according to the base allocation results of the coupled system After that, according to the basic allocation results of the coupled system, comprehensively considering the contribution factors of each member's cooperation gain, applying the asymmetric Nash negotiation theory to secondary allocation of the allocation, and obtaining the allocation results of each member's gain [13].

4.1 Gain Function Based on Resource Aggregation

The bundling of the same type of interest subjects is regarded as a whole, which is denoted as combination A. For the wind and fire coupling system N, since there are only three types of energy sources inside, all the coupling subjects can eventually be aggregated into three types of coupling subjects, namely wind power, photovoltaic and thermal power. According to the cooperative game theory, there are seven combinations of these three types of coupled subjects, and the combinations generated by these coupled subjects are denoted as S. The gain function is as follows:

$$V(S) = F(S) - \sum_{A \in S} F(\{A\}) \tag{18}$$

Where $V(S)$ denote incremental gains from portfolio S, $F(S)$ denotes total revenue generated by portfolio S cooperation, $F(\{A\})$ denotes the revenue generated when individual A in portfolio S is run independently.

4.2 Earnings Distribution Model Based on the Shapley Value Method

Gain allocation based on the Shapley value method is measured by taking the loss of a member leaving the coupled system as the value of marginal contribution to the coupled system. The marginal gain contribution of each coupled subject is quantified according to the gain function Equation (19), and the gain allocation model based on the Shapley value method is constructed as follows:

$$\begin{cases} x_A^{Sh} = \sum\limits_{A \subseteq S} W_S[V(S) - V(S/A)] \\ W_S = \dfrac{(|S| - 1)!(|N| - |S|)!}{|N|!}, \quad \forall S \subseteq N \end{cases} \tag{19}$$

Where x_A^{Sh} defines individual A's initial allocation of the gain from cooperation, $V(S/A)$ is the Incremental gains from cooperation after portfolio S removes individual A, $|S|$, $|N|$ are the number of topics in the portfolio S, the coupled system N. W_S is an assigned weighting factor that takes into account the order in which the individuals of each portfolio interest join the coalition.

4.3 Allocation Models Based on Asymmetric Nash Negotiations

Asymmetric Nash negotiation is an important concept in game theory and negotiation theory, through reasonable negotiation strategy and benefit distribution mechanism, asymmetric Nash negotiation can still prompt the parties to achieve a state of equilibrium. This equilibrium state is the result of mutual cooperation, in which each participant can maximize their own interests. For the coupling body, the contribution of the coupling system members within the coupling body is to be weighed in terms of the contribution of electricity, the contribution of flexibility, and the contribution of environmental costs in the day-ahead and real-time balancing markets, respectively, in order to construct the contribution index system. The specific allocation steps are as follows:

Based on the scheduling results of the coupled system N, the contribution index is established as a quantitative criterion for the fine-grained allocation among the members within the coupled subject A.

(a) Indicator of the contribution of cooperative gains within the wind power subject.

$$\begin{cases} \alpha_{\mathrm{W},i}^{1} = \rho_t^{da} \sum\limits_{t \in T} \left(P_{i,t}^{\mathrm{W/N(1)}} - P_{i,t}^{\mathrm{W/N(0)}} \right) \\ \alpha_{\mathrm{W},i}^{2} = \sum\limits_{k=1}^{K} \gamma_k \begin{bmatrix} \rho_k^{rt+} (P_{i,t}^{\mathrm{W}/B(1)} - P_{i,t}^{\mathrm{W/B(0)}}) \\ \quad + \rho_k^{rt-} (P_{i,t}^{\mathrm{W/B(1)}} - P_{i,t}^{\mathrm{W/B(0)}}) \end{bmatrix} \\ \alpha_{\mathrm{W},i}^{3} = C_{i,t}^{W(0)} - C_{i,t}^{W(1)} + \sum\limits_{t \in T} (G_{i,t,CO_2}^{W} \cdot C_{CO_2} + G_{i,t,SO_2}^{W} \cdot C_{SO_2}) \end{cases} \tag{20}$$

Where $\alpha_{\mathrm{W},i}^{1}$, $\alpha_{\mathrm{W},i}^{2}$, $\alpha_{\mathrm{W},i}^{3}$ defines the electricity contribution, the flexibility contribution, and the environmental contribution of individual wind power i within the wind coupling body, The superscripts (1) and (0) of the variables indicate whether or not they are involved in the coupled system. $P_{i,t}^{\mathrm{W/N}}$ is the transaction power of wind power subjects, $P_{i,t}^{\mathrm{W}/B}$ is the imbalance power,

$C_{i,t}^{W}$ is the cost of carbon. G_{i,t,CO_2}^{W}, G_{i,t,SO_2}^{W} are the and CO_2, SO_2 emission reductions from wind turbines at moment t, C_{CO_2}, C_{SO_2} are the treatment costs for C_{CO_2}, C_{SO_2} emissions.

(b) Indicator of the contribution of the cooperation gain within the PV coupling subject.

$$\begin{cases} \alpha_{S,i}^{1} = \rho_t^{da} \sum\limits_{t \in T} (P_{i,t}^{\mathrm{S/N}(1)} - P_{i,t}^{\mathrm{S/N}(0)}) \\ \alpha_{S,i}^{2} = \sum\limits_{k=1}^{K} \gamma_k \begin{bmatrix} \rho_k^{rt+} (P_{i,t}^{S/B(1)} - P_{i,t}^{S/\mathrm{B}(0)}) \\ +\rho_k^{rt-} (P_{i,t}^{\mathrm{S/B}(1)} - P_{i,t}^{S/\mathrm{B}(0)}) \end{bmatrix} \\ \alpha_{S,i}^{3} = C_{i,t}^{S(0)} - C_{i,t}^{S(1)} + \sum\limits_{t \in T} (G_{i,t,CO_2}^{S} \cdot C_{CO_2} + G_{i,t,SO_2}^{S} \cdot C_{SO_2}) \end{cases} \tag{21}$$

Where $\alpha_{S,i}^{1}$, $\alpha_{S,i}^{2}$, $\alpha_{S,i}^{3}$ define electricity contribution, flexibility contribution, and environmental contribution of PV individual i within the PV coupling body, $P_{i,t}^{\mathrm{S/N}}$ is the transaction power of PV subjects, $P_{i,t}^{S/B}$ is the imbalance power, $C_{i,t}^{S}$ is the cost of carbon, G_{i,t,CO_2}^{S}, G_{i,t,SO_2}^{S} are the CO_2, SO_2 emission reductions from wind turbines at moment t.

(c) Indicators of the contribution of cooperation gains within the thermal coupling body.

$$\begin{cases} \alpha_{D,i}^{1} = \rho_t^{da} \sum\limits_{t \in T} (P_{i,t}^{\mathrm{D/N}(1)} - P_{i,t}^{\mathrm{D/N}(0)}) \\ \alpha_{D,i}^{2} = \sum\limits_{k=1}^{K} \gamma_k \begin{bmatrix} \rho_k^{rt+} (P_{i,t}^{D/B(1)} - P_{i,t}^{D/\mathrm{B}(0)}) \\ +\rho_k^{rt-} (P_{i,t}^{D/\mathrm{B}(1)} - P_{i,t}^{D/\mathrm{B}(0)}) \end{bmatrix} \\ \alpha_{D,i}^{3} = C_{i,t}^{D(0)} - C_{i,t}^{D(1)} + \sum\limits_{t \in T} (G_{i,t,CO_2}^{D} \cdot C_{CO_2} + G_{i,t,SO_2}^{D} \cdot C_{SO_2}) \end{cases} \tag{22}$$

Where $\alpha_{D,i}^{1}$, $\alpha_{D,i}^{2}$, $\alpha_{D,i}^{3}$ are the electricity contribution, flexibility contribution, and environmental contribution of thermal power stakeholder i within the coupled subject; $P_{i,t}^{\mathrm{D/N}}$ is the transacted electricity for thermal power mains, $P_{i,t}^{D/B}$ is the imbalance power, $C_{i,t}^{D}$ is the cost of carbon, G_{i,t,CO_2}^{D}, G_{i,t,SO_2}^{D} are the CO_2, SO_2 emission reductions from thermal turbines at moment t.

According to the contribution index, the initial matrix of gain contribution is established separately for each coupling subject , as shown in Equation (23)

$$\psi_A^{k\times a}=\begin{bmatrix}\alpha_{A,1}^1 & \alpha_{A,1}^2 & \cdots & \alpha_{A,1}^a\\ \alpha_{A,2}^1 & \alpha_{A,2}^2 & \vdots & \alpha_{A,2}^a\\ \vdots & \vdots & & \vdots\\ \alpha_{A,k}^1 & \alpha_{A,k}^2 & \cdots & \alpha_{A,k}^a\end{bmatrix} \tag{23}$$

Where $\alpha$is the number of indicators for contribution, $k$is the number of individuals within a given coupled subject A.

Normalize the matrix elements and calculate the combined contribution-value of $i(i=1,2,\ldots k)$, as shown in Equation (24).

$$H_{A,i}=\sum_{j=1}^{a}\varepsilon_{ij} \tag{24}$$

Where ε_{ij} defines the jth contribution of the ith coupled individual in the gain-contribution matrix all indexes.

Calculate the cooperation gain contribution factor for each subject in each aggregate, as shown in equation (25).

$$\varpi_{A,i}=H_{A,i}\bigg/\sum_{j=1}^{k}H_{A,i'} \tag{25}$$

Combining the results of the initial allocation of Shapley values of various types of coupling subjects, the asymmetric Nash negotiation model of the wind and fire coupling system based on the contribution degree of cooperation gain is constructed, as shown in Equation (26).

$$\begin{cases}\max\prod_{i\in A}(U_i^{Na}-U_0)^{\varpi_{A,i}}\\ U_i^{Na}>U_0\end{cases} \tag{26}$$

5 Case

5.1 Cases and Parameters

In this paper, we set up a simulation sample to study a regional power grid in Liaoning. This local grid contains two 600 MW thermal power

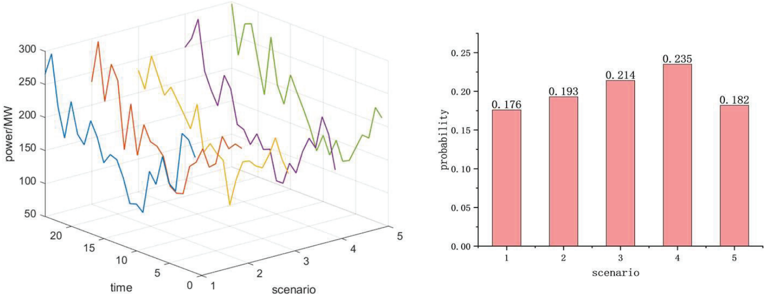

Figure 4 Wind power output scenario and probability.

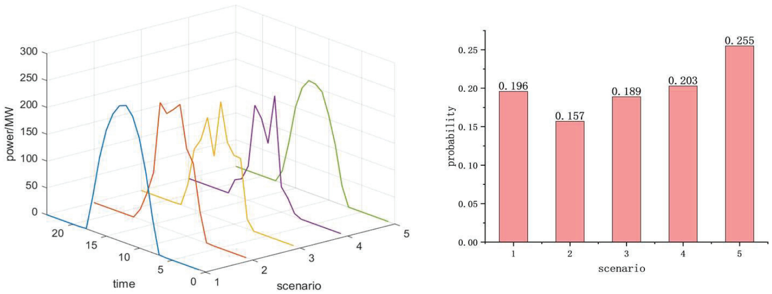

Figure 5 PV 1 (300MW) output scenario and probability.

stations, 300 MW offshore wind power, and 300 MW/100 MW PV power stations, and they form a coupled system at the same grid connection point A. The power grid of this local grid is a coupled system. The parameters of the thermal power units are shown in Table 5.1, and the unit boiler fuel price of 685 RMB/ton. We use scenario analysis to build an uncertain portfolio of renewable energy output. The classical day's wind/PV generation forecast curve of this local grid is used as the original scenario, and 1000 wind/PV output scenarios are generated for each sub-consortium through Monte Carlo sampling based on the statistical error of this forecasting method, and after that the scenarios are reduced to 5 typical scenarios through clustering method, as shown in Figures 4–6. The equilibrium market price θ_{up}, θ_{down} penalty coefficient is taken 1.2, 0.8.

5.2 Comparative Analysis of Returns of Coupled Systems and Independently Operating Market Players

In order to verify the superiority of the wind-fire coupled system, the day-ahead turnover of power when operating independently and the coupled

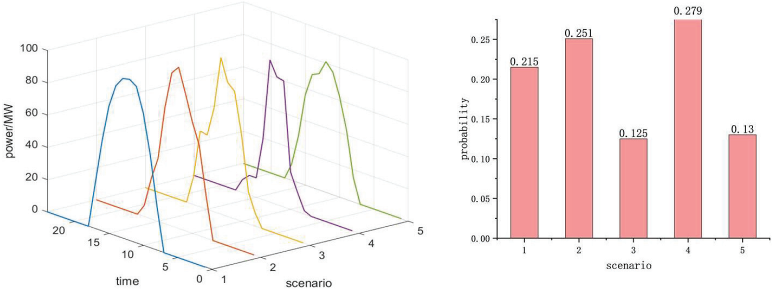

Figure 6 PV 2 (100MW) output scenario and probability.

Table 1 Thermal power unit parameters

Maximum Output (MW)	Minimum Output (MW)	Rate of Climb (MW/min)	Amount	Consumption Characterization Parameters a(t/MW2)	b(t/MW)	c(t)
600	180	6	1	0.000016	0.27601	11.46196
600	180	6	1	0.0000172	0.26315	11.46127

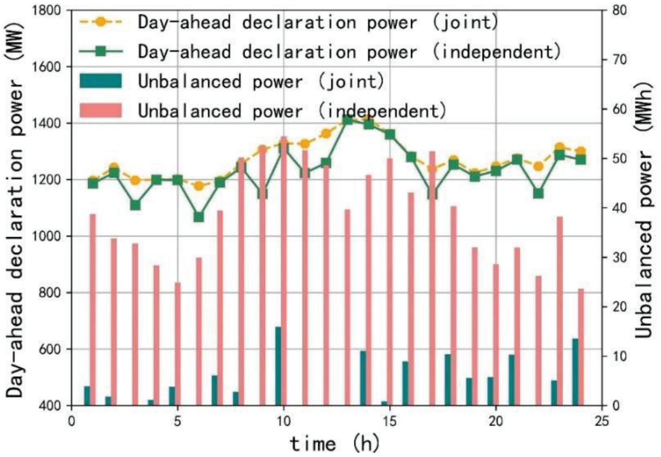

Figure 7 Comparison of declared power and unbalanced power before and after cooperative operation of coupling system.

system is compared with the imbalance power in the real-time balancing market.

A comparison of the simulated imbalance power during standalone and coupled system operation in Figure 7 reveals that the coupled system operation corresponds to lower imbalance power in most of the time periods, which

Table 2 Expected benefits of participants under independent/ coupling system

Members	Day-ahead Market Gains	Real-time Balanced Market Gains	Costs	Consolidated Income
Wind power	1249298	−19089.93	672575	557633.07
Solar power1	321062	−12015.89	165174.60	143871.51
Solar power2	131523	−7245.29	66314.58	57963.13
Thermal power1	3337740	0	2997517.02	340222.98
Thermal power2	3337740	0	2945328.26	444599.92
Total	8377363	−38351.12	6794720.68	1544291.2
Coupling System	8587679	−105304.1	6762123.3	1720251.6

is mainly due to the fact that thermal power exerts its own flexibility in the coupled system to regulate the power. This provision of flexibility helps to smooth out the fluctuations of renewable energy sources, thus reducing the amount of negative imbalance power due to insufficient supply of renewable energy sources and lowering the level of deviation of the whole system. At the same time, this improves the efficiency of the system. As a result, the overall revenue of the coupled system is improved compared to stand-alone operation, as demonstrated by the expected revenue profile of the participants in each market detailed in Table 2.

From the results in Table 2, it can be seen that compared to the independent operation mode, the coupled system market participants can gain more benefits of 175,960 yuan, which is part of the additional benefits gained by each participant after the cooperation between renewable energy and thermal power. Among them, the alliance benefits 210,316 yuan more under the day-ahead market, which is due to the fact that wind power and photovoltaic power are more advantageous in the competition after cooperating with thermal power in joint operation, and the overall declared power in the day-ahead market under the joint operation mode is larger than that of the independent operation mode; in the real-time balancing market, the cooperative alliance will benefit 90,551.29 yuan less, but the imbalance power actually decreases, which is to reduce the rate of abandoned wind and abandoned light , positive imbalance compared to negative imbalance power is greatly reduced.

From Figure 8, it can be seen that when renewable energy is operated independently, it is relatively conservative in declaring power in order to avoid the impact of unbalanced power, which leads to a certain amount of wind and light abandonment, whereas when thermal power is operated in the coupled system, the declared power is reduced relative to the independent operation, which is due to the fact that it is necessary to make space for

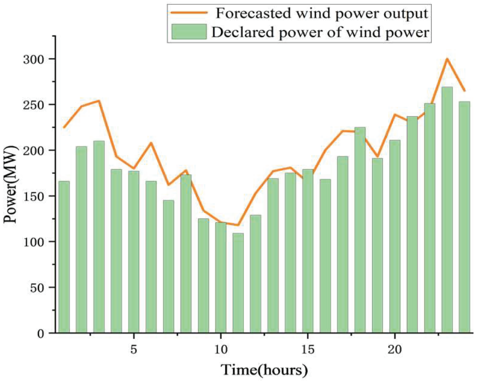

Figure 8(a) Declared power under wind power independent operation mode.

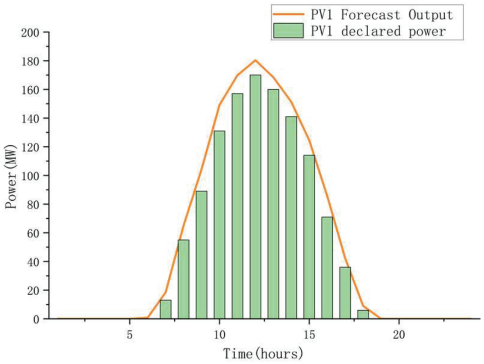

Figure 8(b) Declared power under PV1 independent operation mode.

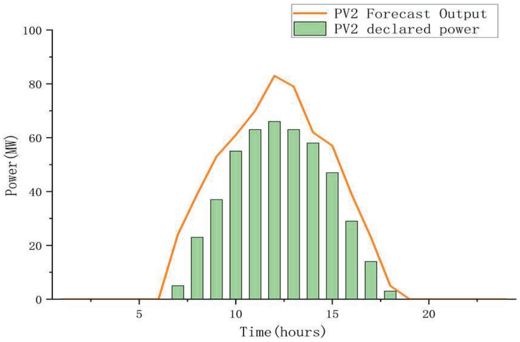

Figure 8(c) Declared power under PV2 independent operation mode.

Table 3

Members	Revenue Distribution Result/RMB		
	Individual	Coupling System	Increase Revenue
Wind power combination	557633.07	5905876.97	33243.90
Solar power combination	201834.64	234264.65	32430.01
Thermal power combination	784822.9	895110.02	110287.12
Wind power	557633.07	590876.97	33243.90
Solar power1	143871.51	167465.03	23593.52
Solar power2	57963.13	66799.62	8836.49
Thermal power1	340222.98	389828.57	49605.59
Thermal power2	444599.92	505281.45	60681.53

renewable to generate power and at the same time to regulate the unbalanced power.

5.3 Comparative Analysis of Returns of Coupled Systems and Independently Cooperating Market Players

Firstly, the same kind of stakeholders in the coupling system are combined to form three stakeholders, and the incremental benefits of the seven combinations are solved. Through the Shapley value method, the cooperative gains of wind power, photovoltaic power and thermal power coupling subjects are 557633.07, 201834.64 and 784822.90 yuan, respectively. Since there is only one wind turbine in the coupling system in this paper, the gain distribution results of the wind turbine do not need to be refined. According to the contribution index, the asymmetric Nash negotiation theory is used to further refine the allocation of each subject in the photovoltaic and thermal power coupling subjects. The contribution indexes of photovoltaic 1/2 are 0.71 and 0.29, respectively, and the contribution indexes of thermal power 1/2 are 0.44 and 0.56, respectively. Comparing the benefits of independent operation with those of the coupled system, it can be seen that the income distribution results of each coupled agent satisfy the overall and individual rationality, as shown in Table 3.

It can be seen that the amount allocated by each participant in the revenue distribution method considering the contribution is directly proportional to the contribution made by each participant to the coupling system, and the thermal power unit as a flexible adjustment can allocate a larger amount, which can better compensate for the economic loss caused by the adjustment of output, and help to stimulate its enthusiasm to provide flexible services.

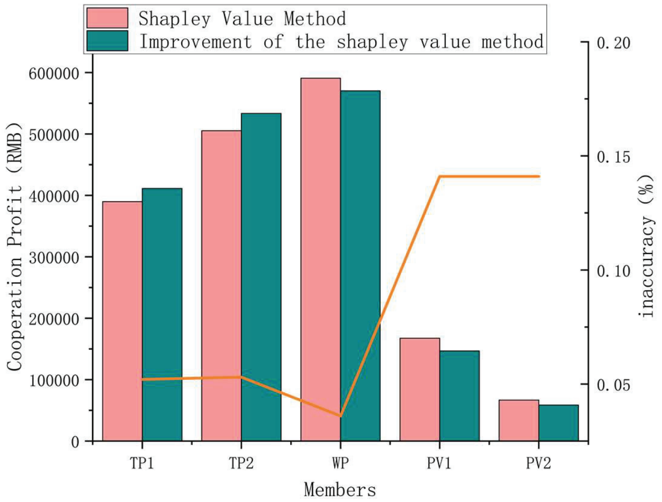

Figure 9 Comparison of the solution accuracy of the improved Shapley value method.

Table 4-2 shows that after the coupling system jointly participates in the spot market, the revenue of wind power is increased by 5.96%, the income of photovoltaic 1/2 increased by 16.4%/15.2%, and the income of thermal power 1/2 increased by 14.6%/13.6% On the one hand, it helps to help improve the quality and reduce the burden of the power grid, and on the other hand, it can effectively promote multi-party cooperation and mutual benefit and win-win results, and can effectively consume renewable energy through market-oriented transactions while maximizing the overall benefits.

5.4 Comparative Analysis of Income Distribution Methods

In order to verify the accuracy and computational efficiency of the revenue allocation method proposed in this paper, it is analyzed in comparison with the shapley value method from the aspects of solution accuracy and computational efficiency, respectively.

By using the shapley value method to measure and evaluate the results of our method compared to the original algorithm, we obtained a similar distribution of data (see Figure 8). From this data, we can see that when we distribute the benefits using the new shapley value method, the difference in the contribution of each participant reaches a range between a maximum of 14.1% and a minimum of 3.6%, which demonstrates that the results of the new method for the distribution of benefits are quite accurate and comparable.

Table 4 Comparison of the computational efficiency of the improved Shapley value method

Method of Distribution	Number of Theoretical Coalitional Solutions for n-subject Coalitions	Number of Solutions to the Examples in this Paper	Calculation Time/s
Shapley Value Method	$2^n - 1$	31	7055
Improvement of the shapley value method	$2^3 - 1$	7	1344

As can be seen from Table 4, the computation time of the improved Shapley value method is much smaller than that of the shapley value method. And it basically remains unchanged with the increase of the number of individuals in the coupled system. The improved Shapley value method proposed in this paper combines the wind and fire coupling system into three coupling subjects without considering the number of members within the coupling system. It only needs to solve the gain calculation of seven combinations, which greatly improves the calculation efficiency. The number of combinations to be calculated by the improved Shapley value method does not increase further with the increase in the number of coupled system entities, and the computational workload increases slightly. However, this increase is due to the increase in the number of members within the coupled body, which leads to an increase in the computational effort to solve the optimal gain. As the number of energy types in the coupled system increases, the number of combinations of the revenue allocation method proposed in this paper only increases and the computational complexity increases. In this regard, for smaller coupled systems, the computational efficiency advantage of our method is not obvious; when the coupled system has fewer energy types as well as a large number of individuals, the computational efficiency of the improved shapley-value method will be greatly improved.

6 Conclusions

In this paper, for the operation mode of the coupled system, the game relationship between wind-light-fire is deeply explored, and the operation strategy of the coupled system participating in the spot market is studied. And based on the Shapley value method and the asymmetric Nash negotiation theory, a revenue allocation method applicable to the wind-light-fire coupled system is proposed. The scheme fully considers the contribution degree of each member of the coupled system in the day-ahead market and the real-time equilibrium market. Based on the arithmetic example for simulation verification, the study can obtain the following conclusions:

(1) The wind-scope-fire coupling system, can further explore the coordinated development potential of renewable energy and thermal power, renewable energy generation can reduce the cost for the alliance, and the flexible adjustment ability of thermal power can reduce the risk of deviation of renewable energy in the real-time balancing market, which realizes the enhancement of the overall economic benefits of the alliance and the improvement of the level of renewable energy consumption;
(2) The advantage of the wind and fire coupling system is that it can realize the mutual supplementation between resources to improve the overall operational efficiency, in which the revenue shared by wind power is improved by 5.96% compared with the independent participation in the market, the PV1/2 revenue is improved by 16.4%/15.2%, and the thermal power1/2 revenue is improved by 14.6%/13.6%, respectively.
(3) The improved shapley value method greatly improves the computational efficiency without affecting the computational accuracy, which is especially obvious when the number of individuals within the coupled system increases.

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