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Coupled modeling of flexibility resources and power market trading mechanism in a new power system

Yang Yu[1], *Jia Chen*[1], *Kejie Zhang*[1], *Yinya Zhang*[1], *Xu Ling*[1] *and Huihong Yuan*[2,*]

[1] Central China Branch of State Grid Corporation of China, Wuhan, Hubei, 430000, China
[2] Beijing Tsintergy Technology Co., Ltd., Beijing, 100084, China

SUMMARY: *In order to explore the trading mechanism between flexibility resources and power market in the new power system, the article firstly elaborates the characteristics of flexibility resources in the new power system, and constructs a power spot market price prediction model optimized based on PSO algorithm and LS-SVM algorithm. In order to clarify the coupling relationship between flexibility resources and power market trading mechanism, a two-layer optimization model of coupled carbon-green certificate-consumption volume of power market trading in the previous day is constructed, and an arithmetic example analysis is carried out to analyze the application effect of the model. The results show that the PSO optimization LS-SVM model proposed in this paper is acceptable for day-ahead market electricity price prediction, and its prediction error is much lower than that of other comparative models, which shows that it can make effective prediction for the electricity market. This paper solves the multi-objective optimization problem of system economic benefits, energy saving and emission reduction benefits, and obtains a total of 83,607,000 yuan of optimization costs for the previous day's clearing, which is 177,000 yuan more than the difference of 8,537,700 yuan of the system cost of considering the economic benefits objective alone, and the difference of the total cost is not significant, which indicates that the multi-objective optimization function constructed in this paper is able to ensure the economic benefits of the system operation, and achieve the environmental benefits on the basis of maximization, to achieve the effect of energy saving and emission reduction.*

KEYWORDS: *Electricity spot market forecasting model; Flexibility resources; Electricity market trading mechanism; Multi-objective optimization; LS-SVM model*

1 Introduction

At present, climate warming is a common crisis and challenge faced by all countries in the world, and the transformation of power supply structure to cleaner has become a consensus for the future development of power systems in various countries [1, 2]. As the proportion of renewable energy continues to expand, its randomness, volatility, intermittency and other output characteristics of the power system will bring more and more obvious impacts on the power system, and the flexibility problems faced by the power system will become more and more prominent [3, 4]. In 2018, China added 20,590 MW of new grid-connected wind power installations, and the cumulative capacity of wind power accounted for 9.7% of the total installed capacity of power generation, while the annual abandoned wind power 27.7 billion kWh, with an average wind abandonment rate of 7%, of which the wind abandonment rate in

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*yuanhh@tsintergy.com

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some major wind power provinces in Northwest and North China is more than 10%.

With the high-speed growth of grid-connected renewable energy ratio, evaluation of power system operation is safe and reliable can no longer only to the generation of sufficient degree as the main evaluation index, in order to ensure the reliable supply of electricity at the same time, to ensure that the grid-connected renewable energy consumption will gradually change into the future of the power system's main problem [5-7]. In the context of promoting the development of renewable energy and guaranteeing the consumption of grid-connected renewable energy, the power system is required to vigorously develop renewable energy at the same time, and build its matching flexibility resources to ensure that the flexibility of regulating capacity is abundant [8, 9]. The development of renewable energy cannot be delayed, and the construction of flexibility resources is also urgent. There are many types of flexibility resources, and different flexibility resources have different technical characteristics, regulation effects and economic sequencing for different time scales of flexibility demand in the system [10]. Therefore, in the construction process of flexibility resources, studying the technical suitability of flexibility resources for flexibility demand at various time scales and analyzing the economic characteristics of flexibility resources under different demand scenarios are conducive to the planning and deployment of flexibility resources in the power system according to local conditions, guiding the reasonable construction of flexibility resources, and improving the capacity of renewable energy consumption in the power system and the economic benefits of power construction [11-14].

Due to the existence of many uncertainties in renewable energy, it brings the problem of abandoned wind and light [15]. In order to solve this problem, it is necessary to take measures to solve the problem of consumption from various aspects, such as management and technology, in combination with the power marketization reform. On the one hand, through the power marketization reform, a new market framework including medium- and long-term market, spot market, and auxiliary service market is established, which is hoped to play an important role in shortening the scheduling and physical delivery transaction cycle, and fully invoking the system flexibility resources [16, 17]. On the other hand, renewable energy is entering the "post-subsidy" or even "subsidy-free" era. Wind and solar power generation are priced at parity and connected to the grid through competitive bidding, and the bidding for grid connection of renewable energy projects is promoting the return of renewable energy power to its true value and playing an important role in optimizing resource allocation in the power market [18].

To realize the new energy grid parity it is necessary to solve the problem of grid consumption, to solve the problem of abandoned wind and light, on the one hand, it can promote the cross-provincial and cross-region transmission and consumption, on the other hand, it can also be locally consumed [19, 20]. For example, when wind power is connected to the power grid, the wind power output is unstable, the load is difficult to predict, and it is difficult to formulate a corresponding power generation plan to ensure the implementation of the wind power generation plan. Therefore, there is an urgent need to adjust and optimize the reform of the power market, use market means to reduce the instability caused by wind power grid connection, improve the utilization rate of wind power, and try to avoid the occurrence of wind abandonment phenomenon [21]. In terms of wind power trading, due to the instability and difficulty in accurately predicting wind power output, it is important to design an appropriate wind power trading model in the power market [22]. Therefore, the study should focus on medium- and long-term electricity trading, and consider the spot market trading mode in which wind power participates, which is of great significance as a guide for constructing the electricity market [23].

At present, because China's power market is still in the development stage, at present and in the future, China's power market trading mode is still based on medium- and long-term power trading, and also actively develops the day-ahead or real-time power spot trading mode [24, 25]. On the one hand, medium- and long-term trading can ensure that most of the electricity consumption of users, on the other hand, it can avoid market risks, so that power producers lock in revenue in advance, and it can be based on market forecasts to develop power generation planning, and power generation in accordance with the plan can maintain the stability of the power market [26].

In the process of energy transition, with the transformation of traditional energy to renewable energy, the “source side” active regulation of resources gradually weakened, people began to pay attention to the “load side” of the adjustable resources [27]. These include electric heating loads, energy storage loads, and electric vehicle loads, etc. These load-side adjustable resources have become an important means of regulating grid loads. However, China's power market is still in its infancy, and all aspects of the trading mechanism are still not perfect, and market mechanisms such as price response and peak compensation have not yet been established, and the resource allocation capacity of China's power grid has yet to be improved with the continuous advancement of power market reform [28, 29]. Along with the increasing penetration of wind power, the uncertainty of wind power under the existing market mechanism has brought difficulties to the safe and stable operation of the power system. In order to solve the above problems it is necessary to explore the regulation potential of flexible resources, study the energy consumption characteristics and control strategies of distributed electric heating groups, and study the power market trading mechanism in depth, so as to make it better cooperate with the consumption of wind power, and promote the market-oriented trading under the source-load interaction [30-32].

Aiming at the flexibility demand caused by the new changes brought about by the high proportion of renewable energy sources connected to the power system, this paper elaborates on the characteristics of the flexibility resources that can be utilized and analyzes the fluctuations caused by them to the electricity spot market price from the perspectives of supply-side, demand-side, grid-side, and storage, respectively. In order to improve the accuracy of electricity price prediction, this paper adopts the particle swarm optimization algorithm to optimize the penalty factor and radial basis kernel function width of the least squares support vector machine, and establishes an electricity spot market price prediction model based on PSO optimization LS-SVM. After that, based on the joint participation of thermal power, wind power and photovoltaic enterprises and power users, a coupling model based on flexibility resources and power market trading mechanism is constructed. Then, an upper and lower level iterative interactive transaction optimization model is established based on the optimal objectives of market members' returns and power market social welfare. Finally, the application effect of the model is analyzed on the IEEE-30 node system.

2 Characterization of flexibility resources and analysis of price fluctuations in new power systems

2.1 New power system flexibility resource characteristics

2.1.1 Supply-side flexibility resources

Supply-side resources mainly include coal power flexibility modifications, gas-fired generation, hydropower, pumped storage, and relatively controllable renewable energy generation. Coal power flexibility retrofits consist of three categories, namely, reducing the minimum stabilized power of a unit, increasing the up/down ramping rate of a unit, and allowing for more frequent and shorter start-up and shutdown times. At the same time, coal power flexibility retrofit technology is mature, the construction period is short, and the cost is low. Therefore, within a short period of time, making full use of the existing coal power unit resources, carrying out coal power flexibility modification, participating in deep peaking, and carrying out hourly and inter-day output adjustment are the main paths for China to improve intra-day peaking capacity and enhance system flexibility.

Gas-fired units have the advantages of fast startup and shutdown and flexible operation. Hydroelectric units are characterized by fast startup and shutdown, low quoted cost and fast climbing rate. Photovoltaic power plant units can be started and stopped for peaking, and the minimum technical output can be up to 15% or less, which can be used as an independent body to provide flexibility. Biomass gas has good ignition characteristics, so biomass gasification coupled to coal-fired units for power generation can reduce the unit's minimum steady burn load without oil injection, which helps to improve the flexibility of coal-fired units to regulate.

2.1.2 Demand-side flexibility resources

Demand-side flexibility resources mainly include electricity demand response, electric vehicles, virtual power plants and microgrids. Demand response refers to allowing power users to temporarily change their electricity demand, increasing or decreasing electricity consumption at specific times, smoothing the load curve, reducing the difficulty of regulating system flexibility, and promoting the balance between power supply and demand. The response speed of demand response can reach the second level, with extremely strong regulation capability. Power users can be divided into three categories: large industrial users, general industrial and commercial users and residential users. Industrial users have large power consumption and more fixed power consumption times, and can respond to demand by adjusting production times, etc. The willingness to respond depends on the trade-off between reduced power costs and increased other costs. General industrial and commercial customers have high load resource potential and flexible regulation, and are the main resource for future demand response. Residential customers are more dispersed, and demand response is difficult, so the potential remains to be explored.

2.1.3 Grid-side flexibility resources

Grid-side flexibility resources mainly refer to the expansion of physical equipment and the enhancement of transmission capacity. Utilizing inter-regional differences, it effectively reduces the fluctuation amplitude of renewable energy generation output and solves the imbalance between supply and demand of renewable energy on multi-day and weekly time scales. Since the improvement of the electricity market mechanism helps to release the flexibility adjustment capacity of own resources, this paper also attributes it to grid-side flexibility resources. Improve the power auxiliary service market, develop appropriate transaction compensation mechanism, mobilize the enthusiasm of coal power flexibility transformation, and release the flexible adjustment capacity of various resources. Establish a sound electricity demand response policy mechanism, and transfer real-time signals to the user side through electricity prices, so as to guide the demand-side resources with conditions to participate in flexibility regulation.

2.1.4 Energy storage resources

The response speed of energy storage can be as fast as milliseconds, and the continuous discharge time is in the range of minutes to hours. The superior performance allows it to be applied in different scenarios and play a flexible regulating role. On the grid side, energy storage can act as a controllable load, provide auxiliary services for peak and frequency regulation, alleviate line blockage, act as a backup power source and black start, and help real-time regulation of the grid. On the user side, energy storage can be combined with demand response, microgrid and other technologies to help users “cut peaks and fill valleys”, effectively reducing the cost of electricity and reducing machine loss. On the supply side, energy storage can be combined with new energy stations to solve the problem of rapid fluctuations in renewable energy output from the source. In the renewable energy sudden demand is insufficient, energy storage can release electricity as a supplemental power, to avoid inaccurate prediction due to the power curve brought about by the penalties; in the renewable energy power excess, energy storage can absorb excess electricity, reduce the generation of wind and light abandonment, and at the same time, reduce the flexibility of the system because of the elimination of too much renewable energy demand.

2.2 Analysis of price volatility in the high percentage renewable electricity market

Electricity market price releases signal incentives for increased power system flexibility. With a high proportion of renewable energy sources connected on a large scale, the need for power system flexibility has increased dramatically in order to cope with the balance of power supply and demand under fluctuating conditions. Under the guidance of power market prices, market players can rationalize their own behavior. When the new energy is large, the price of electricity decreases due to its zero marginal cost, and when the new energy output decreases, the price of electricity gradually increases as determined by the marginal cost of conventional units, and each market player can decide whether to participate in the market to provide services or not according to the price signal. This paper analyzes the current situation of Germany's electricity production and spot market price changes in the 27th week of 2023 as an example.

The German electricity production and spot market prices are shown in Figure 1, with the peak hours of renewable energy output roughly corresponding to the trough hours of electricity prices. It should also be noted that the volatility of renewable energy output leads to more prominent extreme prices at certain times of the day, reflecting the market price signaling the need for flexibility in the power system at short intervals. Incentivized by scarcity prices, market players with flexibility regulation capabilities can provide appropriate services to safeguard the balance between supply and demand in the power system and reap the benefits.

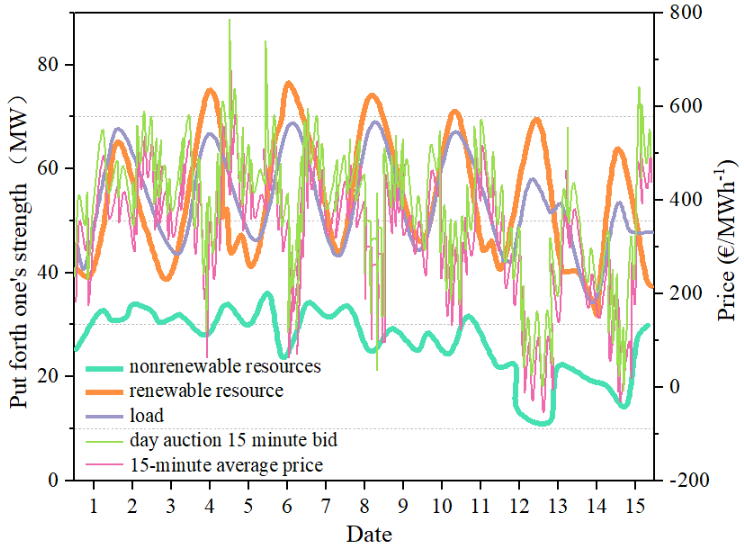


Figure 1: German electricity production and spot market price dates

2.3 PSO-based Optimization LS-SVM Electricity Market Price Forecasting Model

Compared with neural network, LS-SVM is not easy to fall into local optimum, and the regression fitting effect is better, but the fitting accuracy of LS-SVM is greatly affected by the penalty factor C and the width of radial basis kernel function σ, in order to improve the prediction accuracy of the electricity price, this paper adopts the PSO algorithm to optimize the C and σ of the LS-SVM, and establishes an electricity spot market price forecasting model based on the optimization of the LS-SVM by PSO. -SVM to establish an electricity spot market price prediction model based on PSO optimized LS-SVM, the modeling steps are as follows:

1) Data normalization. In order to reduce the influence of data, the input data of the model need to be normalized, the formula is as follows:

$$x_i' = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \tag{1}$$

where x_i is the original input value; $x_{\max}$ and $x_{\min}$ are the maximum and minimum of the original input value, respectively; and x_i' is the normalized value.

2) Initialization of LS-SVM parameters. Set the initial values of C and σ so that $C = 100$, $\sigma = 1.5$, and set the formula for calculating the adaptation value as follows:

$$I = \frac{1}{N}\sum_{i=1}^{N}\left|y_i - y_i^*\right| \tag{2}$$

where N is the sample capacity, is the actual value of electricity price at i moment, and y_i^* is the predicted value of electricity price at i moment.

3) PSO algorithm parameter settings. The population size is set to 25, the acceleration factor is 2.0, the maximum number of iterations is 250, and the inertia weights are set to be decreasing.

4) Take C and σ as the optimization objectives, and take $C = 100$, $\sigma^2 = 2.5$ the current individual optimal solution, compute the initial fitness value, and note it as the current optimal fitness value.

5) Start the iterative calculation, update the particle velocity and position according to the PSO algorithm velocity and position update formula, and calculate the new fitness value of the particle swarm after the update.

6) Compare the new fitness value with the current optimal fitness value, if the new fitness value is better than the current optimal fitness value, then update the new fitness value to the current optimal fitness value, otherwise no change.

7) Repeat step (6), and according to the iteration termination conditions to determine whether to terminate the iteration, if so, go to the next step, otherwise, return to step (5) to continue the iteration.

8) End the calculation, output the optimization results of C and σ, and assign the optimal values of C and σ to LS-SVM to forecast the electricity price.

2.4 Analysis of electricity market price forecast results

The current and real-time historical tariffs and their corresponding loads for 2,300 time periods from 2024-11-01 to 2024-11-25 in the Mengxi power market were selected as training samples to predict the market clearing tariffs for 500 time periods from 2024-11-26 to 2024-11-30.

2.4.1 Electricity price forecasts

MAPE was used to describe the prediction error, the calculation of which is shown in Eq:

$$M = \frac{1}{n}\sum_{i=1}^{n}\left|\hat{y}_i - y_i\right| \times 100\% \tag{3}$$

where: n -number of samples;

$\hat{y}_i$ -predicted electricity price;

y_i -actual electricity price.

The results of the comparison between the forecast and actual values of the day-ahead tariffs are shown in Fig. 2; the results of the comparison between the forecast and actual values of the real-time tariffs are shown in Fig. 3; and the results of the MAPE forecasts for the day-ahead and real-time markets are shown in Table 1. It can be seen that, before the day market in November 28th price fluctuations, error is larger, the rest of the time forecast error in the allowable range; real-time market in November 26th to November 28th more “peak” price, its prediction accuracy needs to be further improved, the rest of the time prediction error is in the allowable range. Since the volatility of real-time market tariffs is significantly higher than that of day-ahead market tariffs, the accuracy of real-time market tariffs is not high. Overall, the PSO optimized LS-SVM model is acceptable for day-ahead market price prediction, and can effectively predict the power market in west China.

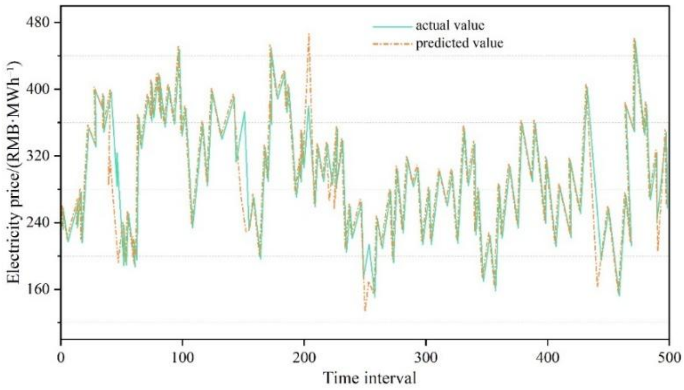


Figure 2: The predicted value and the actual value of the electricity price recently

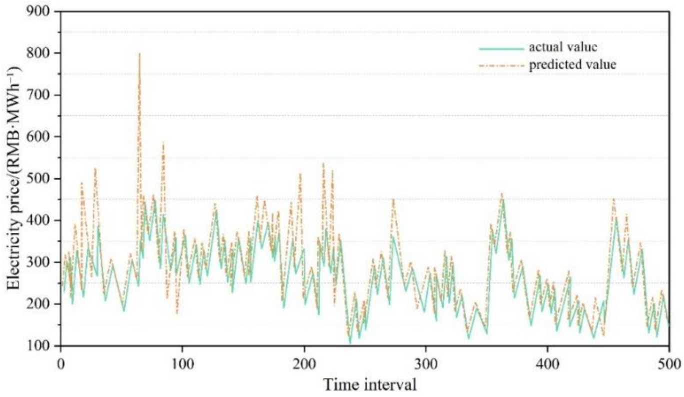


Figure 3: Comparison between real-time electricity price forecast and actual value

Table 1: MAPE forecast results for the near and real-time markets

Date	Recently the market	Real market
26 November	4.95	26.44
27 November	8.84	22.82
28 November	16.96	20.54
29 November	10.17	8.66
30 November	10.99	12.87

2.4.2 Error analysis

The forecast results of this paper's method and the three methods of “polynomial fitting model, BP, and SA-BP” are compared with each other using MAPE. The MAPE comparison results of the four methods for day-ahead tariff prediction are shown in Fig. 4; the MAPE comparison results of the four methods for real-time tariff prediction are shown in Fig. 5. It can be seen that, regardless of the day-ahead market or real-time market, the prediction error of this paper's model is smaller than that of the other three methods, which indicates that the PSO-based optimization LS-SVM prediction model has higher prediction accuracy of the electricity market price.

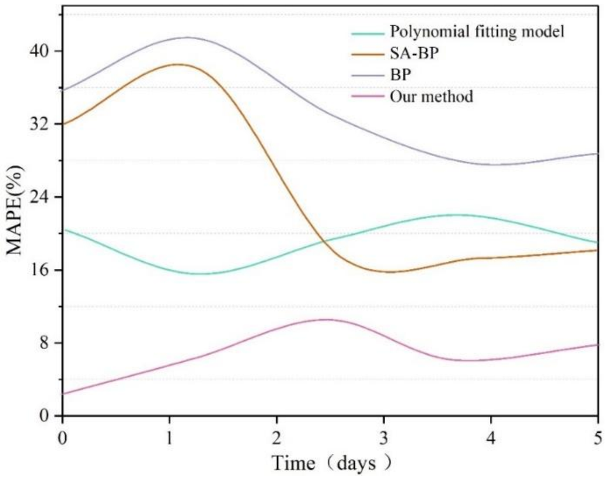


Figure 4: MAPE comparison results of electricity price forecast in recent days

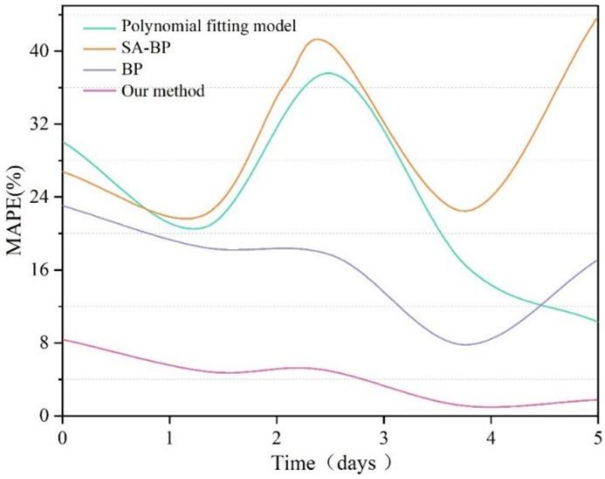


Figure 5: Real-time electricity price prediction MAPE comparison results

3 Coupled modeling and application of resource-transaction mechanisms in new power systems

This section proposes a coupling model based on the trading mechanism of flexibility resources and power market on the basis of the price prediction in the power market, and uses the model to optimize the price trading mechanism of flexibility resources in the power market in the new type of power market, and to realize the optimization of multi-objectives in the new type of power market.

3.1 Modeling the Coupling of Flexibility Resources and Electricity Market Trading Mechanisms

3.1.1 Upper-Level Optimization Model

(1) Thermal power producer revenue model

Due to the carbon market and the green certificate market, the operating costs of thermal power producers include thermal power unit coal consumption costs, carbon trading costs and green certificate trading costs, i.e:

$$\begin{aligned}\max U_{r,j} = & \sum_{t=1}^{T}\left(\alpha_{r,j,t}^{E}P_{r,j,t} - a_{r,j}P_{r,j,t}^{2} - b_{r,j}P_{r,j,t}\right) - c_{r,j} \\ & - p_{CO_2}q_{r,j}^{CO_2} - p_G q_{r,j}^{TGC} - p_P\left(\gamma_G\sum_{t=1}^{T}P_{r,j,t}\gamma - q_{r,j}^{TGC}\right)\end{aligned} \tag{4}$$

where: $U_{r,j}$ is thermal power i revenue; $\alpha_{r,j,t}^{\mathrm{E}}$ is day-ahead clearing tariff; $P_{r,j,t}$ is the declared power optimization value; $q_{r,j}^{\mathrm{CO_2}}$ is the carbon emission; $p_{\mathrm{CO_2}}$ is the carbon market trading price in unit of t; p_{G} is the trading price of green certificates, p_{P} is the penalty price of green certificates; γ_{G} is the proportion of green certificates; γ is the conversion factor in unit of $/(\mathrm{MW\cdot h})$; $q_{r,j}^{TGC}$ denotes the optimized green certificate declaration for thermal power i; $a_{r,j}, b_{r,j}, c_{r,j}$ are the quadratic, primary, and constant term coefficients of the operating cost of node r thermal power unit i.

The all-day carbon trading volume of thermal power i is calculated as follows:

$$q_{r,j}^{CO_2} = \sum_{t=1}^{T}P_{r,j,t}\left(\delta_{f,j} - \delta_f^{*}\right), i \in f, \forall f \tag{5}$$

where: δ_f^{*} is the carbon emission quota baseline coefficient; $\delta_{f,j}$ denotes the actual unit carbon emission coefficient of thermal power i classified as generating unit of category f in $t/(\mathrm{MW\cdot h})$.

Constraints:

1) Green certificate declaration constraints:

$$0 \le q_{r,j}^{TGC} \le \gamma_G \sum_{t=1}^{T} P_{r,j,t}\gamma \tag{6}$$

where: $\gamma_{\mathrm{G}} \sum_{t=1}^{T} P_{r,j,t}\gamma$ is the maximum green certificate demand for a single day.

2) Thermal power declaration power constraint:

$$P_{r,j,\min} \le P_{r,j,t} \le P_{r,j,\max} \tag{7}$$

where: $P_{r,j}$ is the declared power.

3) Thermal power climbing constraint.

Thermal power companies should consider the unit's rate of creep and rate of slippage when making decisions:

$$\Delta P_{r,j}^{down}\Delta t \le P_{r,j,t} - P_{r,j,t-1} \le \Delta P_{r,j}^{up}\Delta t \tag{8}$$

where: $\Delta P_{r,j}^{up}, \Delta P_{r,j}^{down}$ denotes the creeping and slipping rate of thermal power unit i; Δt denotes the time interval of the neighboring trading hours.

(2) Revenue model for wind power/photovoltaic enterprises

Wind power and PV enterprises can sell the green certificates corresponding to the power outside the scope of their renewable power generation assessment in order to gain revenue:

$$\max U_{w,j} = \sum_{t=1}^{T}\left(\alpha_{w,j,t}^{E} P_{w,j,t} - a_{w,j} P_{w,j,t}^{2} - b_{w,j} P_{w,j,t}\right) - c_{w,j} + p_G q_{w,j}^{TGC} \tag{9}$$

Constraints:

1) Wind power green certificate declaration volume constraints:

$$0 \le q_{w,j}^{TGC} \le \gamma\left(1-\gamma_G\right)\sum_{t=1}^{T} P_{w,j,t} \tag{10}$$

2) Wind power declared output constraints:

$$0 \le P_{w,j,t} \le P_{w-pred,j,t} \tag{11}$$

where: $P_{w,j,t}$ is the declared output of wind power j for the t time period; $P_{w-pred,j,t}$ is the predicted output of wind power j for the t time period.

(3) Customer Cost Model

The user participates in the energy trading based on the objective of minimizing energy consumption cost. Due to the influence of the assessment of the responsibility of renewable energy consumption, the user's cost consists of the cost of purchasing electricity in the energy market and the cost of trading the over-consumption volume, and the objective function is as follows:

$$\min F_{L,d} = \sum_{t=1}^{T} \alpha_{L,d,t}^{E} P_{L,d,t} + F_{GEC,d} \tag{12}$$

where: $F_{L,d}$ denotes the user d cost at node L; $P_{L,d,t}$ is the declared output; $\alpha_{L,d,t}^{\mathrm{E}}$ is the day-ahead clearing tariff; and $F_{GEC,d}$ is the transaction cost. The cost/benefit of excess consumption transaction can be expressed as follows:

$$F_{GEC,d} = \begin{cases} p_{RPS}\left(Q_{RPS,d} - Q_{G,d}\right), 0 < Q_{RPS,d} \le Q_{G,d} \; (a) \\ p_{RPS} q_d^{RPS}, Q_{G,d} < Q_{RPS,d} \le Q_{G,d} + q_d^{RPS} \; (b) \\ p_{RPS} q_d^{RPS} + p_{RPS}^{*}\left(Q_{RPS,d} - Q_{G,d} - q_d^{RPS}\right) \\ Q_{G,d} + q_d^{RPS} < Q_{RPS,d} \; (c) \end{cases} \tag{13}$$

where: $Q_{RPS,d}$ is the renewable energy consumption quota; $Q_{G,d}$ is the renewable energy consumption acquired by the market share in the previous day; q_d^{RPS} is the renewable energy consumption purchased in the market of excess consumption; p_{RPS} is the renewable energy consumption trading price; p_{RPS}^{*} is the penalty price; $p_{RPS} q_d^{RPS}$ is the trading cost of consumption for user d; $p_{RPS}^{*}\left(Q_{RPS,d} - Q_{G,d} - q_d^{RPS}\right)$ is the penalty cost of consumption borne by user d. (a) denotes the benefit obtained by user d from selling excess consumption; (b) is the cost of purchasing renewable energy consumption by user d; and (c) denotes the cost to be borne by user d.

The constraints are the user's declared output constraints, specifically:

$$P_{L,d,\min,t} \le P_{L,d,t} \le P_{L-pred,d,t} \tag{14}$$

where: $P_{L,d,\min,t}$ is the lower bound of the declared t time slot load of user d at node L; $P_{L,d,t}$ is the desired t moment of clearing load of user d; and $P_{L-pred,d,t}$ is the predicted t time slot load of user d.

3.1.2 Lower level optimization model

The lower level model is the optimization model of electricity energy market clearing based on the objective of social welfare maximization, and solving the lower level model can get the market clearing price, the clearing power of generators and users in the electricity energy market. The objective function of the lower model is:

$$\max Z = \sum_{t=1}^{T} \begin{pmatrix} \sum_{L\in\Omega^{L}} \alpha_{L,d,t}^{bid} P_{L,d,t}^{deal} - \sum_{r\in\Omega^{r}} \alpha_{r,i,t}^{bid} P_{r,i,t}^{deal} \\ -\sum_{w\in\Omega^{w}} \alpha_{w,j,t}^{bid} P_{w,j,t}^{deal} - \sum_{pv\in\Omega^{pv}} \alpha_{pv,k,t}^{bid} P_{pv,k,t}^{deal} \end{pmatrix} \tag{15}$$

where: Z denotes the social welfare of the day-ahead electricity market; $\alpha_{r,i,t}^{bid}, \alpha_{w,j,t}^{bid}, \alpha_{pv,k,t}^{bid}, \alpha_{L,d,t}^{bid}$ are the thermal i at node r, the wind j at node w, and the photovoltaic k at node pv, and the node L 's user d 's t time period offer; $P_{r,i,t}^{deal}, P_{w,j,t}^{deal}, P_{pv,k,t}^{deal}, P_{L,d,t}^{deal}$ denote the thermal i at node r, the wind j at node w, and the photovoltaic k at node pv, and the user d at node L, at the t time period, respectively clearing power; $\Omega^r, \Omega^w, \Omega^{pv}, \Omega^L$ denote the set of nodes for thermal turbines, wind turbines, photovoltaic, and power consumer access, respectively.

Constraints:

1) System power balance constraints:

$$\sum_{r\in\Omega^r} P_{r,i,t}^{deal} + \sum_{w\in\Omega^w} P_{w,j,t}^{deal} + \sum_{pv\in\Omega^{pv}} P_{pv,k,t}^{deal} = \sum_{L\in\Omega^L} P_{L,d,t}^{deal} : \lambda_{Load}(t) \tag{16}$$

where: λ_{Load} is the Lagrange multiplier vector corresponding to the system power balance constraint.

2) Unit output neutralization constraint:

$$P_{G,g,\min} \le P_{G,g,t} \le P_{G,g,\max} : \mu_{G,g}^{-}(t), \mu_{G,g}^{+}(t) \tag{17}$$

where: G denotes the set of participating market transactions; $P_{G,g,t}$ denotes the winning bidding output of a unit g in the set G in time period t, $P_{G,g,\min}$, $P_{G,g,\max}$ are the minimum and maximum output of unit g; $\mu_{G,g}^{-}(t)$, and $\mu_{G,g}^{+}(t)$ are the Lagrange multiplier vectors corresponding to the unit output constraints.

3) Ramping constraints for thermal power units:

$$\Delta P_{r,i}^{down}\Delta t \le P_{r,i,t}^{deal} - P_{r,i,t-1}^{deal} \le \Delta P_{r,i}^{up}\Delta t : v_{r,i}^{-}(t), v_{r,i}^{+}(t) \tag{18}$$

where $v_{r,i}^{-}, v_{r,i}^{+}$ are the Lagrange multiplier vectors corresponding to the climbing constraints of thermal units.

4) User winning constraint:

$$0 \le P_{L,d,t}^{deal} \le P_{L-pred,d,t} : \mu_{L,d}^{-}(t), \mu_{L,d}^{+}(t) \tag{19}$$

where $\mu_{L,d}^{-}, \mu_{L,d}^{+}$ are the Lagrange multiplier vectors corresponding to the load neutral constraints.

5) Rotation Alternate Constraints:

$$\begin{cases} \sum\limits_{r\in\Omega^r} \min\left\{\Delta P_{r,i}^{up}, P_{r,i,\max} - P_{r,i,t}^{deal}\right\} \ge \Delta R_t : \omega^{+}(t) \\ \sum\limits_{r\in\Omega^r} \min\left\{\Delta P_{r,i}^{down}, P_{r,i,t}^{deal} - P_{r,i,\min}\right\} \ge \Delta R_t : \omega^{-}(t) \end{cases} \tag{20}$$

where: ΔR_t is the capacity demand; ω^{+}, ω^{-} are the Lagrange multiplier vectors respectively. The system rotating standby demand depends on the load, wind and PV forecast deviation capacity as:

$$\Delta R_t = \gamma_{Load} \sum_{L \in \Omega^L} P_{L,d,t}^{deal} + \gamma_{renew} \cdot \left(\sum_{w \in \Omega^w} P_{w,j,t}^{deal} + \sum_{pv \in \Omega^{pv}} P_{pv,k,t}^{deal} \right) : \lambda_R(t) \tag{21}$$

where: γ_{Load} is the proportion of load forecast deviation; γ_{renew} is the proportion of new energy forecast deviation; and λ_R is the Lagrange multiplier vector corresponding to rotating reserve capacity.

6) Carbon emission constraint:

$$\sum_{t=1}^{T} \sum_{f=1}^{F} \sum_{i \in f} P_{r,i,t}^{deal} \delta_{f,i} \le \sum_{t=1}^{T} \sum_{f=1}^{F} \delta_f^* \sum_{i \in f} P_{r,i,t}^{deal} : v_{CO_2} \tag{22}$$

where: $\sum_{t=1}^{T} \sum_{f=1}^{F} \sum_{i \in f} P_{r,i,t}^{deal} \delta_{f,i}$ is the total amount of actual carbon emissions of all thermal power units; $\sum_{t=1}^{T} \sum_{f=1}^{F} \delta_f^* \sum_{i \in f} P_{r,i,t}^{deal}$ is the total amount of carbon allowances allocated to each thermal power unit; v_{CO_2} is the Lagrange multiplier corresponding to the total carbon emission constraint; and F denotes the number of thermal power unit types.

7) Total carbon allowance constraint:

$$\sum_{t=1}^{T} \sum_{f=1}^{F} \sum_{i \in f} P_{r,i,t}^{deal} \delta_f^* \le N_{CO_2} : \mu_{CO_2} \tag{23}$$

where: N_{CO_2} is the total amount of carbon emission allowances; μ_{CO_2} is the Lagrange multiplier corresponding to the total amount of carbon allowance constraints; and $i \in f$ denotes that thermal power plant i belongs to the unit of class f.

8) Line tidal current constraint.

$$-P_{e,\max}^{line} \le P_{e,t}^{line} \le P_{e,\max}^{line} : \varphi_e^-(t), \varphi_e^+(t), \forall e \tag{24}$$

where: $P_{e,t}^{line}$ denotes the transmission power of transmission line e in t time period; $P_{e,\max}^{line}$ denotes the maximum transmission capacity of line e.

9) Green certificate trading volume constraint.

The number of green certificates sold by wind power and photovoltaic enterprises shall not exceed the maximum number of green certificates they can sell in a single day:

$$\begin{cases} 0 \le {}_{r,i}^{TGC-deal} \le \gamma_G \gamma \sum_{t=1}^{T} P_{r,i,t}^{deal} : \mu_{Gr,i}^-, \mu_{Gr,i}^+ \\ 0 \le {}_{w,j}^{TGC-deal} \le \gamma \left(1 - \gamma_G\right) \sum_{t=1}^{T} P_{w,j,t}^{deal} : \mu_{Gw,j}^-, \mu_{Gw,j}^+ \\ 0 \le {}_{pv,k}^{TGC-deal} \le \gamma \left(1 - \gamma_G\right) \sum_{t=1}^{T} P_{pv,k,t}^{deal} : \mu_{Gpv,k}^-, \mu_{Gpv,k}^+ \end{cases} \tag{25}$$

In this paper, we only consider the scenario in which power generation companies participate in green certificate trading in the model, so the number of green certificates sold by wind power and photovoltaic companies is equal to the number of green certificates purchased by thermal power companies:

$$\sum_{r\in\Omega^r} q_{r,i}^{TGC-deal} = \sum_{w\in\Omega^w} q_{w,j}^{TGC-deal} + \sum_{pv\in\Omega^{pv}} q_{pv,k}^{TGC-deal} : \lambda_{TGC} \tag{26}$$

where: $q_{r,i}^{TGC-deal}$ is the green certificate trading volume of thermal i at node r; $q_{w,j}^{TGC-deal}$ is the green certificate trading volume of wind j at node w; $q_{pv,k}^{TGC-deal}$ is the green certificate trading volume of photovoltaic k at node pv; $\mu_{Gr,i}^{-}, \mu_{Gr,i}^{+}, \mu_{Gw,j}^{-}, \mu_{Gw,j}^{+}, \mu_{Gpv,k}^{-}, \mu_{Gpv,k}^{+}, \lambda_{TGC}$ are the constrained corresponding multipliers.

3.1.3 Model solving

In this paper, the ADMM algorithm is used to solve the hierarchical model with alternating iterations, and the declared output of market members and the amount of green certificate reported by the generators, and the clearing power curve and the amount of green certificate traded by the generators are taken as the interaction optimization variables, and the Lagrangian multipliers and penalty factors corresponding to the interaction variables are introduced.

The marginal power clearing method is adopted, and the clearing power price is obtained by solving the Lagrangian pairwise multipliers of the day-ahead market clearing model. Using the KKT condition, the nodal marginal tariff expression for generating units/customers is derived from the power side, and the coupled trading components such as carbon and green certificates in the clearing tariff are dissected.

3.2 Example analysis

3.2.1 Case setup

In order to verify the feasibility of the proposed model, this paper uses the IEEE-30 standard node system to simulate the day-ahead market trading scenario that takes into account the new energy uncertainty and the decomposition of medium- and long-term contracted power. In the example, the six conventional generating units G1-G6 belong to different thermal power, representing different interests, and each generating unit in the IEEE-30 node is attributed to a different node. In the example, the spot day-ahead market operates for 1h, with a total of 24 time slots, and the penalty cost of lost load and energy abandonment is set to 500 RMB/MWh, and the system spinning reserve capacity is set to 15% of the variable day-ahead load.

3.2.2 Medium- and long-term contract power decomposition results

Based on the completion progress of the medium- and long-term contract and the daily load data, the deviation limit of the cooperation progress is set to 5%, the test daily electricity demand is 36080MWh, and the total daily executed electricity of all units participating in the market bidding in the previous day is 42,155MWh. The results of the electricity decomposition of the medium- and long-term contract for units G1-G3 are shown in Table 2. The results show that the upper and lower limits of the executed power of unit G1 on the scheduled day are 1930MWh and 450MWh, respectively; for G2, they are 3700MWh and 810MWh; and for G3, they are 6100MWh and 1150MWh.

For units Gl and G2, the proportion of medium- and long-term contracted power is relatively high, and the remaining generating capacity on the scheduled day is not abundant, so the proportion of the day-ahead market transactions that can be participated in the day-ahead market is relatively low; the proportion of medium- and long-term contracted power for unit G3 is moderate, and the unit can participate in the day-ahead market to fully participate in the bidding. The physical execution of medium- and long-term contracted power is conducive to maintaining system stability and better connecting the medium- and long-term market with the spot market.

Table 2: Decomposition of Medium and Long Term Contract Electricity of G1-G3

Metric	G1	G2	G3
$Q_{n,time}^{\min}$ /MWh	450	810	1150
$Q_{n,time}^{\max}$ /MWh	1930	3700	6100
$E_{n,time}^{\min}$ /MWh	290	850	1150
$E_{n,time}^{\min}$ /MWh	1900	3220	5910
$q_{q,time}^{RPS}$ /MWh	1650	2950	4020

3.2.3 System Uncertainty Solving

(1) Wind power density function solution

For the wind power stochastic distribution model, the wind farm is set to have a cut-in wind speed of 3.5m/s, a cut-out wind speed of 24m/s, and a rated wind speed of 12m/s. The wind power density function is then solved by the wind power density function. In this paper, BS two-parameter distribution is used to fit the wind speed distribution characteristics of wind farms, for the BS distribution function, set its shape parameter $\lambda = 2$, the scale parameter $\beta = 0.5$, then this paper obtains the wind speed probability density function based on the BS two-parameter distribution is:

$$f(v) = \frac{1}{3.394}\left[\left(\frac{0.6}{v}\right)^{\frac{1}{2}} + \left(\frac{0.6}{v}\right)^{\frac{3}{2}}\right] e^{\left[\frac{1}{18}\left(\frac{5v}{3}+\frac{3}{5v}-2\right)\right]} \tag{27}$$

(2) Day-ahead market price regression function

The actual day-ahead electricity price data for the DK1 region of the Nordic electricity market is shown in Figure 6. The actual day-ahead electricity market price is based on the day-ahead electricity price data in the DK1 region, with the new energy penetration rate and time as the independent variable, and the day-ahead electricity price as the dependent variable for curve fitting, which together form a multiple linear regression equation. The residual effect of multiple linear fitting is better, all the points are uniformly distributed on both sides of a straight line, and it can be considered that the residuals load the requirements of normal distribution. The histogram of the regression standardized residual distribution is shown in Figure 7, where the yellow line is the fitted curve. The statistical significance of the multiple regression equation is tested, and the adjusted R2 of the regression model can be obtained as 0.6213, which is considered that the degree of explanation of the overall independent variable for the dependent variable reaches 62.13%, and the fitting effect is relatively good, indicating that the model is relatively stable. The autoregressive model that has been tested for validity is used to simulate the actual clearing process using the market price curve of the previous day as the benchmark.

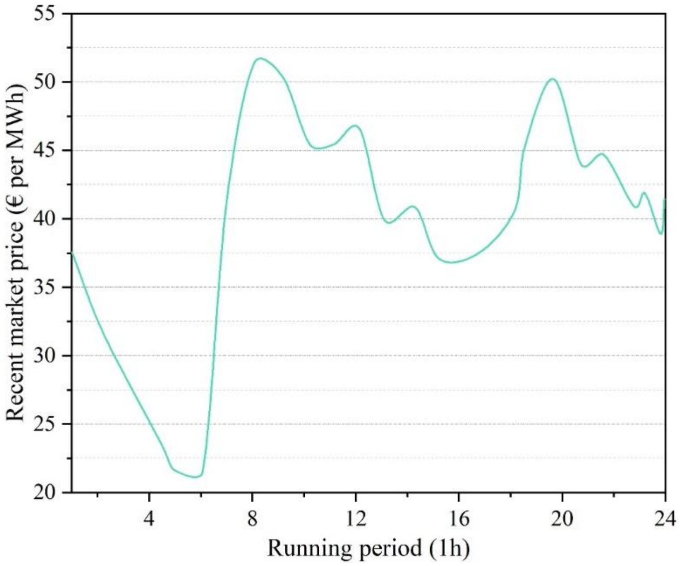


Figure 6: Actual daily electricity price data for the DK1 area

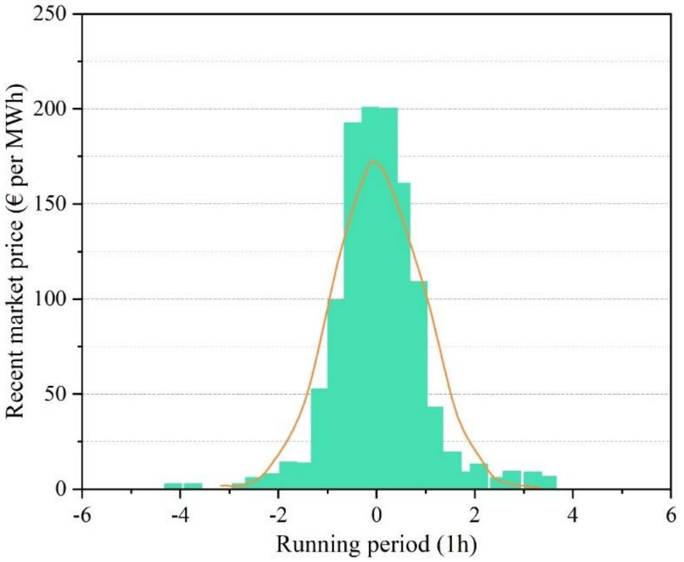


Figure 7: Histogram of the normalized residual distribution

3.2.4 Results of electricity market clearing before the spot day

In this paper, when calculating the results of power purchase in the day-ahead market, we first take the system economic efficiency and energy-saving and emission efficiency as the objectives for the day-ahead market clearing calculation, and then calculate the multi-objective trading optimization results and analyze the results of the two clearings.

(1) Single-objective clearing results

For the energy saving and emission reduction target, the coal price for thermal power units is set at 700 yuan/ton. The clearing results of different optimization objectives are shown in Table 3. In the total system cost obtained with system economic benefit and energy saving and emission reduction benefit respectively, the total optimization cost of the previous clearing is 79,299,000 yuan, and if energy saving and emission reduction benefit is taken as the optimization goal, the total system cost is 8,537,700 yuan, and the cost of energy consumption has increased by 6,078,000 yuan.

Table 3: Clearing results of different optimization objectives

Prime cost	Systemic economic benefits per 10,000 yuan	Energy-saving and emission-reduction benefits per 10,000 yuan
Electricity purchasing cost	710.84	-
Punishment cost	82.15	-
Cost of coal consumption	-	545.27
Pollution cost	-	308.5
Total	792.99	853.77

(2) Multi-objective clearing results

When using multi-objective calculation of the market clearing results a few days ago, the economic benefits of the system and energy saving and sincere emission benefits are processed by fuzzy preferential treatment, and the results of multi-objective optimization of the market clearing are shown in Fig. 8. In this paper, the economic benefits of the system, energy saving and emission reduction benefits of the multi-objective clearing calculation found that the cost of 83,607,000 yuan, with a certain gap between the cost of the system alone considering the economic benefits of the target, but the total cost of the difference is not significant, indicating that the model in this paper in order to ensure that the economic benefits of the system operation on the basis of the environmental benefits of the maximization of energy saving and emission reduction effect.

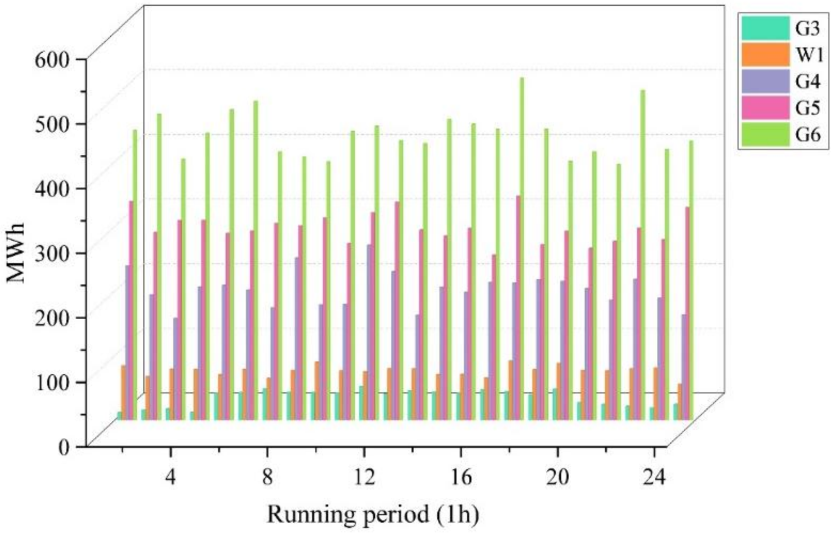
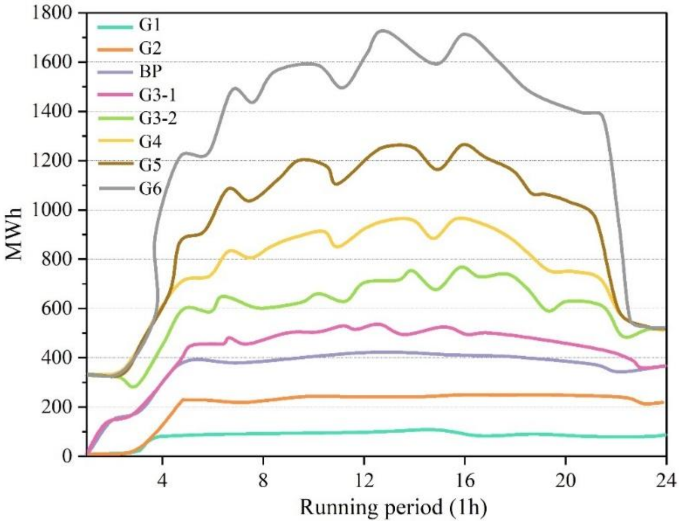


Figure 8: Multi-objective optimization of market clearing results

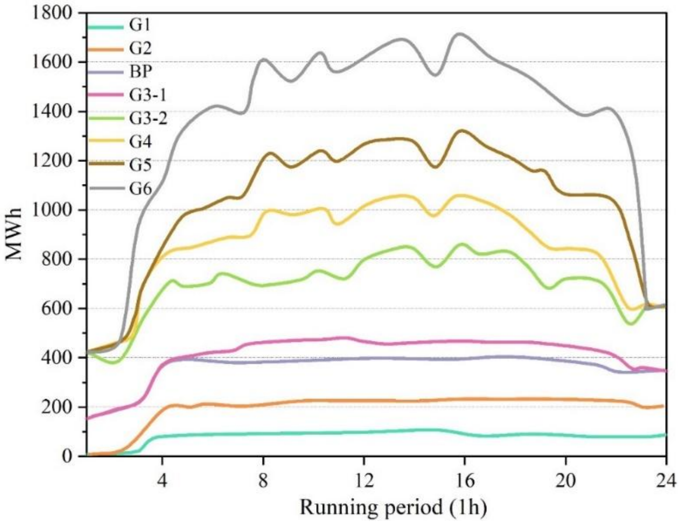
3.2.5 Impact of new energy penetration on multi-objective optimization results

New energy penetration rate is an important sensitivity analysis factor in the context of high percentage renewable energy penetration. In order to further analyze the impact of new energy penetration rate on the spot market clearing results, on the basis of adopting the original new energy output uncertainty impact, the installed size of wind farms accessed at the 21st node in the IEEE-30 node system is set to 300MW and 500MW in turn, i.e., during the peak load period, the new energy penetration rate of wind power generation is 12.32% and 18.54%, respectively, and the lost load, abandoned energy penalty factor is still set at 500 yuan/MWh, while the wind power output data are converted in equal proportions to the former day-ahead market clearing results.

The current day market clearing results under different new energy penetration rates are shown in Figure 9, in which G3-1 and G3-2 represent the medium- and long-term contracted power and the current day market transacted power, respectively, and (a) and (b) represent the new energy penetration rates of 12.32% and 18.54%, respectively. It can be seen that with the increase of new energy penetration, the transacted power of conventional units in the system decreases, and the pre-market clearing tariff decreases. Analyzing the results of pre-market clearing under different new energy penetration rates, the main reason is that the large-scale access of wind power squeezes the generation space of conventional units, in addition to the increase of new energy penetration with volatility and intermittency, which further increases the uncertainty of the system, resulting in an increase in the cost of system standby capacity. The above reasons are combined in the day-ahead market clearing transactions that take into account the breakdown of medium- and long-term contracted power and new energy sources, resulting in a decline in the day-ahead market clearing tariffs and in the amount of power cleared from conventional units.



(a) The penetration rate of new energy is 12.32%



(b) The penetration rate of new energy is 18.54%

Figure 9: Market clearing results under different new energy penetration rates

4 Conclusion

In this paper, a prediction model based on PSO and LS-SVM algorithm optimization is first constructed to predict the new electricity market price; after that, a two-layer optimization model for day-ahead electricity market trading based on coupled carbon-green certificate-consumption is constructed on the basis of flexibility resources and electricity market trading. The experimental results show that the prediction model proposed in this paper can effectively predict the market electricity price, and its MAPE values for both day-ahead and real-time prediction prices are <15%, which are significantly lower than those of other comparison models. Example analysis shows that when the new energy penetration rate, which is volatile and intermittent, increases from 12.32% to 18.54%, it will cause the day-ahead market clearing tariff and the conventional unit clearing power to decrease, which shows that there is an obvious coupling correlation between the flexibility resources and the power market transaction.

It should be noted that this paper only simulates the intraday short time scale flexibility demand and supply without considering the unit start-stop constraints, investment costs and operation costs of various types of flexibility resources. In future work, it is necessary to characterize the long-term operating characteristics of market players and to make appropriate connections between long-term and short-term cost constraints.

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