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Combined Heat and Power Low-carbon Economic Dispatch Considering Carbon Trading and Demand Response

Jiqin Zhang[1, *], Yumei Wang[1]

[1]School of Electrical Engineering and Automation, Henan Polytechnic University, Jiaozuo 454000, China
[*] **Corresponding author**: ZHOU Yongxin (Email: 1182010405@qq.com)

Abstract: To address the problems of "thermoelectric conflict" and abandoned wind power during winter heating, a low-carbon economic dispatch model for combined heat and power that takes into account carbon trading costs and price-based demand response is proposed, while electric boilers and heat storage devices are introduced to decouple the coupling limits of thermoelectricity to study the impact of different operation modes on optimal dispatch. Carbon trading costs are considered in the system to limit carbon emissions, and the user-side demand response is used to enhance the peak regulation capability of the grid and optimise the load curve, effectively cutting the peak-to-valley difference in load and providing space for wind power to go online. Finally, the CPLEX solver is used for solving and simulation analysis is carried out based on the improved IEEE-30 node system. The results show that the wind power consumption is increased by 83.72% and carbon emissions are reduced by 2211t under the scheduling method of this paper, which verifies the reliability of the scheduling model.

Keywords: Combined heat and power generation, Carbon transaction cost, Demand response, Carbon emissions.

1. Introduction

The fluctuating nature of wind power will not only lead to wind curtailment, but also make coal-fired units take on more spare capacity, resulting in increased carbon emissions. References [1-3] studied how to solve the problem of wind power consumption in combined heat and power systems; Reference [4] studied the combined heat and power dispatching of coordinated heating for start-up and shutdown of electric boilers from the perspectives of economy and low carbon; References [5] Considering the environmental cost, an economic operation model of a multi-source power generation system considering carbon emissions is established; Reference [6] further taps the carbon emission reduction potential of coal-fired units based on the carbon trading mechanism, so as to achieve the goal of low-carbon economy; Reference [7] studied the impact of carbon trading mechanism on the thermal power system with energy storage; Reference [8] introduced coupling equipment such as electric boilers into the model, and considered the carbon trading cost of each unit. The output of coal-fired units increases the online space for wind power. Reference [9] introduces price-based demand response to change the electricity consumption behavior of users, which can play a role in shaving peaks and filling valleys; Reference [10] considers demand-side resources and establishes a multi-type demand response combined heat and power system to optimize operation Model; Reference [11] builds a system optimal configuration model by using time-of-use electricity price for source-load uncertainty; Reference [12] integrates and optimizes additional heat sources and demand-side response in combined electric and heat systems to enhance the peak shaving capability of the power grid.

Based on the above literature research, this paper based on carbon transaction cost and price-type demand response research on the combined heat and power dispatching of electric boilers and heat storage devices, guided by low-carbon and economic signals, to promote the active participation of the source and the load to promote the consumption of wind power.

2. Low Carbon Realization Model of Electric Heating System

2.1. Carbon Trading Costs

The carbon trading mechanism is a market-based emission reduction mechanism to limit carbon emissions [6]. During the operation of each carbon emission source, the part of carbon emission exceeding
the quota will generate carbon transaction costs, so as to limit the carbon emission of coal-fired units.

2.1.1. Carbon Trading of Thermal Power Units

The part of the carbon emission of thermal power units that exceeds the quota needs to be purchased, and the extra cost incurred is called the carbon transaction cost of thermal power units, as shown in formula (1):

$$C_{\mathrm{e}} = \delta(Q_{\mathrm{e}t} - Q_{\mathrm{q}t}) \tag{1}$$

In the formula, C_{e} is the carbon transaction cost of the thermal power unit; $Q_{\mathrm{e}t}$ is the carbon emission of the thermal power unit at time *t*; $Q_{\mathrm{q}t}$ is the carbon emission quota of the thermal power unit at time *t*; δ is the carbon trading price at time *t*.

The formula for calculating the carbon emissions $Q_{\mathrm{e}t}$ of thermal power units is shown in formula (2):

$$Q_{\mathrm{e}t} = \sum_{i=1}^{n} l_i (P_{i,t} - \lambda P_{\mathrm{w},t}) \tag{2}$$

In the formula, l_i is the carbon emission intensity per unit of electricity of thermal power unit *i*; $P_{i,t}$ is the electrical power of *i* thermal power units at time *t*; $P_{\mathrm{w},t}$ is the power generation of wind power at time *t*; λ is the wind power reserve capacity factor, which is taken as 0.14.

The calculation formula of carbon emission quota $Q_{\mathrm{q}t}$ for thermal power units is shown in formula (3):

$$Q_{\mathrm{q}t} = \beta \sum_{i=1}^{n} P_{i,t} \tag{3}$$

In the formula, β is the carbon trading quota per unit of electricity, which is taken as 0.789t/MWh.

2.1.2. Carbon Trading Costs for CHP Units

The carbon transaction cost of CHP units is shown in formula (4):

$$C_{\mathrm{r}} = \delta(Q_{\mathrm{ret}} - Q_{rqt}) \tag{4}$$

In the formula, $Q_{\mathrm{re}t}$ and $Q_{\mathrm{rq}t}$ are the carbon emissions and carbon emission quotas of CHP units at time *t*, respectively; among them, the calculation formulas of $Q_{\mathrm{re}t}$ and $Q_{\mathrm{rq}t}$ are shown in formulas (5) and (6):

$$Q_{\mathrm{re}t} = \sum_{i=1}^{N} l_i (p_{i,t}^{\mathrm{CHP}} - c_v Q_{i,t}^{\mathrm{CHP}}) \tag{5}$$

$$Q_{\mathrm{rq}t} = \beta \sum_{i=1}^{N} (p_{i,t}^{\mathrm{CHP}} - c_v Q_{\mathrm{i,t}}^{\mathrm{CHP}}) \tag{6}$$

In the formula, C_{r} is the carbon transaction cost of the CHP unit; $p_{i,t}^{\mathrm{CHP}}$ and $Q_{i,t}^{\mathrm{CHP}}$ are the electrical load and thermal load of the *i*-th CHP unit at time *t*, respectively.

2.1.3. Carbon Trading Costs for Wind Turbines

After wind power is connected to the grid, it is necessary to increase the rotating reserve capacity of thermal power units, so the cost of increasing carbon emissions is defined as the carbon transaction cost of wind power units [8], as shown in formula (7):

$$C_{\mathrm{w}} = \delta(Q_{\mathrm{we}t} - Q_{\mathrm{w}t}) \tag{7}$$

In the formula, C_w is the carbon transaction cost of wind turbines; $Q_{\mathrm{we}t}$ and $Q_{\mathrm{w}t}$ are the carbon emissions and carbon emission quotas of wind power at time t, respectively.

Among them, the calculation formulas of $Q_{\mathrm{we}t}$ and $Q_{\mathrm{w}t}$ are shown in formulas (8) and (9):

$$Q_{\mathrm{we}t} = \sum_{i=1}^{m} l_i P_{i,t} - Q_{\mathrm{e}t} \tag{8}$$

$$Q_{\mathrm{w}t} = \beta \sum_{i=1}^{m} P_{\mathrm{w},t} \tag{9}$$

It can be seen from the above that the total carbon transaction cost in the system is shown in formula (10):

$$F_{CET} = C_{\mathrm{e}} + C_{\mathrm{r}} + C_{\mathrm{w}} \tag{10}$$

2.2. Price-based Demand Response Model

Price Demand Response (PDR) Mainly through the implementation of time-of-use electricity prices to guide users to adjust the electricity time period [13]. The user participates in the time-of-use electricity price to transfer part of the peak load to the flat and valley periods, so as to achieve the purpose of "shaving peaks and filling valleys", and at the same time, users can obtain corresponding compensation from the power grid. In this paper, 24 hours a day is divided into peak period, normal period and trough period [14].

The response of electricity price to electricity price is expressed by the electricity price elasticity matrix method. The elements $m_{t,\,i}$ charge in the elasticity matrix $\boldsymbol{M}$ are the elasticity coefficient[14] of electricity consumption at time *t* to electricity price at time *i*, as shown in the formula (11) shows:

$$\mathrm{m} = \frac{P}{L} \times \frac{\Delta L}{\Delta P} \tag{11}$$

In the formula, *m* is the PDR elastic coefficient; *L* is the electricity quantity; *P* is the electricity price; ΔL and ΔP are the changes of electricity quantity and electricity price, respectively.

The load variation model after user PDR is shown in formula (12):

$$p_t = p_t^0 + \Delta p_t = \begin{bmatrix} p_1 \\ \vdots \\ p_t \end{bmatrix} + \begin{bmatrix} p_1 & & \\ & \ddots & \\ & & p_1 \end{bmatrix} M \begin{bmatrix} \frac{\Delta \mathrm{q}_1}{\mathrm{q}_1} \\ \vdots \\ \frac{\Delta \mathrm{q}_t}{\mathrm{q}_t} \end{bmatrix} \tag{12}$$

In the formula, p_t^0 and p_t are the electricity consumption in the period *i* before and after the response, respectively, and Δp_t is the change in electrical load.

3. Combined Heat and Power Low-Carbon Economic Dispatch Model

3.1. Objective Function

This paper builds a low-carbon economic dispatch model with the goal of minimizing the overall operating cost of the system. The objective function is shown in Equation (13):

$$\min F = F_{\mathrm{TP}} + F_{\mathrm{CHP}} + F_{\mathrm{w}} + F_{\mathrm{q}} + F_{\mathrm{d}} + F_{\mathrm{CET}} \tag{13}$$

In the formula, *F* is the total operating cost; F_{TP}, F_{CHP}, F_{w}, F_{q}, F_{d}, F_{CET} are the operating cost of the thermal power unit, the operating cost of the CHP unit, the operation and maintenance cost of the wind turbine, the penalty cost of wind abandonment, and the operation of the electric boiler equipment. cost, carbon transaction cost.

(1) The operating cost of thermal power units in period *t* is shown in formula (14):

$$F_{TP} = \sum_{t=1}^{T}\sum_{i=1}^{n}\left[a_i^{\mathrm{TP}} p_{i,t}{}^2 + b_i^{\mathrm{TP}} p_{i,t} + c_i^{\mathrm{TP}} + S_i(u_{i,t} + w_{i,t})\right] \quad (14)$$

In the formula, a_i^{TP}, b_i^{TP}, and c_i^{TP} are the fuel cost coefficients of unit i; are the start-stop cost coefficients of unit i; represent the 0-1 variable that unit i starts at time period t, and 0 indicates the shutdown state; A 0-1 variable for shutdown, with 0 indicating the startup state.

(2) Operating cost of CHP unit CHP

The CHP unit undertakes the heating task. According to its electrothermal operation characteristics, the electrical output and thermal output of the unit are converted into the electrical output under pure condensing conditions [17], as shown in formula (15):

$$F_{\mathrm{CHP}} = \sum_{t=1}^{T}\sum_{i=1}^{N}\Big[a_i^{\mathrm{CHP}}(p_{i,t}^{\mathrm{CHP}} + \mathrm{c}_{\mathrm{v},i}\cdot Q_{i,t}^{\mathrm{CHP}})^2 + b_i^{\mathrm{CHP}}(p_{i,t}^{\mathrm{CHP}} + \mathrm{c}_{\mathrm{v},i}\cdot Q_{i,t}^{\mathrm{CHP}}) + c_i^{\mathrm{CHP}}\Big] \quad (15)$$

In the formula, a_i^{CHP}, b_i^{CHP}, c_i^{CHP} are the fuel cost coefficient of unit i ; $p_{i,t}^{\mathrm{CHP}}$, $Q_{i,t}^{\mathrm{CHP}}$ are the electrical output and thermal output of the i-th CHP unit at time t, respectively.

(3) The operation and maintenance cost of wind turbine is shown in formula (16):

$$F_{\mathrm{w}} = k_{\mathrm{w}}\sum_{t=1}^{T} P_{\mathrm{w},t} \quad (16)$$

In the formula, $P_{\mathrm{w},t}$ is the output of wind power at time t; k_{w} is the operation and maintenance cost coefficient of the wind turbine, which is 170 yuan/MW.

(4) The wind abandonment penalty cost [21] is shown in equations (17) and (18):

$$F_{\mathrm{q}} = k_{\mathrm{q}}\sum_{i=1}^{T} P_{\mathrm{wq},t} \quad (17)$$

$$P_{\mathrm{wq},t} = P_{\mathrm{w},t}^{\mathrm{p}} - P_{\mathrm{w},t} \quad (18)$$

In the formula, is the abandoned wind power at time t; is the predicted power at time t; is the wind abandonment penalty coefficient, which is 500 yuan/(MW·h).

(5) Operating cost of electric boiler equipment

Electric boiler equipment is used as energy conversion equipment, and its operating cost is relatively high, as shown in formula (19):

$$F_{\mathrm{d}} = K_{\mathrm{d}}\sum_{i=1}^{T} P_{\mathrm{d},t} \quad (19)$$

In the formula, K_{d} is the operating cost coefficient; $P_{\mathrm{d},t}$ is the electric power of the electric boiler equipment at time t.

3.2. Restrictions

During the CHP operation, the balance of electric power and thermal power and the operating constraints of each unit need to be satisfied.

3.2.1. Power Balance Constraints

Regardless of network losses, the system includes power constraints of both electrical and thermal loads, as shown in equation (20):

$$\begin{cases} \sum_{i=1}^{N_{\mathrm{G}}} P_{\mathrm{G}i,t} + \sum_{i=1}^{N_{\mathrm{CHP}}} P_{i,t}^{\mathrm{CHP}} + P_{\mathrm{w}i,t} + P_{\mathrm{EES}i,t} = P_{\mathrm{LD},t} + P_{\mathrm{d},t} \\ \sum_{i=1}^{N_{\mathrm{CHP}}} H_{i,t}^{\mathrm{CHP}} + H_{\mathrm{EB}i,t} + H_{\mathrm{HS}i,t} = H_{\mathrm{LD},t} \end{cases} \quad (20)$$

In the formula, $P_{\mathrm{w}i,t}$ is the wind power output of the wind turbine at time t; $P_{\mathrm{d},t}$ is the active power of the electric boiler equipment at time t; $H_{\mathrm{HS}i,t}$ is the heat storage and release power of the heat storage device at time t; $P_{\mathrm{LD},t}$ is the total electricity load at time t; $H_{\mathrm{LD},t}$ is the total power consumption at time t heat load.

3.2.2. Operational Constraints of Thermal Power Units

The constraints of thermal power units include output constraints, slope constraints, start-stop constraints and rotating reserve constraints, as shown in equations (21-24):

$$P_{i,\min} \le P_{i,t} \le P_{i,\max} \quad (21)$$

$$-R_{i,\mathrm{d}} \le P_{i,t} - P_{i,t-1} \le R_{i,\mathrm{u}} \quad (22)$$

$$\sum_{t=1}^{T}\left|U_{i,t} - U_{i,t-1}\right| \le M_i \quad (23)$$

$$\begin{cases} U_{\mathrm{S}} = \sum_{i=1}^{n}\min(P_{i,\max} - P_{i,t}, P_{i,\mathrm{u}}) \ge P_{\mathrm{s}} + \lambda P_{\mathrm{w},t} \\ U_{\mathrm{d}} = \sum_{i=1}^{n}\min(P_{i,t} - P_{i,\min}, P_{i,\mathrm{d}}) \ge P_{\mathrm{s}} + \lambda P_{\mathrm{w},t} \end{cases} \quad (24)$$

In the formula: $P_{i,\min}$, $P_{i,\max}$ are the output upper limit and output lower limit of thermal power unit i at time t, respectively; $R_{i,\mathrm{d}}$, $P_{i,\mathrm{u}}$ are the upward and downward ramp rates of thermal power unit i, respectively; M_i is the maximum number of starts and stops in the cycle of the thermal power unit; P_{s} is the rotating reserve capacity.

3.2.3. CHP Unit Related Constraints

The CHP unit generates electric energy and heat energy at the same time during operation, and needs to meet the constraints of electric power and thermal power and the constraints of the unit ramp rate, as shown in equations (25) and (26):

$$\begin{cases} P_{i,\min}^{\mathrm{CHP}} \le P_{i,t}^{\mathrm{CHP}} \le P_{i,\max}^{\mathrm{CHP}} \\ H_{i,\min}^{\mathrm{CHP}} \le H_{i,t}^{\mathrm{CHP}} \le H_{i,\max}^{\mathrm{CHP}} \end{cases} \tag{25}$$

$$-P_{i,\mathrm{d}}^{\mathrm{CHP}} \le P_{i,t}^{\mathrm{CHP}} - P_{i,t-1}^{\mathrm{CHP}} \le P_{i,\mathrm{u}}^{\mathrm{CHP}} \tag{26}$$

In the formula, $P_{i,\max}^{\mathrm{CHP}}$, $P_{i,\min}^{\mathrm{CHP}}$ are the upper and lower limits of the electrical output of the CHP unit *i*; $H_{i,\max}^{\mathrm{CHP}}$, $H_{i,\min}^{\mathrm{CHP}}$ are the upper and lower limits of the thermal output of the CHP unit *i*; $P_{i,\mathrm{u}}^{\mathrm{CHP}}$, $P_{i,\mathrm{u}}^{\mathrm{CHP}}$ are the upper and lower limits of the ramp rate of the thermal power unit *i*.

3.2.4. Thermal Storage Device Operating Constraints

The operating constraints of the heat storage device include heat storage capacity constraints and heat storage and heat release power constraints, as shown in equations (27) and (28)

$$\begin{cases} C_{\mathrm{s,min}} \le C_{\mathrm{s},t} \le C_{\mathrm{s,max}} \\ C_{\mathrm{s},0} = C_{\mathrm{s},T} \end{cases} \tag{27}$$

$$\begin{cases} C_{\mathrm{s},t} - C_{\mathrm{s},t-1} \le P_{\mathrm{c,max}} \\ C_{\mathrm{s},t-1} - C_{\mathrm{s},t} \le P_{\mathrm{f,max}} \\ P_{\mathrm{c},t} \cdot P_{\mathrm{f},t} = 0 \end{cases} \tag{28}$$

In the formula, $C_{\mathrm{s,max}}$ and $C_{\mathrm{s,min}}$ are the upper and lower limits of the heat storage capacity, respectively; $C_{\mathrm{s},t}$ is the heat storage at time *t*; $C_{\mathrm{s},0}$ and $C_{\mathrm{s},T}$ are the beginning and end values of the heat storage device in the cycle, respectively; $P_{\mathrm{c,max}}$ and $P_{\mathrm{f,max}}$ are the upper limit of the heat storage power and the heat release power of the heat storage device, respectively; $P_{\mathrm{c},t}$ is the heat storage power of the heat storage device at time *t*, $P_{\mathrm{f},t}$ is the heat release power of the heat storage device at time *t*, and at the same time, the heat storage device can only work in one state.

3.2.5. Electric Boiler Operation Constraints:

$$0 \le P_{\mathrm{EB},t} \le P_{\mathrm{EB,max}} \tag{29}$$

$$H_{\mathrm{EB},t} = \eta P_{\mathrm{EB},t} \tag{30}$$

In the formula, $P_{\mathrm{EB,max}}$ is the output upper limit of the electric boiler equipment at time *t*; $H_{\mathrm{EB},t}$ is the heating power of the electric boiler equipment at time *t*; η is the electric-heat conversion efficiency, which is taken as 97%.

4. Simulation Analysis

4.1. Simulation Data

This paper conducts simulation analysis based on the improved IEEE-30 node system. The IEEE30 node model is shown in Figure 1. Nodes 1 and 2 are CHP units, nodes 3, 4, 5, and 6 are conventional thermal power units. Wind farm, the capacity of wind turbines is 200MW. The parameters of the thermal power unit are shown in Table 1, and Reference [15] for parameters of CHP unit. Taking one day of the winter heating period in Northeast China as the scheduling period, the data is selected as the actual data of multiple parks. The parameters [16] in the model analysis process are set as follows: the carbon emission intensity *li* per unit of electricity of thermal power units 3-6 are 0.96, 1.08, 0.97, The division of peak-valley time-of-use electricity price is shown in Table 2.and 1.15 respectively; The transaction price is 100 yuan/t.

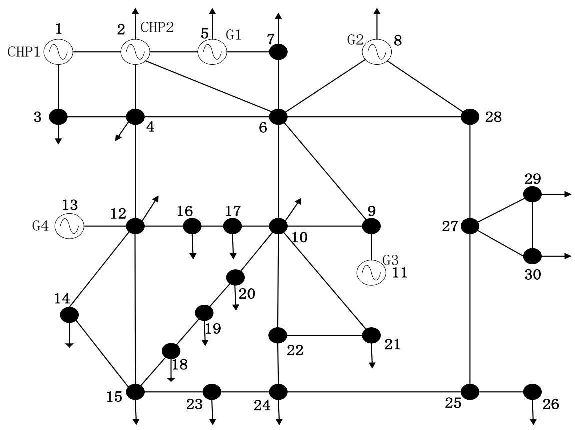

Figure 1. IEEE-30 node topology diagram

Table 1. Parameters of thermal power unit

unit	maximum output	minimum output	climb rate	fuel cost factor		
	Pmax/MW	Pmin/MW	Rui/（MW/h）	*a*/(yuan /MW2）	*b*/(yuan MW)	*c*/ yuan
3	50	25	25	0.0023	100	1250
4	35	10	18	0.0015	225	167
5	30	10	15	0.0009	150	500
6	40	12	20	0.0008	200	500

Table 2. Time-of-use price

electricity price period	electricity price / yuan· (MW·h)-1	period
peak	625	12:00-14:00，19:00-22:00
valley	375	23:00-07:00
flat	500	08:00-11:00，15:00-18:00

The predicted output curve of the user's electric and thermal load load is shown in Figure 2:

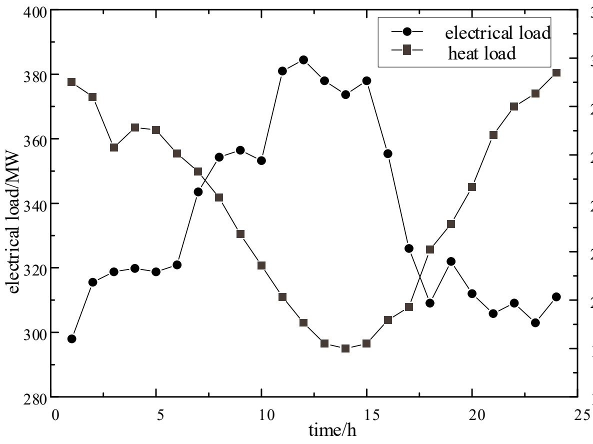

Figure 2. Forecast output of electricity and heat load of users at each moment

To verify the validity of the proposed model considering carbon transaction costs and demand response, three optimization scenarios are designed for simulation comparison:

Scenario 1: Conventional thermal power unit operation mode, the system does not contain electric boilers and heat storage devices.

Scenario 2: On the basis of scenario 1, an electric boiler and a heat storage device are added for thermal decoupling.

Scenario 3: On the basis of scenario 2, consider the carbon trading mechanism, and adjust the user-side load through price-based demand response.

4.2. Comparative Analysis of Scheduling Results in Various Scenarios

The comparison results of the economic cost, wind power consumption and carbon emission of the system under the three scenarios are shown in Table 3.

Table 3. Comparison of combined costs and wind power consumption rates

scenes	comprehensive cost / ten thousand yuan	wind power consumption /%	carbon emission /t
一	38.28	16.28	8632
二	40.78	93.75	6942
三	41.12	100.00	6421

The comparison curves of wind curtailment power under the three scenarios are shown in Figure 3. The curtailment of wind mainly occurs during the periods of 00:00-06:00 and 20:00-24:00, during which the demand for electrical load is low and the demand for heat load is high.

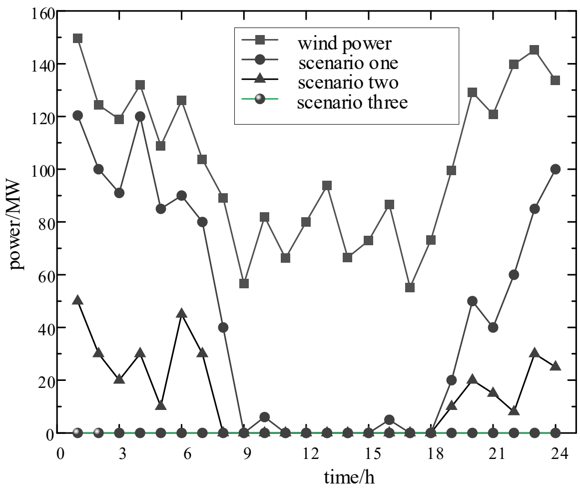

Figure 3. Predicted wind power and wind power abandonment for three scenarios

In Scenario 1, the combined heat and power unit operates in a conventional manner, and the abandoned wind power is the largest; in Scenario 2, an electric boiler and a heat storage device are added on the basis of Scenario 1, and the abandoned wind rate is significantly reduced; Scenario 3 considers on the basis of Scenario 2 Carbon trading costs and load-side demand response, curtailed wind is basically completely absorbed. The routine operation of CHP units limits the grid connection of wind power, which will lead to serious wind curtailment.

Analysis and comparison of scheduling results in various scenarios:

Scenario 1 has the lowest comprehensive cost, but the highest curtailed wind power and carbon emissions. In Scenario 2, electric boilers and heat storage devices are introduced. The use of electric boiler equipment also promotes the consumption of wind power at night and reduces the heat output of CHP units; contribute. Considering the operation and maintenance costs of electric boilers and heat storage devices, although the comprehensive cost of scenario 2 is 25,000 yuan more than that of scenario 1, its carbon emissions are reduced by 1,690t, and the amount of abandoned wind is also relatively reduced.

When Scenario 3 is adopted, carbon trading costs are considered in the system, and additional carbon emissions from coal-fired units in the system need to be purchased additionally, but wind farms, as clean energy sources, can benefit from the carbon trading market. Secondly, the peak-valley time-of-use electricity price changes the electricity consumption habits of users through electricity price incentives, so that the electricity load is transferred from the peak electricity price period to the electricity price valley period, which reduces the energy supply pressure of the unit. Compared with the second scenario, its comprehensive cost has increased by 3,400. Yuan, but the abandoned wind at night was completely absorbed, and the carbon emission was also reduced by 521t.

4.3. The Impact of Carbon Trading Price on Dispatch Results

The carbon trading price will affect the carbon emissions of the system. In order to verify the actual impact of the carbon trading price on carbon emissions, taking scenario 3 as an example, when the carbon trading price is changed, the relationship between the carbon trading price and carbon emissions is shown in Figure 4. Show. The carbon emission of the system decreases with the increase of the carbon trading price. When the carbon trading price rises to 100 yuan/t, the carbon emission of the system basically remains unchanged, and the carbon emission reduction capacity of the system reaches the upper limit.

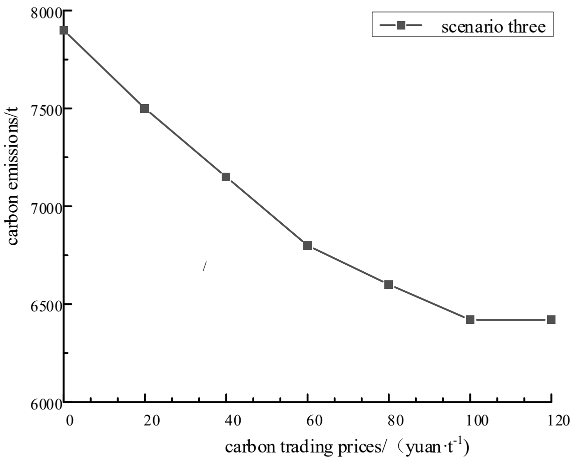

Figure 4. Carbon emissions - carbon price relationship under scenaior three

4.4. Analysis of Optimization Scheduling Results

Based on the scheduling method of scenario 3, the power output of each unit is shown in Figure 5. The power load of the system is mainly provided by thermal power and wind power. After taking into account the cost of carbon trading, the output of thermal power units within the dispatch day is stable and the coal consumption cost is low. ; The power output of each unit is shown in Figure 6. The heat load is mainly provided by the CHP unit, electric boiler equipment and heat storage device. The sum of the heat output value of each unit meets the heat load value of the system and ensures the heat demand of the user.

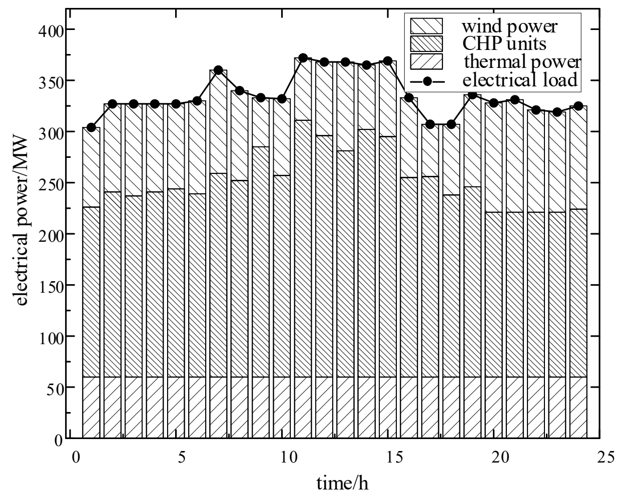

Figure 5. Electric power scheduling value of each unit

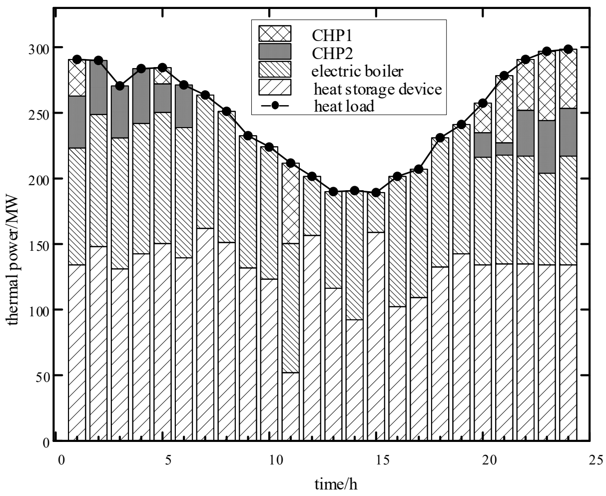

Figure 6. Heat power scheduling value of each unit

Electric boiler equipment mainly works during the period of 00:00-06:00 and 20:00-24:00. At this time, the demand for heat load is relatively large and the demand for electric load is relatively low; while the CHP unit supplies heat, the electric boiler will use excess heat. Wind power is converted into heat load and supplied to users. Figure 7 shows the heat storage and release power of the heat storage device. When the heat power is positive, it is a heat storage state; when the heat power is negative, it is a heat release state.

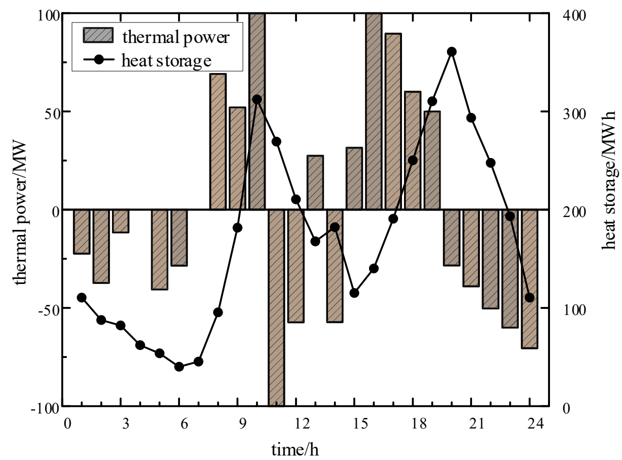

Figure 7. Heat storage power and exothermic power of thermal storage system

In Figure 7,the heat release process of the heat storage device is mainly concentrated in the time periods at night (00:00-02:00, 20:00-24:00) and noon (11:00-15:00). The electricity load demand is low, while the heat load demand is high. The heat storage device releases heat to meet the user's heating demand, reduce the electricity and heat output of the CHP unit, and increase the wind power output; (11:00-15:00) At this time, the heat load demand is low and the electrical load demand is high. At this time, the heat storage device releases heat, which can reduce the heat energy supply pressure of the CHP unit and increase its electrical load output. When the heat storage device releases heat, according to the actual energy demand on the load side, the power of the CHP unit will be converted between heat and electricity, so as to meet the purpose of the system load. The use of the heat storage device decouples the electro-thermal coupling relationship of the CHP unit and promotes the consumption of wind power.

The electric load curves before and after demand response optimization are shown in Figure 8.

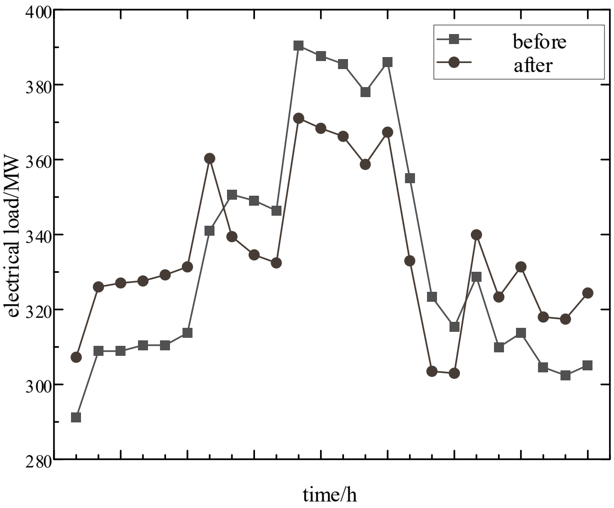

Figure 8. Electric load curve before and after optimization

Before the optimization, the peak-to-valley difference of the original load curve was large. After the optimization, the peak-to-valley difference of the electrical load was significantly reduced, and the load curve was smoother. The overall optimization effect is obvious, which reduces the load conflict of the system, reduces the energy consumption pressure, and effectively promotes the consumption of wind power. Therefore, the scheduling model in this paper can maximize resource utilization and effectively reduce the operating cost of the system.

5. Conclusion

In this paper, in the combined heat and power system with electric boiler and heat storage device, an optimal dispatch model considering carbon transaction cost and demand response is constructed, and the feasibility of the proposed model is verified by simulation solution, and the following conclusions are drawn:

1) In the combined wind power and heat system considering carbon transaction costs and demand response, carbon emissions are reduced by 2211t, wind power is completely absorbed, and the utilization rate of wind power is improved.

2) Reasonable selection of carbon trading price can maximize wind power consumption and improve the low-carbon economic operation capacity of the system.

3) Reasonable implementation of the peak-valley time-of-use price according to the user's load demand can achieve reasonable dispatch and allocation of energy, maximize resource utilization, and effectively reduce the operating cost of the system.

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