Optimal Operation of CHP Units and Thermal Storage Electric Heating Considering Wind Power Consumption

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Abstract In the background of "dual carbon," as the scale of wind turbines connected to the grid becomes larger, the grid needs to improve the capacity of wind power consumption. At the same time, considering the weak peaking capacity of combined heat and power (CHP) units during the winter heating period in northern regions due to the problem of "heat-determined electricity," a large amount of abandoned wind is generated. In order to limit the wind abandonment and carbon emission, this paper introduces the wind abandonment penalty and carbon trading mechanism and establishes the system operation model with the optimal system operation cost.

Keywords Regenerative electric heating · CHP unit · Wind power consumption · Carbon trading scheme

1 Introduction

Wind power generation belongs to clean energy [1, 2]. Due to its advantages of wide distribution and renewable, the scale of wind turbines connected to the power grid has been increasing [3]. At the same time, due to the large thermal load at night during the heating period in the north, the problem of "fixing power by heat" exists in the thermoelectric units [4], which results in the compression of wind power consumption space in the low period at night. Therefore, it is of great significance to improve the operating characteristics of CHP units, realize thermoelectric decoupling, and reduce the wind abandonment and carbon emission of power system [5].

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At present, a large number of scholars have carried out research on the consumption of heating and wind power. In terms of wind power consumption, the literature [6] considers the factor of peak regulation period in the wind power model to increase the local consumption capacity of wind power. The literature [7] considers the wind power factor in the peak-regulating right trading model and proposes a power market model involving wind power to further promote the consumption of wind power. The literature [8, 9] established a heat storage system model, introduced control links to adjust energy storage, and improved the consumption rate of wind power. In terms of improving unit characteristics, the literature [10] improves the problem of "fixing power by heat" by adding heat storage device on the far side and improves the wind abandon absorption by guiding the system on the load side through time-of-use electricity price. The literature [11] established a system model including CHP unit and electric boiler and established a linear model of electric heating characteristics. In terms of regenerative electric heating operation, the literature [12] uses electric boilers to increase the power load of the system and improve the Internet space of wind power. The literature [13] proposes to install regenerative electric heating at the end of the power grid to make use of wind power abandonment. The literature [14] dynamically simulates the heating process of the regenerative device and establishes the relationship between energy utilization rate and heat release of the regenerative device, which is conducive to the establishment of the mathematical model of regenerative electric heating.

Most of the current studies only consider the role of CHP units, heat storage units, and electric boilers in absorbing wind power, rarely consider the combined operation of CHP units and regenerative electric heating, and do not consider the impact of carbon emission mechanism and wind abandonment penalty on system operation. Therefore, this paper establishes a joint optimization operation model of CHP units and regenerative electric heating, which considers carbon trading mechanism [15] and wind abandonment penalty, which can effectively improve the wind power consumption while reducing the system operation cost. The feasibility and superiority of the proposed model are verified through the analysis of numerical examples.

2 CHP Unit and Regenerative Electric Heating Combined Operation System Structure

Wind turbines, coal-fired thermal power units, and CHP units can provide electric energy. While providing electric energy, CHP units use steam generated by turbogenerator to provide thermal power to users, which has a higher energy utilization rate than traditional thermal power units. As a clean energy, wind power generation can reduce carbon emissions of the system, but it has the characteristics of anti-peak regulation. The combined operation of wind power and regenerative electric heating can improve the stability of the power system.

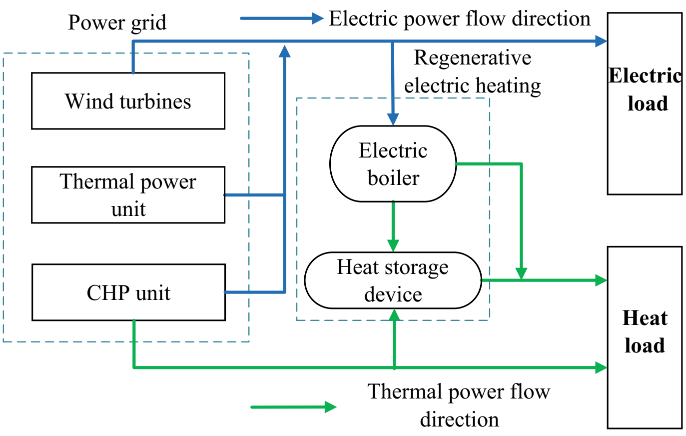

Fig. 1 System operation structure diagram

As a common regenerative electric heating equipment [16], regenerative electric boiler can be divided into two parts, namely direct heat electric boiler and regenerative device. The heat storage device stores heat in the off-peak hours and releases heat in the peak hours, which reduces the output of the CHP unit and improves the economic benefits of the system. As a kind of adjustable load, regenerative electric heating decouples the thermoelectricity produced by thermal power plant, which is conducive to peak regulation of power grid and heat network and improves the absorption rate of new energy. Based on the objective function of minimization of operation cost, this paper considers the wind abandoning penalty and carbon trading mechanism and considers environmental benefits while pursuing economic benefits. The combined operation system structure of CHP unit and regenerative electric heating considering wind power consumption is shown in Fig. 1.

3 Model of Electric-Thermal System Equipment

3.1 Model of Wind Turbine

Wind turbines convert captured wind energy into electricity, whose output power has reverse peak regulation and uncertainty. The output power of the wind turbine is related to the wind speed, as shown in Eq. (1).

$$P_{\mathrm{WT}}(t) = \begin{cases} 0 & , v(t) < v_{\mathrm{CI}} \text{ or } v(t) > v_{\mathrm{CO}} \\ P_{\mathrm{R}} \frac{v(t) - v_{\mathrm{CI}}}{v_{\mathrm{R}} - v_{\mathrm{CI}}} & , v_{\mathrm{CI}} \le v(t) < v_{\mathrm{R}} \\ P_{\mathrm{R}} & , v_{\mathrm{R}} \le v(t) < v_{\mathrm{CO}} \end{cases} \tag{1}$$

Here, P_R is the rated output power of wind power; $P_{WT}(t)$ and $v(t)$ are, respectively, wind power output and wind speed at time t; v_{CI}, v_{CO}, and v_R are, respectively, the wind speed in time t, cut out wind speed, and rated wind speed.

Existing studies show that wind speed follows Weibull distribution [17], and its probability distribution is as follows:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

Here, k and c are shape and scale parameters of Weibull distribution, respectively.

3.2 Thermal Power Unit

In this paper, the coal-burning pure condensing unit is used, and its operation mode is steam Rankine cycle. Only electrical power is output during unit operation. The generation cost of thermal power F_G includes the generation fuel cost F_{G1} and start–stop cost F_{G2}, as shown in Formula (3).

$$F_G = F_{G1} + F_{G2} \tag{3}$$

In the formula, the formulas of F_{G1} and F_{G2} are shown in Formula (4) and Formula (5), respectively. Among them, the power generation fuel cost of thermal power unit is expressed in the quadratic form of its power generation, and the formula is shown in Eq. (4).

$$F_{G1} = \sum_{t=1}^{T}\sum_{i=1}^{N}\left(a_i P_{G,i,t}^2 + b_i P_{G,i,t} + c_i\right) \tag{4}$$

Here, F_G is the power generation cost of thermal power unit; T and N, respectively, represent the total operation period and the number of thermal power units in operation. $P_{G,i,t}$ is the output power of the i-th thermal power unit at time t; a_i, b_i, and c_i is the generation cost coefficient of thermal power unit.

$$F_{G2} = \sum_{t=1}^{T}\sum_{i=1}^{N}\left[u_{i,t}\left(1 - u_{i,t}\right)C_i\right] \tag{5}$$

Here, $u_{i,t}$ is the start–stop state of the i-th thermal power unit at time t; C_i is the start–stop cost of the i-th thermal power unit.

3.3 CHP Unit

The thermoelectric ratio of the backpressure CHP unit is fixed, and the electrical output is fixed after the heat load is determined. Compared with the back pressure CHP unit, the extraction steam CHP unit uses steam as the heat source and determines the amount of steam extracted according to the need of heat production. The thermoelectric ratio can be adjusted, and the system has better flexibility. Therefore, in this paper, the extraction CHP unit is used, and its operating characteristics are shown in Fig. 2.

In order to ensure the thermal load demand of the extraction CHP unit, it is not necessary to consider the start–stop cost of the unit. The fuel cost of the CHP unit is shown in Formula (6).

$$F_C = \sum_{t=1}^{T}\sum_{i=1}^{K}\left(a_{i,0}P_{e,i,t}^2 + b_{i,0}P_{e,i,t} + c_{i,0}P_{h,i,t}P_{e,i,t} + d_{i,0}P_{h,i,t}^2 + e_{i,0}P_{h,i,t} + f_{i,0}\right) \tag{6}$$

Here, K is the total number of CHP units; $a_{i,0}$, $b_{i,0}$, $c_{i,0}$, $d_{i,0}$, $e_{i,0}$, and $f_{i,0}$ is the coal consumption coefficient of CHP; $P_{e,i,t}$ and $P_{h,i,t}$, respectively, represent the generating power and heating power at time t of extraction type CHP unit *i*.

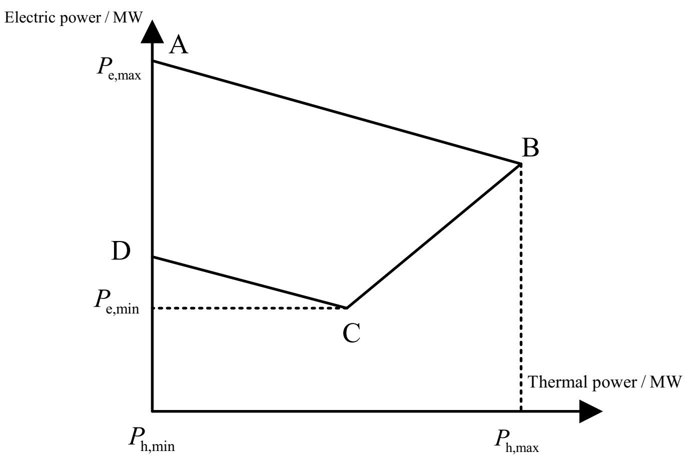

Fig. 2 Thermoelectric relationship of extraction CHP unit

3.4 Regenerative Electric Heating

Despite the randomness of wind power, wind power output is generally large at night, when the grid is in the trough period, resulting in the phenomenon of wind curtailment. Regenerative electric heating uses the "wind curtailment" electricity at night to store the heat generated and release it in the daytime peak hours, which not only improves the economic benefits of the system, but also further expands the consumption space of wind power. In this paper, regenerative electric heating mainly refers to regenerative electric boiler, including electric boiler and heat storage device.

Electric Boiler. The electric boiler provides heat supply through electric power, which is safe and reliable in operation. Its energy conversion efficiency is high, and the energy loss is reduced. At the same time, compared with coal-fired heating, electric boilers have better environmental benefits. The output of CHP units can be further reduced and coal consumption reduced by using wind abandoned electricity for heating at night by electric boilers. The mathematical model of the electric boiler is shown in Eq. (7).

$$P_{h,\mathrm{EB},t} = \eta_{\mathrm{EB}} P_{\mathrm{EB},t} \tag{7}$$

Here, η_{EB} is the thermoelectric conversion efficiency of electric boiler; $P_{h,\mathrm{EB},t}$ and $P_{\mathrm{EB},t}$ are, respectively, the output thermal power and input electric power of the electric boiler at time t.

Heat Storage Device. The electric boiler with heat storage device has a stronger capacity of heating regulation, which breaks the mode of "fixing electricity by heat" and plays the role of thermoelectric decoupling. According to the different ways of heat storage, the regenerative electric heating can be divided into water heat storage, solid heat storage, and phase change heat storage. The mathematical model of the heat storage device can be expressed in Eq. (8).

$$S_{\mathrm{H},t} = (1-\delta)S_{\mathrm{H},t-1}\left(P_{h,\mathrm{H_{in}},t}\eta_{\mathrm{H_{in}},t} - \frac{P_{h,\mathrm{H_{out}},t}}{\eta_{\mathrm{H_{out}},t}}\right)\Delta t \tag{8}$$

Here, $S_{\mathrm{H},t}$ is heat storage capacity at time t; δ is heat dissipation loss rate; $P_{h,\mathrm{H_{out}},t}$ and $P_{h,\mathrm{H_{in}},t}$ are the heat release and heat storage power of the heat storage device at time t, respectively; $\eta_{\mathrm{H_{out}},t}$ and $\eta_{\mathrm{H_{in}},t}$ are, respectively, the heat release and heat storage efficiency of the heat storage device at time t.

4 The Optimal Operation Model of Regenerative Electric Heating and CHP Unit Considering Wind Power Consumption

4.1 Objective Function

In this paper, a joint optimization system of CHP unit and regenerative electric heating is proposed to improve the thermoelectric decoupling capacity of the system, and wind abandonment penalty is considered to further increase the consumption rate of wind power. At the same time, the carbon trading mechanism has been introduced to limit the coal consumption of CHP units and thermal power units, which is conducive to increasing the output of regenerative electric heating and reducing carbon emissions. In this paper, the minimum operation cost of the system is taken as the objective function, that is, the optimal economy of the system operation. The objective function is shown in Eq. (9).

$$F = \min\left(F_G + F_C + F_{\text{wind}} + F_{\text{co}_2}\right) \tag{9}$$

Here, F_{G} is the operating cost of thermal power unit, as shown in Eq. (3); F_C is the operating cost of CHP unit, as shown in Eq. (6); F_{wind} and F_{CO_2} are wind curtailment penalty cost and carbon trading cost, respectively.

(1) Abandon wind punishment

In addition to economy, the goal of system operation should be to reduce air abandonment volume. Therefore, this paper considers the penalty cost of wind abandonment, which is shown in Eq. (10).

$$F_{\text{wind}} = \sum_{j=1}^{M}\sum_{t=1}^{T}\alpha_j\left(P_{\text{SW},t,j} - P_{\text{W},t,j}\right) \tag{10}$$

Here, α_j is the unit wind abandon cost of wind turbine *j*; $P_{\text{SW},t,j}$ and $P_{\text{W},t,j}$ are the predicted power and generating power at time *t* of wind turbine *j*, respectively.

(2) Carbon emission cost

The carbon emissions of the model proposed in this paper mainly come from thermal power units and CHP units, and the carbon emission allocation of the system at time t is shown in Eq. (11).

$$E^* = \beta_{\text{e}}^*\left(\sum_{t=1}^{T}\sum_{i=1}^{N}P_{\text{G},i,t} + \sum_{t=1}^{T}\sum_{i=1}^{K}P_{e,i,t}\right) \tag{11}$$

Here, E^* is the system's free carbon emission quota; β_{e}^* is the free carbon quota per unit of electricity.

The calculation method of actual carbon emission E_a is basically consistent with Eq. (11), but different in the value of carbon emission coefficient. Carbon trading costs are shown in Eq. (12).

$$F_{co_2} = k_C(E_a - E^*) \tag{12}$$

Here, k_C is the price of carbon trading market.

4.2 Constraints

The normal operation of the system also needs to meet the electrical balance, thermal balance, and operation constraints of each unit and equipment.

(1) Electrical equilibrium constraint

$$\sum_{i=1}^{N} P_{G,i,t} + \sum_{i=1}^{K} P_{e,i,t} + \sum_{j=1}^{M} P_{W,t,j} = P_{e,\text{Load},t} + P_{\text{EB},t} \tag{13}$$

Here, $P_{e,\text{Load},t}$ is the electric load at time t.

(2) Thermal equilibrium constraint

$$\sum_{i=1}^{K} P_{h,i,t} + P_{h,\text{Hout},t} + P_{h,\text{EB},t} = P_{h,\text{Load},t} \tag{14}$$

Here, $P_{h,\text{Load},t}$ is the heat load at time t.

(3) Constraints on thermal power units

The upper and lower limits of unit output are shown in Eq. (15).

$$P_{G,i}^{\min} \le P_{G,i,t} \le P_{G,i}^{\max} \tag{15}$$

The upper and lower limits of unit output are shown in Eq. (16).

$$-\Delta r_{i,\text{ down}} \le P_{G,i,t} - P_{G,i,t-1} \le \Delta r_{i,\text{ up}} \tag{16}$$

Here, $P_{G,i}^{\max}$ and $P_{G,i}^{\min}$ are the maximum and minimum output values of thermal power unit *i*, respectively; $\Delta r_{i,\text{ up}}$ and $\Delta r_{i,\text{ down}}$ are climbing and downclimbing restrictions of thermal power unit *i*, respectively. The output and climb limits of CHP units are similar to those of thermal power units.

(4) Constraints on wind turbines

$$0 \leq P_{\mathrm{W},t,j} \leq P_{\mathrm{W},j}^{\max} \tag{17}$$

Here, $P_{\mathrm{W},j}^{\max}$ is the upper limit of j output of wind turbine.

(5) Constraints of regenerative electric boiler

The constraint of electric boiler is shown in Eq. (18).

$$0 \leq P_{\mathrm{EB},t} \leq P_{\mathrm{EB}}^{\max} \tag{18}$$

Here, $P_{\mathrm{EB}}^{\max}$ is the maximum electric power of the electric boiler at time t.

The constraints of the heat storage device are shown in Eq. (19).

$$\begin{cases} S_{\mathrm{H,\,min}} \leq S_{\mathrm{H},t} \leq S_{\mathrm{H,\,max}} \\ 0 \leq P_{h,\mathrm{H_{in}},t} \leq \eta_{\mathrm{H_{in}},t} S_{\mathrm{H,n}} \\ 0 \leq P_{h,\mathrm{H_{out}},t} \leq \eta_{\mathrm{H_{out}},t} S_{\mathrm{H,n}} \\ P_{h,\mathrm{H_{in}},t} P_{h,\mathrm{H_{out}},t} = 0 \end{cases} \tag{19}$$

Here, $S_{\mathrm{H,\,min}}$ and $S_{\mathrm{H,\,max}}$ are divided into the minimum and maximum capacities of the heat storage device in normal operation; $S_{\mathrm{H,n}}$ is the rated capacity of the heat storage device.

5 Example Analysis

5.1 Basic Data

In this paper, the winter heating in a northern region is taken as the background. The system is equipped with six pumping steam CHP units and three thermal power units. Among them, the rated electric power of the CHP unit is 300 MW and the rated heating power is 400 MW. The other specific parameters are detailed in the reference [18]. In this paper, day-ahead scheduling is used, with a scheduling cycle of 24 h and a unit scheduling time of 1 h. The parameters of regenerative electric heating are shown in Table 1, and the real-time electricity price is shown in Table 2.

Table 1 Regenerative electric heating parameters

Device attribute	Parameter
Heating power/MW	40
Heat storage/GJ	550
Maximum heat storage temperature/°C	750
Thermal efficiency	95%

Table 2 Real-time tariff

Time	Time period	Electricity price/yuan/kWh
8:00–11:00 18:00–21:00	Peak load period	0.699
7:00–8:00 11:00–18:00	Medium load period	0.548
21:00–7:00	Low load period	0.279

In order to integrate operation cost, wind power consumption, and carbon trading cost, four operation optimization scenarios are proposed in this paper.

Scenario 1: Without carbon trading mechanism, only CHP unit heating is considered, not regenerative electric heating.

Scenario 2: The thermal power output of the CHP unit and the electric boiler meets the thermal load without considering the carbon trading scheme.

Scenario 3: Without considering the carbon trading mechanism, add the heat storage device, and the combined thermal power output of the CHP unit and the regenerative electric heating meets the heat load.

Scenario 4: The model proposed in this paper is adopted, that is, the carbon trading mechanism is taken into account, and the heat load is borne by the joint operation of the CHP unit and the regenerative electric heating.

5.2 *Calculation Result*

In this paper, the YALMIP toolbox of MATLAB is used to compile and call the solver GUROBI, and the running results under different scenarios are shown in Table 3.

Table 3 shows the results of four optimized operation scenarios. Scenario 2 considers the output of electric boiler on the basis of scenario 1, which can reduce the nighttime output of CHP units, increase the nighttime electrical load demand, and improve the wind power consumption rate. Therefore, scenario 2 has better operating costs and curtailment rate than scenario 1. Scenario 3 adds a heat storage device based on Scenario 2. Compared with the reduction of operating cost and curtailment

Table 3 Optimize the comparison of run scenario results

Running scenario	Wind power consumption / MWh	Carbon trading cost/Ten thousand yuan	Running cost/Ten thousand yuan	Wind abandonment rate/%
1	98.20	0	103.29	84.89
2	186.21	0	92.36	71.35
3	411.23	0	71.21	36.73
4	554.29	2.54	55.40	14.72

rate in scenario 2 and scenario 1, the reduction rate of operating cost in scenario 3 is larger. The reason is that the addition of a heat storage device can not only reduce the output of CHP units at night, but also further reduce the output of CHP units by heat release in the daytime. Due to the existence of peak-valley electricity price, the electricity consumption in the daytime peak hours is reduced, while the consumption of electricity and wind power in the night trough hours is increased, and the operation cost is greatly reduced.

Scenario 4 adds a carbon trading mechanism on the basis of Scenario 3. Although the carbon trading cost of 25,400 yuan is generated, the overall operating cost decreases. After considering the carbon trading mechanism, the system still takes the minimum operation cost as the objective function, so it needs to reduce carbon emissions and reduce the cost of the carbon trading mechanism. Therefore, the system needs to increase the output of regenerative electric heating to reduce the thermal power output of CHP units, so as to reduce the coal consumption of the system. Scenario 4 increases the output of the heat storage device while reducing carbon emissions and further reduces the wind abandonment rate and reduces the cost of wind abandonment by using the characteristics of "peak cutting and valley filling" of regenerative electric heating. Figures 3, 4, 5 and 6 shows the thermal power balance of each scenario.

Figures 3, 4, 5 and 6 shows the comparative analysis of the treatment of CHP units in four scenarios. As can be seen from Fig. 3, when there is no regenerative electric heating involved in heating, the output of CHP units reaches its trough between 8:00 and 17:00 in a day, and the output of CHP units at night is higher. In Fig. 4, electric boiler is added on the basis of CHP unit heating, but CHP unit still maintains

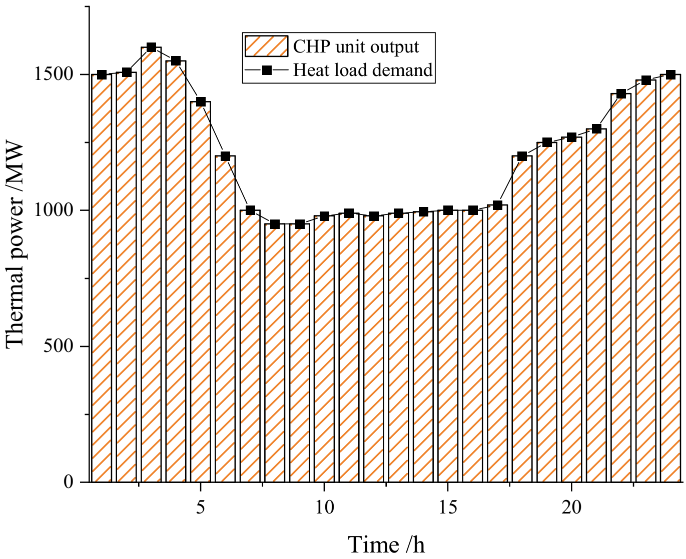

Fig. 3 Thermal power balance diagram for scenario 1

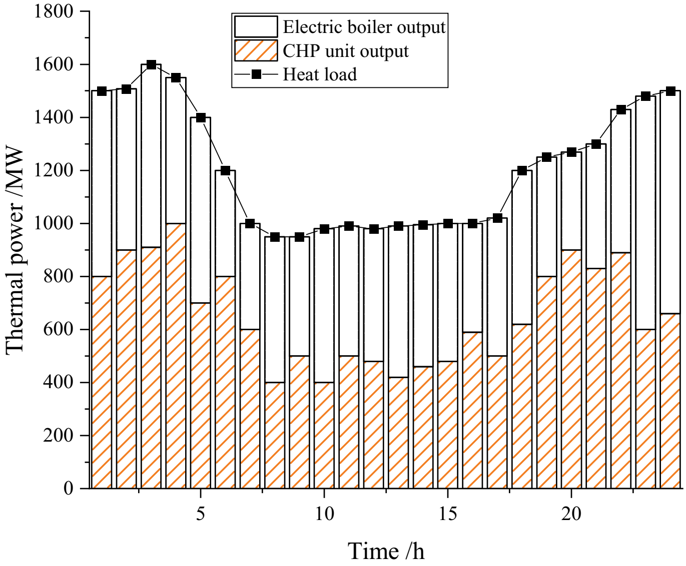

Fig. 4 Thermal power balance diagram for scenario 2

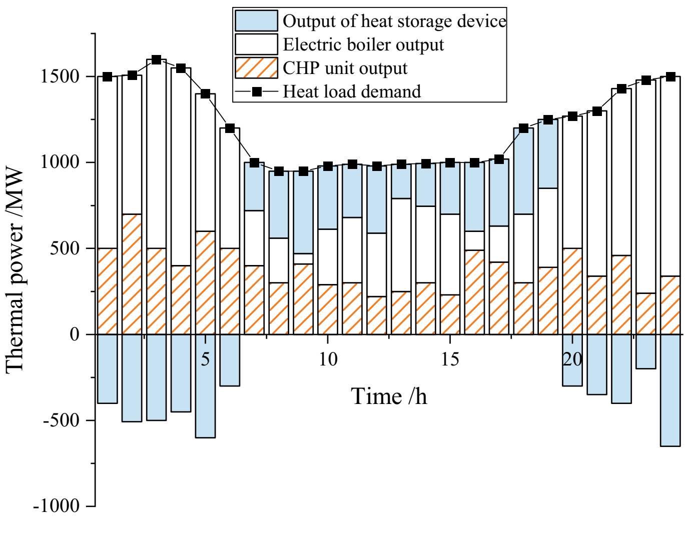

Fig. 5 Thermal power balance diagram for scenario 3

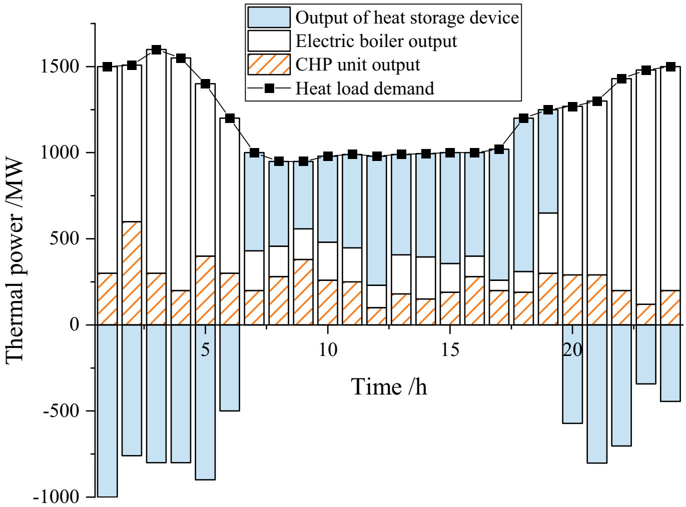

Fig. 6 Thermal power balance diagram for scenario 4

high output; In Fig. 5, a heat storage device is added on the basis of scenario 2, which effectively reduces the output of CHP units and correspondingly reduces the wind power discard volume. In Fig. 6, the carbon trading mechanism is added, which further increases the output proportion of the heat storage device and further increases the wind power grid space. Compared with the scenario without the implicit heat device, the wind abandonment situation is significantly improved.

6 Conclusion

As more wind turbines are connected to the grid, the problem of wind curtailment is exacerbated by the “heat-to-power” problem of CHP units in the north. This paper presents a combined operation model of CHP unit and regenerative electric heating considering wind power absorption. On this basis, the carbon emission and air abandonment volume are further restricted by introducing the wind abandonment penalty and carbon trading mechanism and verified by simulation examples. The analysis of numerical examples shows that.

(1) The combined operation system of wind turbine, CHP unit, and regenerative electric heating can greatly reduce the wind abandonment rate and increase the wind power consumption. At the same time, the regenerative electric heating can play the role of “peak cutting and valley filling” and reduce the operating cost of the system.

(2) Through the introduction of carbon trading mechanism, the output power of CHP units can be reduced while the output of regenerative electric heating is increased, which can reduce the coal consumption of the system and improve the economic benefits of the system.

The combined operation model considering wind power consumption and carbon trading mechanism proposed in this paper can well guarantee the economic and environmental benefits of the system, which is conducive to the "thermoelectric decoupling" of CHP units in northern China, and further improve the wind power consumption capacity of the power system.

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