A Scheduling Model for Wind Power Consumption Considering Source-Charge Coordination of Combined Heat and Power System in Low-Carbon Environment

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Abstract. Increasing the penetration and consumption rate of new energy sources will help reduce or control carbon dioxide emissions and better promote green and low-carbon development. Based on the establishment of deep peak-load regulation model of pure condensing thermal power units, the model for the expansion of combined heat and power plant adjustment range, interruptible electro-thermal flexible load model and combined heat and power units carbon emission model, this paper introduces a quota-based carbon emission trading mechanism and constructs a source-load coordination scheduling model of combined heat and power system that considers the characteristics of heating network and aims at minimizing the total cost of units operation and carbon emission trading. The total coal consumption and wind curtailment absorption effect in three cases are compared by cases study. The outcomes display that the model in this paper can coordinate the scheduling resources on both sides of source and load, further diminish the total coal consumption and improve wind power consumption capacity based on improving the flexibility of source and load side, and achieve wind power consumption in low-carbon environment.

1. Introduction
In the face of global climate change, reducing carbon dioxide emissions has become a top priority for all countries in the world. Developing new energy sources and reducing the coal consumption of traditional thermal power are effective methods. However, wind curtailment problem becomes more and more prominent in the northern China. The main reasons for the serious problem in the northern region are the constraint of "Power Determined by Heat" of combined heat and power (CHP) units and peak-load regulation range limitation. For the reasons, Reference [1] proposes a deep peak-load regulation model for thermal power units. Reference [2] considers the heat storage feature of the heating network. In [3], the demand response is introduced to take part in active peak-load regulation based on adding heat storage devices on the source side.

The above references do not take into account the carbon emissions. With the implementation of the national energy-saving scheduling policy, low-carbon has become one of the core indexes concerned by enterprises. In many models involving carbon emissions trading, most of them are only concentrated in power system [4-5]. Although the models of the CHP system in low-carbon environment are constructed in [6], the effects of heating network characteristics are not taken into account, and ignore the influence of CHP units on the total carbon emissions.

In view of the above research, this paper establishes the deep peak-load regulation model of pure condensing thermal power units, the model for the expansion of CHP plant adjustment range,
interruptible electro-thermal flexible load model, and introduces the carbon emission trading model of thermal power units and CHP units based on quota. Then the paper establishes the source-load coordination scheduling model of CHP system in consideration of the features of heating network with the purpose of minimizing the total cost of units operation and carbon emission trading. Finally, the simulation analyses of three cases reveal that the proposed model can further decrease the overall coal consumption and wind curtailment rate on the basis of improving the flexibility of on both sides of source and load, and improve the wind power absorption level of the CHP system.

2. Source-load model of CHP system

2.1. Deep peak-load regulation model
Deep peak-load regulation reconstruction of thermal power units can improve source side flexibility, and the process can be divided into three stages: basic peak-load regulation, non-oil steady state combustion deep peak-load regulation and oil-assisted combustion deep peak-load regulation [7].

At basic peak-load regulation stage, only the coal consumption of units should be considered.

\[
C_{\text{OP}} = p_{\text{coal}} \left(a_0 + a_1 P + a_2 P^2\right)
\]

Where: \(C_{\text{OP}}\) is the coal consumption cost (Yuan); \(p_{\text{coal}}\) is the coal price (Yuan/t); \(a_0\), \(a_1\), and \(a_2\) are coefficients of thermal power unit consumption characteristic; \(P\) is generation power (MW).

With the increase of peak-load regulation depth, the rotor loss increases during the non-oil steady state combustion period and the service life decreases [8]. Moreover, oil is required to support burning during the oil-assisted combustion period. Therefore, the operation cost \(C_{\text{CON}}\) (Yuan) of deep peak-load regulation at different stages can be indicated by the piecewise function in [9].

For the sake of enhancing the passion for deep peak-load regulation, the units participating in the deep peak-load regulation should be given subsidy, which can be expressed by Equation (2). Moreover, the subsidy shall be shared by thermal power units that are not referred to deep peak-load regulation and wind turbines, and the sharing cost can be expressed as Equation (3).

\[
C_{\text{SUB}} = \begin{cases} 0, & P \geq P_{\text{min}} \\ p_{\text{SUB}} \left(P_{\text{min}} - P\right), & P < P_{\text{min}} \end{cases}
\]

Where: \(C_{\text{SUB}}\) is the deep peak-load regulation subsidy (Yuan); \(p_{\text{SUB}}\) is the subsidy price of the unit power below the minimum technical output (Yuan/(MW·h)); \(P_{\text{min}}\) is the lower power limit of thermal power unit (MW).

\[
C_{\text{SHARE}} = q_{\text{SHARE}} C_{\text{SUB}}
\]

Where: \(C_{\text{SHARE}}\) is the sharing cost (Yuan), and \(q_{\text{SHARE}}\) is the sharing ratio, which is determined by the ratio of rated capacity of the unit to total rated capacity of all the thermal power units that are not involved in deep peak-load regulation and wind power units.

2.2. Model for the expansion of CHP plant adjustment range
The coal consumption cost of a CHP unit can be calculated by Equation (4):

\[
C_{\text{CHP}} = p_{\text{coal}} \left(e_0 + e_1 P + e_2 D + e_3 P^2 + e_4 P D + e_5 D^2\right)
\]

Where: \(C_{\text{CHP}}\) is the coal consumption cost (Yuan); \(D\) is steam extraction rate for heating (t/h); \(e_0 \sim e_5\) are coefficients of consumption characteristic;

The relationship between steam extraction rate and heat output \(Q\) (GJ/h) of CHP unit is:

\[
Q = D \Delta H /1000
\]

Where: \(\Delta H\) is vapour enthalpy drop (kJ/kg).
The most economical scheme for expanding the regulation range of CHP unit is to configure thermal storage tanks in CHP plants. Heat storage tanks store heat during non-wind curtailment period while release heat in wind curtailment period. As shown in Figure 1, the interval ABCD is the original electro-thermal output regulation range of the CHP unit. After the thermal storage tank is installed, the range extended to the interval AA'B'C''D'. In addition, \( P^u \) and \( P^l \) are the upper and lower power limit of CHP unit (MW), respectively; \( D^u \) and \( D^l \) are the upper and lower steam extraction rate limit of CHP unit (t/h), respectively.

![Diagram](image)

Figure 1. Schematic diagram of expanding regulation range with thermal storage tanks.

Set the heat storage at the initial time is \( E_0 \) (MW·h), and the relationship between heat storage and heat storage or release power can be indicated by Equation (6):

\[
E_t = E_{t-1} + h'_t \tag{6}
\]

Where: \( E_t \) is the heat storage at time \( t \) (MW·h); \( h'_t \) is the heat storage or release power at time \( t \) (MW). This paper stipulates that the heat storage is positive and the heat release is negative.

The balance of heat storage and release should be satisfied in one cycle.

\[
\sum_{t \in T} h'_t = 0 \tag{7}
\]

Where: \( T \) is the total number of scheduling cycles (h).

2.3. Electro-thermal flexible load

Installation of electric boilers is one of the effective measures to consume wind curtailment. This paper assumes that the electric boilers are installed on the load side, and uses wind curtailment start-up and shut-down control [10]. The electric boilers work during the wind curtailment period, consuming power while heating, decreasing heat power of CHP units, and they are stop working during the non-wind curtailment period. Therefore, the electric boilers can be regarded as an electro-thermal flexible load that is interruptible and adjustable in size. The relationship between power \( P^e \) (MW) consumed by electric boiler and heat output \( Q^e \) (GJ/h) of electric boiler can be referred to [11].

Taking the power generation of the pure condensing units, the electro-thermal power of CHP units, and the power consumed by electric boilers as the optimization variables, which can make full use of the scheduling resources on both sides of the source and load, and realize the coordination of the source and load of the CHP system.

3. Heating network model

Heating network is partitioned into water supply network and return water network. The topological structure of thermal system is shown in Figure 2. \( T' \), \( T'' \) and \( T' \) are the supply, return and return mixing temperature of node, respectively. \( m \) is the pipeline flow. \( m^i \) is the node injection water flow.
Heat load

(8)

Equation: \( m^l_j = \frac{(Q^l_j - Q^l_i)}{C^p(T^i - T^j)} \)

Where: \( Q^l_j \) is the load at heat load node \( j \) (GJ/h) and \( C^p \) is specific heat capacity (kJ·kg\(^{-1}\)·K\(^{-1}\)).

The heat loss in the process of hot water transportation is [12]:

\[ \Delta Q_q = 2 \pi \lambda^d (T_j - T_0) l_j / \ln(D_j / d_j) \]

Where: \( T_j \) and \( \Delta Q_q \) are the temperature of medium (K) and heat loss (GJ/(m·h)) of the pipeline \( ij \), respectively. \( \lambda^d \) is the thermal conductivity of insulation layer of pipeline (GJ·m\(^{-1}\)·K\(^{-1}\)); \( T_0 \) is the surface temperature of insulation layer (K); \( l_j \), \( D_j \) and \( d_j \) are the length, external diameter and internal diameter of pipeline \( ij \) (m), respectively.

The time delay characteristic equation of the heating network is:

\[ \tau_q = \pi \rho l_j d_j^2 / 4m_q \]

Where: \( \tau_q \) is heat transmission time (h), and \( \rho \) is water density (kg/m\(^3\)).

4. Carbon emission trading model

A market model of global carbon emissions trading is a market based on quota, which determines transactions by the difference in size between actual emissions and quota-based emissions [13].

The cost of carbon emissions trading can be expressed as:

\[ C^{\text{carbon}} = \sum_{j=1}^{T} p^{\text{carbon}} (E^c_j - E^q_j) \]

Where: \( C^{\text{carbon}} \) is the total cost of carbon emissions trading (Yuan); \( p^{\text{carbon}} \) is the carbon transaction price (Yuan/t); \( E^c_j \) is the actual carbon emission of units at time \( t \) (t); \( E^q_j \) is the quota-based carbon emission of units at time \( t \) (t).

Because the output of CHP unit includes electric energy and heat energy, it is necessary to convert heat into equivalent electric quantity when calculating the carbon emissions of CHP units.

Among them, the actual carbon emissions of the units are:

\[ E^c_j = \sum_{j=1}^{N_i} \sigma_j P_{\text{CON},j} + \sum_{j=1}^{N_i} \sum_{n=1}^{N} \sigma_n (P_{\text{CHP},i,n} + Q_{\text{CHP},i,n} / 3.6 \beta) \]

Where: \( \sigma_j \) and \( \sigma_n \) are the carbon emission intensity of thermal power unit and CHP unit, respectively (t/MW·h); \( P_{\text{CON},j} \) is the power of thermal power unit \( j \) at time \( t \) (MW); \( S \) is the total number of thermal power units; \( N_i \) is the total number of CHP units in CHP plant \( i \); \( P_{\text{CHP},i,n} \) and \( Q_{\text{CHP},i,n} \) are the power (MW) and heat power (GJ/h) of CHP unit \( n \) in CHP plant \( i \) at time \( t \), respectively; \( \beta \) is thermo-electric ratio; \( R \) is the number of CHP plants.
The carbon emission quota amount of units can be expressed as:

\[
E_i^q = q \left[ \sum_{j=1}^{N} P_{CON}^{j} + \sum_{n=1}^{N} \sum_{j=1}^{M} \left( P_{CHP}^{j,n} + Q_{CHP}^{j,n} / 3.6 \beta \right) \right]
\]

Where: \( q \) is the power carbon emission quota (t/MW·h), which is determined by the "regional grid baseline emission factor".

5. Scheduling model of CHP system

5.1. Objective function

The goal is to minimize the overall operating cost and carbon emission transaction cost of all units. Furthermore, the operating cost of pure condensing thermal power units includes not only the basic coal consumption cost, but also the subsidy and the allocation cost of units.

\[
\min F = \sum_{j=1}^{J} \left[ \sum_{i=1}^{I} \sum_{n=1}^{N} C_{CON}^{i,j} + \sum_{i=1}^{I} \left( C_{SUB}^{i,j} + C_{SHARE}^{i,j} \right) \right] + C_{carbon}
\]

Where: \( F \) is the total cost (Yuan).

5.2. Constraints

Power balance constraints, district heat balance constraints, unit ramping constrains, upper and lower limits of unit output constraints, electric boiler capacity constrains, thermal storage tanks capacity constraints and heat storage or release power constraints are all calculated according to [14].

Heat output of heat source nodes constraints can be expressed as:

\[
Q_{CHP}^{j,n} - \sum_{n=1}^{M} 3.6 h_{i,n} = C_{j}^{CHP} m_{j}^{CHP} (T_{s}^{CHP} - T_{r}^{CHP})
\]

Where: \( Q_{CHP}^{j,n} \), \( T_{s}^{CHP} \) and \( T_{r}^{CHP} \) are the heat output (GJ/h), the supply temperature (K) and the return temperature (K) of the heat source node \( j \) at period \( t \), respectively; \( m_{j}^{CHP} \) is the flow of the heat source node \( j \) (10^6 kg/h); \( M \) is the total number of thermal storage tanks.

6. Case study

6.1. Case system

The case system composes of two thermal power plants, two CHP plants and one wind farm. Each thermal power plant contains three pure condensing thermal power units. The CHP plant 1 and 2 are equipped with three and four CHP units respectively. The installed capacity of the wind farm is 400 MW. Each CHP plant has three thermal storage tanks and three heat-exchanger stations. Assuming that only one thermal power unit in each thermal power plant takes part in the deep peak-load regulation transformation. The carbon emission intensity of each unit is shown in Table A1. Other parameters involved in the model are shown in Table A2. Take one day as a scheduling cycle and one hour as a scheduling period. Heating network structure and the parameters of pipeline are shown in [14]. The consumption characteristics coefficients, operation parameters of each unit, electric boiler capacity, power load data, heat load data and wind power prediction data are all mentioned in [15].

6.2. Study of wind power absorption effect

In this paper, the following three cases are simulated and researched.

Case 1: Consider only source-load coordination
Case 2: Source-load coordination considering carbon emissions
Case 3: Source-load coordination considering carbon emissions and heating network characteristics

Total coal consumption and wind curtailment rate in three cases are shown in Table 1. Figure 3 is the curve of power of thermal power plant, power consumption of electric boiler and capacity of thermal storage tanks in case 1. The heat output curves of three cases are illustrated in Figure 4. Figure
Case 1

Comparing the data of case 1 and case 2 in Table 1, we can see that the total coal consumption decreases and wind curtailment rate decreases slightly after the introduction of carbon emission transaction cost into the objective function, while wind curtailment rate of case 3 decreases greatly when the characteristics of the heating network are considered in the model. Combining with Figure 4, it can be seen that the heat output of the CHP unit decreases greatly in case 3, which further reduces the total coal consumption.

From Figure 3 and Figure 4, it can be pointed out that the deep peak-load regulation in case 1 makes the power of thermal power plant relatively low. Moreover, during the wind curtailment period, the thermal storage tank releases heat and the electric boiler works; during the non-wind curtailment period, the thermal storage tank stores heat and the electric boiler shuts down, which reduces the heat output of CHP plants. Therefore, source-load coordination can improve the flexibility of the system, thereby enhancing the wind power absorption ability.

Furthermore, comparing the heat output curves of the CHP plants in case 2 and case 3 in Figure 4, it can be seen that under the influence of the time delay characteristics, the curve of case 3 is shifted to the left, and when the model takes into account the characteristics of heating network, the heat output of the CHP plant decreases dramatically, which further enlarges the space for wind power into grid. Therefore, the model in this paper can further improve the wind power absorption rate and alleviate the peak-load regulation pressure of grid more effectively.

Since the carbon emission trading mechanism of thermal power units and CHP units is considered in case 2, the system will give priority to reducing the output of units with higher carbon emission intensity and increase the output of units with lower carbon emission intensity, in order to attain the goal of low-carbon. Therefore, in Figure 5 and Figure 6, it is clear that the power of thermal power unit 3-1 (\(\sigma_{3,1} = 1.20\) t/MW·h) and CHP unit 1-1 (\(\sigma_{1,1} = 1.20\) t/MW·h) decrease significantly, while the power of thermal power unit 4-3 (\(\sigma_{4,3} = 0.42\) t/MW·h) and CHP unit 2-3 (\(\sigma_{2,3} = 0.42\) t/MW·h) increase slightly.

### Table 1. Total coal consumption and wind curtailment rate in each case.

| case     | Total coal consumption (t) | Wind curtailment rate |
|----------|---------------------------|-----------------------|
| case 1   | 14938.12915              | 4.620%                |
| case 2   | 14912.27582              | 4.619%                |
| case 3   | 14392.04154              | 2.306%                |

Figure 3. Power of thermal power plants, power consumption of electric boilers and thermal storage tanks capacity in case 1.

Figure 4. Heat output of CHP plants in 3 cases.
Moreover, the (MW)

7. Conclusions
A dispatch model for wind power consumption considering source-charge coordination of CHP system in low-carbon environment is proposed in this paper. With the introduction of carbon emission transaction cost into the objective function, the output of units with higher carbon emission intensity decrease, and the total coal consumption of the system decreases accordingly. Moreover, the characteristics of heating network make the heat output curve of CHP units shift, and the peak value of the heat output decreases. In addition, the simulation analyses of various cases shows that the model of this paper can further reduce the total coal consumption, improve the wind power consumption level based on improving the flexibility of the source-load side, and achieve wind power absorption in low-carbon environment.

8. Appendices

Table A1. Carbon emission intensity of each unit.

| Unit number | 1-1 | 1-2 | 1-3 | 2-1 | 2-2 | 2-3 | 2-4 | 3-1 | 3-2 | 3-3 | 4-1 | 4-2 | 4-3 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( \sigma_n/\sigma_j \) | 1.2 | 0.9 | 1.1 | 1.2 | 0.9 | 0.4 | 0.5 | 1.2 | 0.9 | 1.1 | 0.4 | 0.9 | 0.4 |
| (t/MW·h)    | 0   | 6   | 2   | 0   | 8   | 2   | 0   | 0   | 6   | 2   | 0   | 8   | 2   |

Table A2. Other parameters.

| Parameter | \( \Delta H \) | \( p_{\text{coal}} \) | \( p_{\text{NU}} \) | \( C^\rho \) | \( \rho \) | \( p_{\text{carbon}} \) | \( \beta \) | \( q \) | \( E_0 \) |
|-----------|----------------|----------------|----------------|---------|-------|----------------|------|------|------|
| Value     | 2327.53        | 680            | 72             | 4.18    | 100   | 74.2           | 0.8  | 0.78 | 25   |

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