Research on the scheduling of unit operation mode for combined heat and power plants considering new energy consumption in heating season

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Abstract. China aims to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. The traditional coal power plants need to reduce their power load as much as possible to reduce CO₂ emissions and improve the consumption capacity of intermittent renewable energy. Nevertheless, in part of northern China, areas with a high proportion of combined heat and power (CHP) units in coal power, CHP units need to provide heat load during heating season so that the flexibility of power load adjustment for CHP units is restricted. The plant minimum operation mode model is proposed to excavate the plant-level lower boundary of power load. By analysing the heat-power coupling mechanism of each unit, under different unit commitments, the plant-level lower boundary of power load can be calculated through dispatch heat load reasonably. Then the scheduling scheme of optimal unit commitment for plant is obtained. The comparison of results with the actual operation of a case CHP plant shows that the consumption capacity of renewable energy can be increased by 1.92 billion kWh and the CO₂ emissions of the reference plant could be reduced by 52.5% under the scheduling scheme of optimal unit commitment during the heating season. The reduction of CO₂ emissions for the scheduling scheme of optimal unit commitment will remain more carbon allowance which can bring revenue from carbon trade market. The scheduling of unit operation mode provides a way of operation under the current policy and environmental background, how to depress the power load of CHP plants and reduce CO₂ emissions in heating season.

1. Introduction
Chinese power system is accelerating shift toward a new power system based on low-carbon and clean energy. The development of coal power will be strictly controlled. Traditional coal power needs to reduce generating capacity as much as possible to provide more capacity consumption for renewable energy and reduce carbon emissions. The long-term deployment of renewable energy in the future will require the flexibility of coal power to maintain stability and adjustment. The traditional coal power industries are facing great challenges and opportunities. Actually, the CHP generation can improve the energy efficiency for coal power [1, 2]. It is effective for CHP units to reduce the CO₂ and other emissions produced per kWh. These units need to run as long there is not enough alternative energy available. However, in the northern regions of China where CHP units account for a relatively high scales, CHP units need to provide heat load during heating season so that the flexibility of power load
adjustment of CHP units is restricted by the heat-power coupling mechanism [3]. It has affected the flexibility of scheduling for the grid in such region. The reduction of generating capacity for coal power while ensuring certain heat load is a matter of concern in the regions with high-proportion CHP units in coal power. For CHP plants, it is crucial to improve their own flexibility and comprehensive energy supply capacity, which can make them perform better under the current policy and market environment.

For a single CHP unit, despite the thermal electrolytic coupling modification [4], the adjustable range of a single unit is limited. Single unit is usually fragmented in the plant system which makes its full potential is not fully utilized [5]. The power and heat load should be dispatched in plant level for the units. From the perspective of the plant with multiple units, it is of practical significance to maximize the adjustable range of the power loads through the optimal dispatch of units’ heat loads to enhance the flexibility of power load supply [6].

Currently, intelligent algorithms have been widely applied to the load dispatch problems. P. Subbaraj et al [7] used an adaptive real-coded genetic algorithm to optimize combined heat and power economic dispatch, and it has some advantages over other methods in terms of solution quality, processing constraints and computation time. Zou et al [8] summarized a series of methods for economic dispatch of CHP and proposed an improved genetic algorithm, using a novel crossover and variational mechanism to solve the economic scheduling problem. Because of strong generality and operability, Genetic algorithm (GA) have received attention from electric power workers and started to be applied in the optimal load dispatch. In this paper, GA is used to find the heat load dispatch scheme of different unit commitments for CHP plants. Usually, the aim of optimization studies focuses on economic dispatch (ED) problems to improve overall economy.

Actually, the types and operating characteristics of each unit in a CHP plant are different [9]. There will be the optimal heat load dispatch scheme for different unit commitments under the certain heat load to maximize downward-adjustment range of the whole plant power load [10]. The scheduling of unit operation mode of CHP plants considering new energy consumption pay attention to the downward-adjustment range for the lower boundary of power load according to dispatching the heat load and determining unit commitment rationally during the heating season. It helps the grid dispatching department to obtain theoretical minimum power load level of CHP plants during the heating season and to make the optimal unit commitment dispatching scheme to meet the heat load for new energy consumption. It provides a way of operation under the current policy and environmental background, how to depress the power load and reduce CO₂ emissions for CHP plant in heating season.

In this paper, the heat-power coupling mechanism of each unit is analyzed through design data. The plant minimum operation mode model was established to excavate the lower boundary of power load of CHP plant. According to the heat-power coupling mechanism of each unit, under different unit commitments, the plant-level lower boundary of power load can be calculated through dispatching heat load reasonably. Considering new energy consumption, the scheduling scheme of optimal unit commitment can be determined under certain heat load. The model can reflect the capacity of a CHP plant to integrate increasing scale of intermittent renewable energy and form scheme of carbon reduction. In addition, the feasibility of implementing the scheduling of unit operation mode for CHP plant is analyzed focusing on the revenue of carbon trade.

2. Mechanism and model

2.1. Heat-power coupling mechanism of single unit

For single CHP unit, heat supply condition diagram of steam turbine shows the adjustable range of the unit in various operating conditions [11]. Heating supply condition figure of steam turbine shows the relationship among the main steam mass flow rate($m_0$), heating steam extraction mass flow rate($G$) and power generation($P$). The parameter of main steam mass flow is limited by the minimum inlet steam of low-pressure turbine (LPT). When two of the three parameters mentioned above ($m_0$, $G$, $P$) are known, the third parameter can be determined. $P$ is adjusted with the change of $G$. In Figure 1, the
diagonal lines 1~5 indicate the heating steam extraction lines, line 6 is the minimum inlet steam flow limit line for the LPT, horizontal line 7 is the maximum main steam flow limit line, and horizontal line 8 is the minimum main steam flow limit line.

Figure 1. Heating supply conditions. Figure 2. Heat-power coupling mechanism.

The power load range of unit can be determined by the allowable variation interval of \( m_0 \) at a certain \( G \). As can be seen from Figure 1, the range of power load is limited by the maximum/minimum \( m_0 \) and the minimum mass flow of inlet steam of the LPT (\( m_L \)). The power load range of unit can be determined by heating extraction steam and the steam flow constraint limits, so the upper and lower power load boundary points are obtained for fitting to get the lower boundary of power load (\( P_{\text{min}} \)) under corresponding \( G \) shown in Figure 2. \( P_{\text{min}} \) can be calculated by

\[
P_{\text{min}} = f_{\text{min}}(G) = \begin{cases} k_1 G + b_1, & \text{if } G < G_0 \\ k_2 G + b_2, & \text{if } G \geq G_0 \end{cases}
\]

where \( k_1 \) and \( b_1 \) are the slope and intercept of line AB in Figure 2, respectively; \( k_2 \) and \( b_2 \) are the slope and intercept of line BC in Figure 2, respectively; \( G_0 \) stands for critical heating extraction steam mass flow rate.

In Figure 2, the \( P_{\text{min}} \) decreases at first and then increases with the increase of \( G \). Since there is a minimum inlet steam flow of the LPT, which prevents the wall of the LPT from overheating. As the \( G \) increases, the \( m_L \) decreases, which reduces \( P \). When the \( m_L \) is reduced to the minimum, the \( m_0 \) needs to be increased accordingly to meet the heat supply requirements, which leads to an increase of \( P \).

Figure 3. Solving process of the model.
2.2. The plant minimum operation mode model
Due to the heat-power coupling mechanism of CHP units, the power load is determined by the unit’s heat load. Moreover, the heat-power coupling mechanism of each unit is somewhat different. Taking the whole CHP plant as a system, which have various types of units, there is an optimal heat load dispatch scheme. Figure 3 shows the specific steps. Under a certain heat load, all unit commitments which has the capability to afford the heat load can be obtained. $P_t$ will be calculated under all unit commitments. The lowest $P_t$ of the results and corresponding solution are the scheduling of unit operation mode considering new energy consumption for the plant with the given heat load.

2.2.1. Objective function. A certain CHP plant consists of several CHP units. The objective function is $P_t$, which can be expressed as the sum of lower boundary of power load of each unit involved in operation, then $P_t$ can be calculated as

$$P_t = \sum_{i=1}^{n} P_{\text{min}}(G_i)$$

(2)

where $P_{\text{min}}(G_i)$ is the lower boundary of power load of the No. $i$ unit, MW; $G_i$ is the heating steam extraction mass flow rate of the No. $i$ unit, t/h; $n$ is the number of CHP units in plant.

In Figure 2, the unit’s lower boundary of power load is the function of the heating extraction steam mass flow rate. Then $P_{\text{min}}$ of each unit can be calculated with Equation (3)

$$P_{\text{min}} = f_{\text{min}}(G)$$

(3)

2.2.2. Constraints. The model is influenced by the heating load need and single unit operating limits. The constraints can be expressed as following:

(1) In heating season, the heat load of the whole plant should meet the need of heating supply:

$$Q_t = \sum_{i=1}^{n} G_i(h_{e,i} - h_{es,i})$$

(4)

where $Q_t$ stands for the heat demand, MW; $h_{e,i}$ is the heating extraction steam enthalpy of the No. $i$ unit, kJ/kg; $h_{es,i}$ is the drainage water enthalpy of the No. $i$ unit, kJ/kg; $n$ stands for the number of CHP units in operation.

(2) For the reasons, such as design conditions and safe operation of each unit, different heating restrictions exist for different CHP units, the heating extraction steam mass flow rate of each unit is calculated as

$$0 \leq G_i \leq G_{\text{max},i}$$

(5)

where $G_{\text{max},i}$ is the maximum extraction steam mass flow rate of the No. $i$ unit, t/h.

2.2.3. Model solution. Multi-unit heat load dispatch is a constrained multidimensional optimization problem so GA is used in the paper. As GA has no special requirements on the objective function and are not subject to restrictive assumptions in the search space compared to traditional mathematical optimization methods. In this paper, the solution was carried out by GA. Each solution of the model is an individual. Individuals are genetically manipulated by coding, and then decoded to obtain the actual solution after a series of genetic manipulations.

3. Reference case and result

3.1. Reference case
A reference CHP plant with four CHP units including two 350 MW subcritical units and two 600MW supercritical units was presented in this section. The important parameters of the referenced CHP units in plants are listed in Table 1. The thermal efficiencies of boiler for two types units are 92% and 95% respectively. The thermal efficiency of pipelines is 98%. The thermal efficiency of the plant can be considered as 45%.

As shown in Table 1, compared to unit 3 and unit 4, the capacity of unit 1 and unit 2 are relatively lower, which are represented by type “a” below. Correspondingly, Unit 3 and unit 4 are represented by type “b” below.
| CHP units                                      | Unit 1 | Unit 2 | Unit 3 | Unit 4 |
|-----------------------------------------------|--------|--------|--------|--------|
| Rated power (MW)                              | 350    | 350    | 600    | 600    |
| Maximum heating extraction steam mass flow rate (t/h) | 420    | 420    | 800    | 800    |
| Rated heating extraction steam pressure (MPa)  | 0.45   | 0.45   | 0.43   | 0.43   |
| Heating extraction steam temperature (°C)      | 248    | 252    | 333    | 333    |
| Heating extraction steam enthalpy (kJ/kg)      | 2969.19| 2976.52| 3128.29| 3128.29|
| Drainage water enthalpy (kJ/kg)                | 339.12 | 355.92 | 393.78 | 385.36 |

The heat-power coupling mechanism between the two types of units were obtained from the heat supply condition diagram with the method described above. So, the \( P_{\text{min}} \) of the two types of units can be calculated as follows:

\[
P_{\text{min},a} = \begin{cases} 
-0.19G_a + 281.11, & \text{if } 0 \leq G_a < 330 \\
0.41G_a + 83.33, & \text{if } 330 \leq G_a < 420 
\end{cases} \tag{6}
\]

\[
P_{\text{min},b} = \begin{cases} 
-0.2755G_b + 500.90, & \text{if } 0 \leq G_b < 600 \\
0.33G_b + 141, & \text{if } 600 \leq G_b < 800 
\end{cases} \tag{7}
\]

According to Equations (2), (6), (7), \( P_t \) can be calculated under different cases of any unit commitments. The units participating in the dispatch are subject to the following constraints.

\[
Q_t = \sum_{i=1}^{n} G_i (h_{e,i} - h_{es,i}) \\
0 \leq G_a \leq 420 \\
0 \leq G_b \leq 800 \tag{8}
\]

3.2. Result

Different unit commitments can afford different maximum heat loads which are shown in Figure 4.

![Figure 4. Maximum heat load that can be afforded by different unit commitments.](image)

![Figure 5. The lower boundary of power load for different unit commitments.](image)

When the heat load reaches a certain value, smaller total capacity of unit commitments cannot supply enough heat load so that the optimal unit commitments will change. The comparison of the lower boundary of power load under different unit commitments is shown in Figure 5, which can obtain the lower boundary of power load of optimal unit commitments under the corresponding heat load.

Figure 5 shows the \( P_t \) of different unit commitments varies under different total heat load. The overall level of \( P_t \) for different unit commitments is different. Under different heat load the unit commitment of the lowest \( P_t \) will change. The scheduling scheme of optimal unit commitment in different heat load can be obtained, which is shown in Figure 6.
Figure 5 indicates that many jumps occur in the trend for the $P_t$ of optimal unit commitment in Figure 6(a). As the heat load increases beyond the maximum heat load that the current unit commitments can afford, the proportion of high-capacity type units in unit commitment needs to be increased or the number of units needs to be increased.

Through the model, the scheduling scheme of optimal unit commitment can be obtained by the historical data in one heating season. The actual heat load and corresponding operating lower boundary of power load are shown in Figure 7.

Figure 7. Heat load and corresponding power load.

The downward space for the lower boundary of power load of the optimal unit commitment is shown in Figure 8. Through the model, the scheduling of power load before and after the optimized dispatch for optimal unit commitment is shown in Figure 9.

Figure 8. The space of reduced power load for the optimal unit commitment.

The downward space for the lower boundary of power load of the optimal unit commitment is shown in Figure 8. Through the model, the scheduling of power load before and after the optimized dispatch for optimal unit commitment is shown in Figure 9.

Figure 9. The power load scheduling scheme.
It shows that the plant-level lower boundary of power load for the optimal unit commitment has certain downward-adjustment range to be tapped compared with actual power load under the same condition of the heat load. Figure 8 show the trend of $P_t$ for the optimal unit commitment with the same heat load showed in Figure 7. Statistical calculation of the results in Figure 8 shows that the consumption capacity of renewable energy can be increased by 1.92 billion kWh if the reference CHP plant operates following the scheduling scheme of optimal unit commitment in the heating season continuously, which accounts for 5.6% of renewable energy generating capacity of the province the plant located during the heating season in 2020. For regional grids with a large share of CHP units, the level of consumption capacity for new energy can be improved considerably when plants operate with the scheduling scheme of optimal unit commitment.

Correspondingly, the comparisons of the heat load scheduling scheme to each unit before and after the optimized dispatch for optimal unit commitment is shown in Figure 10.

3.3. Potential revenue for CO$_2$ emissions reduction

The scheduling scheme of optimal unit commitment reduces generating capacity for the whole plant. The reduced carbon emissions bring certain revenue from carbon trade market.

The coal consumption rate is calculated with

$$B = B_p + B_h$$

where $B_p$ is the coal consumption rate for power supply, t/h; $B_h$ the rate of coal consumption for heating supply, t/h.

$B_p$ can be calculated with

$$B_p = \sum_{i=1}^{n} \frac{P_i}{\eta_{r_i} \eta_m \eta_{el} \eta_t Q_L} = \frac{P}{\eta_p Q_L}$$

where $P$ is power load, MW; $Q_L$ is the low calorific value of coal, kJ/kg; $\eta_{r_i}$ is turbine relative internal efficiency; $\eta_m$ is mechanical efficiency; $\eta_{el}$ is generator efficiency; $\eta_t$ is cycle thermal efficiency; $\eta_p$ is thermal efficiency of power plant.

$B_h$ can be calculated with

$$B_h = \frac{Q_h}{\eta_b \eta_p Q_L}$$

where, $\eta_b$ is the thermal efficiency of boiler and $\eta_p$ is the thermal efficiency of pipe.
\( Q_h \) is calculated with

\[
Q_h = G^* (h_e - h_{es})
\]

(12)

where \( G \) is heating extraction steam mass flow rate of the unit; \( h_e \) is heating extraction steam enthalpy, kJ/kg; \( h_{es} \) is drainage water enthalpy, kJ/kg.

Then the coal saving (\( \Delta \dot{B} \)) is expressed as

\[
\Delta \dot{B} = \sum_{i=1}^{n} \dot{B}_{i} - \sum_{i=1}^{n} \dot{B}_{i,m}
\]

(13)

where \( \dot{B}_{i} \) is the coal consumption rate before optimization, t/h; \( \dot{B}_{i,m} \) is the coal consumption rate of optimal minimum operation mode, t/h.

\( \Delta \dot{B} \) can reflect the reduction of CO\(_2\) emissions. The reduction of CO\(_2\) emissions rate can be calculated with

\[
\Delta m_{CO_2} = K \frac{M_{CO_2}}{M_c} \Delta \dot{B}
\]

(14)

where, \( M_{CO_2} \) is the relative molecular mass of CO\(_2\); \( M_c \) is the relative atomic mass of carbon; \( K \) is emission factor of standard coal.

Calculated with the value of standard coal, \( K \) is 0.714 and \( Q_L \) is 29307.6 kJ/kg [12]. The reduction of coal consumption rate for the scheduling scheme of optimal unit commitment can be calculated with equal (9) - (13) during the heating season. If the plant operates with the scheduling scheme of optimal unit commitment for the heating season, the CO\(_2\) emissions can be reduced by 1.32 million tons, compared with actual operation. The plant will reduce CO\(_2\) emissions by 52.5 %.

Moreover, the reduction of CO\(_2\) emissions for the scheduling scheme of optimal unit commitment will remain more carbon allowance. As shown in Figure 11, it is obvious that the carbon allowance price in China is still a bit lower than that in the mature carbon trade markets of other countries or regions, though the carbon allowance price after the official opening of the Chinese carbon trade market in 2021 has increased compared to 2020, the large difference in carbon allowance prices could exist a large potential space for possible revenue.

![Figure 11. Carbon allowance price for different countries or regions in 2020 [13].](image1)

Figure 11. Carbon allowance price for different countries or regions in 2020 [13].

![Figure 12. The revenue of carbon trade for the scheduling scheme of optimal unit commitment.](image2)

Figure 12. The revenue of carbon trade for the scheduling scheme of optimal unit commitment.

The extra carbon allowance can bring certain revenue from carbon trade market. The average carbon allowance price from November 22, 2021 to November 26, 2021 is 6.68 USD/ton (The average CNY/USD exchange rate is 6.46 in the first 11 months of 2021), according to the China Carbon Emission Trade Exchange. The revenue of carbon reduction for the scheduling scheme of optimal unit commitment can be calculated compared with the actual power load. Figure 12 shows the revenue of carbon emissions reduction under the scheduling scheme of optimal unit commitment. Under the scheduling scheme of optimal unit commitment, the CO\(_2\) emissions reduction of the reference plant can bring the revenue of 8,828,434.7 USD in the heating season.

4. Conclusions

In this paper, a plant minimum operation mode model was established. GA is introduced to solve the model. Based on analysing a reference CHP plant, the main conclusions are as followed:
(1) The plant minimum operation mode model is proposed to excavate the plant-level lower boundary of power load. The scheduling scheme of optimal unit commitment solved by GA helps to provide the most downward-adjustment range for new energy consumption under certain heat load. If the reference CHP plant is in the scheduling scheme of optimal unit commitment in heating season continuously, the consumption of renewable energy generating capacity can be increased by 1.92 billion kWh.

(2) The fluctuation of heat load in the heating season will constraint the optimal unit commitment of the CHP plant. As the heat load increases beyond the heat load that the current unit commitment can afford, the proportion of units with small capacity of the current combination is changed first, and then the number of units is increased to obtain a new unit commitment.

(3) If the reference plant operates with the scheduling scheme of optimal unit commitment for the heating season, the CO₂ emissions can be reduced by 52.5% compared with actual operation. The CO₂ emissions reduction for the scheduling scheme can bring certain revenue, which reaches 8,828,434.7 USD in the heating season. Due to the large disparity of carbon allowance prices from different carbon trade markets, there is a large potential space for possible carbon trade revenue.

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