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Assessing the flexibility of coal-based CHP plants in different heating modes

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ABSTRACT

The increasing deployment of renewable energy requires larger flexibility in the energy system, in which conventional combined heat and power (CHP) plants are also an important source of flexibility. However, the provision of flexibility depends on the operation region of a CHP plant, i.e., the electricity and heat production of a CHP plant are inter-related.

Therefore, this paper aimed to assess the flexibility of coal-based CHP plants in various heating modes. To this aim, various heating modes of CHP plants, including: main steam bypass heating, reheat steam bypass heating, intermediate-pressure turbine (IPT) outlet steam heating, high back-pressure (HBP) heating, and low-pressure turbine zero output (LZO) heating, were respectively investigated. An energy balance matrix method was employed to determine the operation regions of CHP plants in various heating modes.

Results show that, compared with other heating modes, CHP plants in the reheat steam bypass heating mode and in the HBP heating mode can provide larger power-adjustment flexibilities without affecting heating loads. This implies that CHPs in these heating modes can obtain larger profits on a day-ahead market. A CHP plant in the LZO heating mode can reduce its power load to the lowest level and thus it yields the largest flexibility for accommodating renewable energy.

Keywords: Flexibility, Combined heat and power, District heating, Operation region, Energy balance matrix

1. INTRODUCTION

Boosting the share of renewable energy in primary energy is a key solution to the world's climate challenge. As the world's largest emitter of CO2, China is massively developing its renewable energy and has made a solemn commitment to reach carbon neutrality before 2060 [1]. However, the intermittent nature of solar and wind power seriously threatens the stable operation of the power grid. Hence, the current power system needs a higher level of flexibility to accommodate renewable energy, while the traditional operation mode of thermal power plants weakens it [2]. In addition, centralized heating in winter is required in northern China. Therefore, combined heat and power (CHP), an effective joint production technology of thermal power plants in northern China, provides relatively higher flexibility via switching and coordinating the production between power and heat.

However, the provision of flexibility depends on the operation region of a CHP plant, i.e., the electricity and heat production of a CHP plant are inter-related. The heating mode determines the operation region of a CHP plant. Currently, there are various available heating sources for coal-based CHP plants, which has been investigated by many scholars. The outlet steam from the intermediate-pressure turbine (IPT) is used as the most common heating source due to the appropriate temperature and pressure [3-5]. Besides, the retrofits of low-pressure turbines (LPTs), including the high back-pressure (HBP) retrofit and the LPT zero output (LZO) retrofit, are proposed in order to improve the heating capacity of CHP units. According to Zhao et al. [4], the heating capacity of the HBP retrofitted unit is improved by 92.89 MW. Wang et al. [5] reported the feasible maximum heat loads of the 330 MW CHP unit is enhanced from 345MW to 580 MW. In addition, auxiliary devices such as heat pumps (HPs), electric boilers (EBs) and thermal energy storage (TES) provide multiple heating modes for coal-based CHP systems. Cho H et al. [6] and Zhang et al. [7] used HPs to recover waste heat from CHPs for district heating. Liu et al. [8] assessed the flexibility and thermodynamic performance of applying EBs into CHP systems. Wojcik et al. [9] investigated the potential of various types of TES for enhancing the heating capacity of CHP systems.

As discussed above, some research has been conducted regarding the heating modes of the coal-

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based CHP plants. Previous studies generally focused on one certain heating mode. However, there are multiple available steam sources for district heating in CHP units due to its wide steam temperature range, which has not been well studied. Therefore, to fill this gap, the flexibility of coal-based CHP plants in different heating modes is assessed in this paper. The main steam bypass, reheat steam, IPT outlet steam, HBP and LZO retrofits are selected as available heating modes and their technical constraints are considered. The thermodynamic models of the CHP plant with various heating modes are developed, and the operation regions reflecting the heat-power adjustment flexibility are calculated.

2. THERMODYNAMIC MODELS

In this section, thermodynamic models of the CHP plant are developed via energy balance matrix methods. Multiple available heating sources in the CHP plant are considered, and the corresponding technical constraints the above heating modes are discussed in detail.

2.1 Multiple heating sources in CHP plants

The 330 MW coal-based CHP plant is selected as the subject of this study. As shown in Fig. 1, there are five feasible heating modes for the studied CHP plant. The main design parameters of the CHP plant are listed in Table 1.

Table 1.
Design parameters of the studied CHP plant

Items	Value
Design power load / MW	330
Main steam pressure / MPa	16.67
Main steam temperature / ℃	537
Reheat steam pressure / MPa	3.2
Reheat steam temperature / ℃	537
IPT outlet steam pressure / MPa	0.846
IPT outlet steam temperature / ℃	343
Exhaust steam pressure / MPa	0.0054

The thermodynamic system diagram of the CHP plant without heating is shown in Fig. 1(a), which can be used as the benchmark for various heating modes. The feedwater is heated to main steam in the boiler and can be extracted for district heating before entering the high-pressure turbine (HPT), as shown in Fig 1(b). Due to the high temperature and pressure, the main steam needs to be mixed with cooling water in the desuperheater to make its parameters adapt to the heat users.

Reheat steam, the steam before entering the IPT, can also be used for district heating. As shown in Fig. 1(c), the reheater overheating issue of the boiler is not a concern since the steam is already leaving the boiler. Therefore, the heating capacity of reheat steam is greater than that of main steam, which will be demonstrated in Section 3. Similar to the main steam heating mode, reheat steam heating requires a desuperheating and depressurization process.

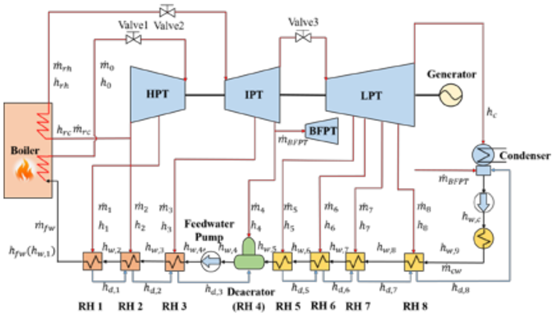
The outlet steam from the IPT is used as the most common heating source due to the appropriate temperature and pressure. Currently, the majority of CHP units in northern China currently adopt this mode for district heating, as shown in Fig. 1(d). This mode has a larger heating capacity than main steam and reheat steam, and its main constraint is the minimum steam flow rate to cool the LPT.

As shown in Fig. 1(e), the theory of the HBP retrofit is to increase the pressure and corresponding saturation temperature of the exhaust steam from the LPT. As a result, the exhaust steam capable to heat the return water for district heating. In this studied CHP plant, the last two stages blades of the LPT are removed, and the retrofitted back pressure is increased to 45 kPa.

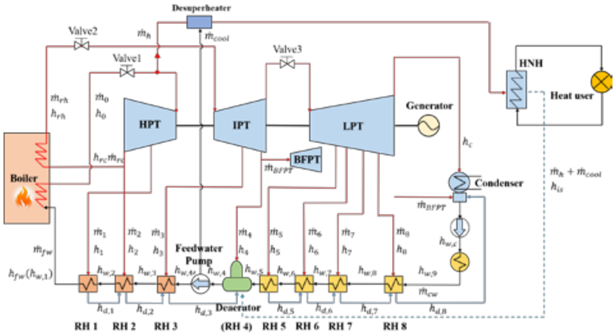
As shown in Fig. 1(f), the theory of the LZO retrofit is to enable the overwhelming majority of the exhaust steam of the IPT for district heating, except for a small portion of steam to cool the low-pressure rotor. As a result, the output power and the output heat are completely coupled, i.e. the both can be uniquely determined from each other. Moreover, the constraint of the minimum steam flow rate to cool the LPT is eliminated.

2.2 Energy balance matrix modeling

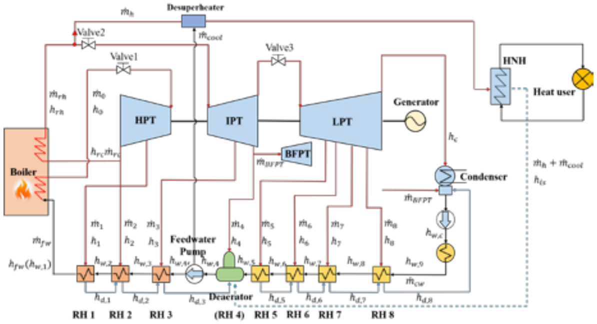
Energy balance matrix modeling method is an effective way to establish the steady-state thermodynamic models of coal-based CHP plants [5,10,11]. The thermodynamic models of the CHP plant without heating and the IPT outlet steam heating mode are proposed in Ref. [5]. Then, the thermodynamic models of the CHP plant with the HBP heating mode and the LZO heating mode are developed in our previous work [10]. In this paper, the CHP plant with the main steam bypass heating mode and the reheat steam bypass heating mode are firstly proposed. Moreover, the accuracy of the energy balance matrix modeling method is verified in Ref. [5] and Ref. [10]. The energy balance matrixes of various heating modes of the CHP plant are shown in Table 2.



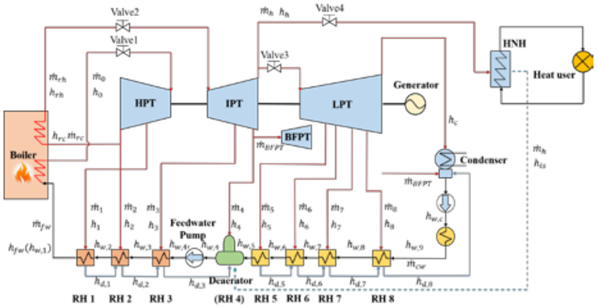
(a) CHP plant without heating



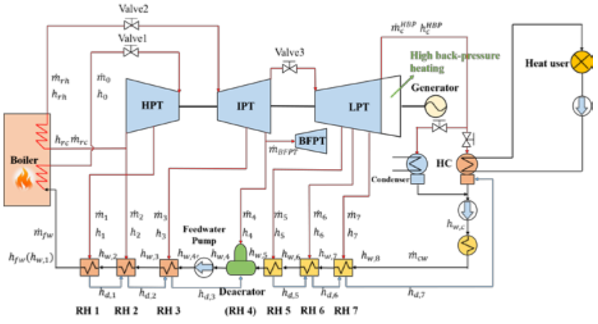
(b) Main steam bypass heating



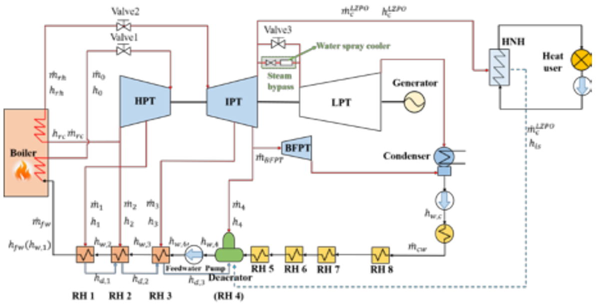
(c) Reheat steam bypass heating



(d) IPT outlet steam heating



(e) HBP heating



(f) LZO heating

Fig. 1. Multiple heating modes of the CHP plant

where, $\dot{m}_{fw}$, $\dot{m}_{cool}$, $\dot{m}_h$ and $\dot{m}_i$ are the mass flow rates of the feedwater, cooling water, heating extraction steam, and the extracted steam into No. *i* regenerative heater (RH), t/h. The q_i, y_i and τ_i are the enthalpy variation associated with imports and exports of RHs, which can be expressed.

$$q_i = h_i - h_{d,i} \tag{1}$$

$$y_i = h_{d,(i-1)} - h_{d,i} \tag{2}$$

$$\tau_i = h_{w,i} - h_{w,(i+1)} \tag{3}$$

where, h_i is the enthalpy of the extracted steam into the RH*i*, kJ/kg. $h_{d,i}$ and $h_{w,i}$ are the enthalpies of the drainage water and the outlet water of the RH*i*, kJ/kg.

2.3 Technical constraints

The below technical constraints of the CHP plant are considered.

Constraints 1: The turbines of the CHP plant are limited by the allowable maximum inlet steam flow, i.e., the turbine maximum continuous rating (TMCR) operating condition.

Constraints 2: The boiler of the CHP plant is limited by a minimum steady combustion load, which corresponds to the 40% turbine heat acceptance (THA) operating condition.

Constraints 3: To prevent over temperature of boiler reheat surface, when extracting main steam for heating, the maximum flow is quantified as 5% of the reheat steam flow.

Constraints 4: To avoid the valve vibration and pipeline noise, the pressure ratio after and before the valve2 should not be less than 0.546.

Constraints 5: To maintain the safe operation of the LPT, the steam flow into the LPT should not be less than 250t/h.

Table 2
Energy balance matrixes of various heating modes of the CHP plant

	Energy balance matrix
CHP plant without heating	$\dot{m}_{fw}\begin{bmatrix}\tau_1\\\tau_2\\\tau_3\\\tau_4\\\tau_5\\\tau_6\\\tau_7\\\tau_8\end{bmatrix}=\begin{bmatrix}q_1&&&&&&&\\y_2&q_2&&&&&&\\y_3&y_3&q_3&&&&&\\y_4&y_4&y_4&q_4&&&&\\\tau_5&\tau_5&\tau_5&\tau_5&q_5&&&\\\tau_6&\tau_6&\tau_6&\tau_6&y_6&q_6&&\\\tau_7&\tau_7&\tau_7&\tau_7&y_7&y_7&q_7&\\\tau_8&\tau_8&\tau_8&\tau_8&y_8&y_8&y_8&q_8\end{bmatrix}\begin{bmatrix}\dot{m}_1\\\dot{m}_2\\\dot{m}_3\\\dot{m}_4\\\dot{m}_5\\\dot{m}_6\\\dot{m}_7\\\dot{m}_8\end{bmatrix}$
Main steam bypass heating	$\dot{m}_{fw}\begin{bmatrix}\tau_1\\\tau_2\\\tau_3\\\tau_4\\\tau_5\\\tau_6\\\tau_7\\\tau_8\end{bmatrix}=\begin{bmatrix}q_1&&&&&&&\\y_2&q_2&&&&&&\\y_3&y_3&q_3&&&&&\\y_4&y_4&y_4&q_4&&&&\\\tau_5&\tau_5&\tau_5&\tau_5&q_5&&&\\\tau_6&\tau_6&\tau_6&\tau_6&y_6&q_6&&\\\tau_7&\tau_7&\tau_7&\tau_7&y_7&y_7&q_7&\\\tau_8&\tau_8&\tau_8&\tau_8&y_8&y_8&y_8&q_8\end{bmatrix}\begin{bmatrix}\dot{m}_1\\\dot{m}_2\\\dot{m}_3\\\dot{m}_4\\\dot{m}_5\\\dot{m}_6\\\dot{m}_7\\\dot{m}_8\end{bmatrix}+\dot{m}_h\begin{bmatrix}0\\0\\0\\h_{is}-h_{w,5}\\\tau_5\\\tau_6\\\tau_7\\\tau_8\end{bmatrix}+\dot{m}_{cool}\begin{bmatrix}0\\0\\0\\h_{is}\\0\\0\\0\\0\end{bmatrix}$
Reheat steam bypass heating	
IPT outlet steam heating	$\dot{m}_{fw}\begin{bmatrix}\tau_1\\\tau_2\\\tau_3\\\tau_4\\\tau_5\\\tau_6\\\tau_7\\\tau_8\end{bmatrix}=\begin{bmatrix}q_1&&&&&&&\\y_2&q_2&&&&&&\\y_3&y_3&q_3&&&&&\\y_4&y_4&y_4&q_4&&&&\\\tau_5&\tau_5&\tau_5&\tau_5&q_5&&&\\\tau_6&\tau_6&\tau_6&\tau_6&y_6&q_6&&\\\tau_7&\tau_7&\tau_7&\tau_7&y_7&y_7&q_7&\\\tau_8&\tau_8&\tau_8&\tau_8&y_8&y_8&y_8&q_8\end{bmatrix}\begin{bmatrix}\dot{m}_1\\\dot{m}_2\\\dot{m}_3\\\dot{m}_4\\\dot{m}_5\\\dot{m}_6\\\dot{m}_7\\\dot{m}_8\end{bmatrix}+\dot{m}_h\begin{bmatrix}0\\0\\0\\h_{is}-h_{w,5}\\\tau_5\\\tau_6\\\tau_7\\\tau_8\end{bmatrix}$
HBP heating	$\dot{m}_{fw}\begin{bmatrix}\tau_1\\\tau_2\\\tau_3\\\tau_4\\\tau_5\\\tau_6\\\tau_7\end{bmatrix}=\begin{bmatrix}q_1&&&&&&\\y_2&q_2&&&&&\\y_3&y_3&q_3&&&&\\y_4&y_4&y_4&q_4&&&\\\tau_5&\tau_5&\tau_5&\tau_5&q_5&&\\\tau_6&\tau_6&\tau_6&\tau_6&y_6&q_6&\\\tau_7&\tau_7&\tau_7&\tau_7&y_7&y_7&q_7\end{bmatrix}\begin{bmatrix}\dot{m}_1\\\dot{m}_2\\\dot{m}_3\\\dot{m}_4\\\dot{m}_5\\\dot{m}_6\\\dot{m}_7\end{bmatrix}$
LZO heating	$\dot{m}_{fw}\begin{bmatrix}\tau_1\\\tau_2\\\tau_3\\\tau_4\end{bmatrix}=\begin{bmatrix}q_1&&&\\y_2&q_2&&\\y_3&y_3&q_3&\\y_4&y_4&y_4&q_4\end{bmatrix}\begin{bmatrix}\dot{m}_1\\\dot{m}_2\\\dot{m}_3\\\dot{m}_4\end{bmatrix}$

The correspondence between the heating modes and the technical constraints is as follows.

(a) CHP plant without heating: Constraints 1+2.

(b) Main steam bypass heating: Constraints 1+2+3+5.

(c)Reheat steam bypass heating: Constraints 1+2+4+5.

(d) IPT outlet steam heating: Constraints 1+2+5.

(e) HBP heating: Constraints 1+2+5.

(f) LZO heating: Constraints 1+2.

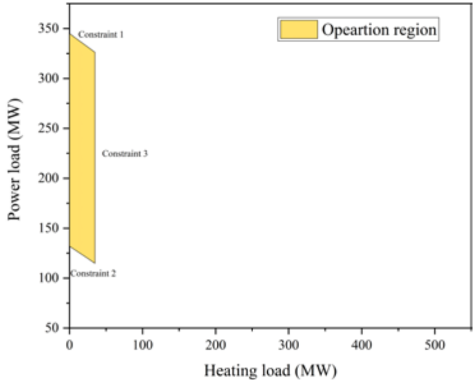
3. RESULTS AND DISCUSSION

Operation region, reflecting the heat-power adjustment space, is selected as the metric to assess the flexibility provided by multiple heating modes in coal-based CHP plants. Results are shown in Fig. 2.

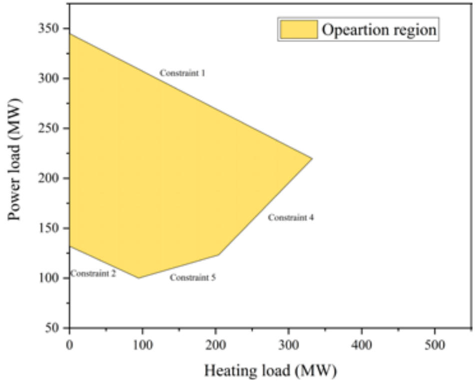
Except for the LZO heating mode, the operation regions of all heating modes present an enclosed space. The feasible maximum heating loads for the five heating modes are 34.8 MW, 332.3 MW, 382.7 MW, 455.8 MW and 543.4 MW. The feasible minimum power loads for the five heating modes are 114.9 MW, 100.0 MW, 111.6 MW, 112.6 MW and 77.5 MW. Different from the HBP heating mode, the feasible maximum power loads decrease with the increase of heating load when the CHP plants using the main steam bypass, reheat steam, and IPT outlet steam for district heating.

Compared with other heating modes, CHP plants in the reheat steam bypass heating mode and in the HBP heating mode can provide larger power-adjustment flexibilities without affecting heating loads. The former provides the most flexibility for the coal-based CHP plant at heat loads less than 144.2 MW, while the latter provides the most flexibility at heat loads greater than 144.2 MW. This implies that CHPs in these heating modes can obtain larger profits on a day-ahead market.

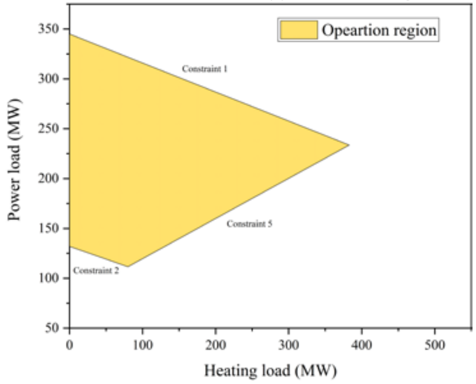
A CHP plant in the LZO heating mode can reduce its power load to the lowest level when the heating load is higher than 219.0 MW and thus it yields the largest flexibility for accommodating renewable energy.



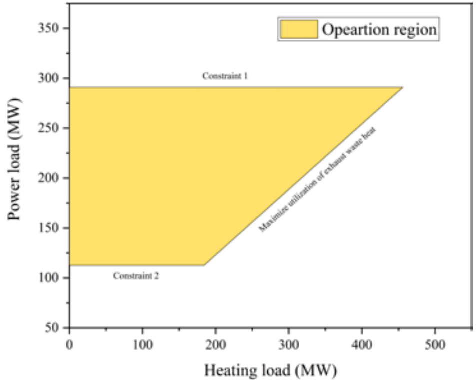
(a) Main steam bypass heating



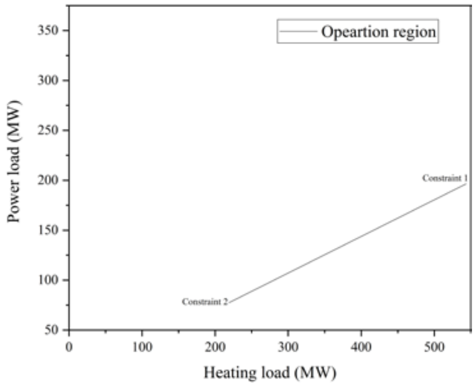
(b) Reheat steam bypass heating



(c) IPT outlet steam heating



(d) HBP heating



(d) LZO heating

4. CONCLUSIONS

The The main steam, reheat steam, IPT outlet steam, HBP heating mode and LZO heating mode are considered as five available heating modes in CHP plants. Then, the flexibility of coal-based CHP plants in different heating modes is assessed in this paper. The main conclusions are as follows.

(1) Except for the LZO heating mode, the operation regions present an enclosed space when the CHP plants using the main steam bypass, reheat steam, IPT outlet steam, and HBP heating mode for district heating.

(2) Compared with other heating modes, CHP plants in the reheat steam bypass heating mode and in the HBP heating mode can provide larger power-adjustment flexibilities without affecting heating loads. This implies that CHPs in these heating modes can obtain larger profits on a day-ahead market.

(3) A CHP plant in the LZO heating mode can reduce its power load to the lowest level and thus it yields the largest flexibility for accommodating renewable energy.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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