Flexibility Improvement of CHP Unit for Wind Power Accommodation

Dongming Zhang, Yong Hu, and Yaokui Gao

Abstract—**Improving the flexibility of combined heat and power (CHP) units is an important way to solve the problem of wind power accommodation in northern China. Firstly, this paper analyzes the principle of an extraction-type CHP unit, calculates its safe operation range, and analyzes its contradiction between heating and peaking. Secondly, the safe operation ranges of the CHP unit with several flexibility modifications are further calculated, which involve two-stage bypass, low-pressure cylinder (LPC) removal, heat storage tank, and electric boiler. Finally, based on the safe operation ranges, their effects on improving the capabilities of deep peak shaving and wind power accommodation are compared, and their adaptabilities to different wind scenarios are analyzed. The results show that: ① all flexibility modifications can improve the deep peak shaving capability of the CHP unit, especially for the two-stage bypass and the electric boiler; ② LPC removal modification can accommodate wind power to some extent, but most of wind power is still abandoned; ③ heat storage tank modification is unstable in different wind scenarios, which is determined by the surplus heating capability during the daytime.**

Index Terms—**Combined heat and power (CHP), flexibility, bypass, low-pressure cylinder (LPC) removal, heat storage tank, electric boiler.**

I. Introduction

SINCE the climate in northern China is severely cold in winter [1], the heating load demand in these areas is urgent, and the annual heating time ranges from 6 to 8 months. In order to meet the heating load demand, a large number of combined heat and power (CHP) units have been built in these areas [2]. With the continuous development of urbanization, the heating load demand for CHP units is still increasing year by year [3]. Simultaneously, the modern power supply will be mainly based on renewable energy. According to West Inner Mongolia (WIM) Energy Development and Planning (2017-2020), the total installed electricity capacity will achieve 165 GW, including coal-fired power of 100 GW, wind power of 45 GW, and photovoltaic power of 15 GW [4]. With the large-scale access of renewable energy, the demand for deep peak shaving of CHP units is increasingly prominent [5]. Due to the constraint of "ordering power by heat" for CHP units, only by improving their flexibilities can the demand for both heating and peaking be met [6].

Flexibility modification is an important way to solve this problem. Currently, several flexibility modifications have been carried out in China, mainly including two-stage bypass [7], low-pressure cylinder (LPC) removal [8], heat storage tank [9], and electric boiler [10]. This paper studies their effects on accommodating wind power, so as to provide a theoretical basis for flexibility improvements in thermal power plants.

Recently, extensive research works on flexibility modifications have been carried out. Reference [11] studies the flexibility potential of different CHP applications in Denmark and provides guidelines for minimizing heat costs and balancing the local energy portfolio. Reference [12] studies the model of a CHP unit modified by absorption heat pump (AHP) and two-stage bypass, and proposes a deep peak regulation control strategy. Reference [13] studies the effect of electric boiler and heat storage tank on improving the flexibility of CHP units. The results show that electric boilers are more effective in accommodating wind power, while heat storage tanks are more energy-saving. Reference [14] proposes a method for determining the optimal capacity of heat storage tank, thereby improving the flexibility of a CHP unit and maximizing its economic benefits. Considering the characteristics of CHP unit, heat storage tank, electric boiler, and heat supply network, [6] proposes a scheduling model to maximize the flexibility of the power system. Reference [15] proposes a calculation method for the safe operation range of CHP units based on the uniform design, whose accuracy is equivalent to that of heat balance diagram. References [16] and [17] analyze the safe operation range of several heating methods, and establish a unified model to evaluate the flexibility and heating costs of each heating method. The result shows that the LPC removal and heat storage tank would not increase the coal consumption, while the two-stage bypass and electric boiler would increase it due to the use of high-quality heat sources. Reference [18] calculates and analyzes the peak shaving capability of CHP unit with heat storage tank, which provides guidance for the safe and flexible operation of CHP units. Based on this, [19] proposes a calculation method for the safe operation range of a CHP unit with AHP, and the results show that AHP can improve

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the heating and peaking capacity of CHP unit. However, due to its back pressure requirements, the minimum power generation load fails to be further decreased. In summary, the predecessors have carried out extensive research on the flexibility modification of CHP units, and have made certain improvements in modeling, control, scheduling, and safety analysis, but they have not comprehensively compared and analyzed the effects of these flexibility modifications on wind power accommodation.

This paper analyzes the principle of an extraction-type CHP unit, calculates its safe operation range, and analyzes its contradiction in heating and peaking. Based on further analysis of two-stage bypass, LPC removal, heat storage tank, and electric boiler, the safe operation ranges of CHP units with different flexibility modifications are calculated, and their effects on improving deep peak shaving and wind power accommodation capabilities are compared.

The remainder of this paper is organized as follows. Section II analyzes the necessity of flexibility modification of CHP units. Section III calculates several flexibility modifications of CHP unit. Section IV compares each flexibility modification. Section V gives the conclusion.

II. Necessity of Flexibility Modification of CHP Units

A. Principle of Extraction-type CHP Unit

The exhaust steam from the intermediate-pressure cylinder (IPC) is mainly divided into two parts, as shown in Fig. 1 [20], one of which enters the LPC to generate power, and the other enters the heater to heat the return water in the heat-supply network. In Fig. 1, HPC is the high-pressure cylinder; and GV is the gate valve.

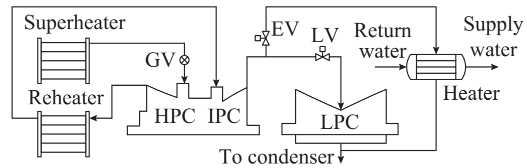

Fig. 1. Principle of extraction-type CHP unit.

In practical applications, the heating load can be controlled by the extraction valve (EV) and the link valve (LV). The steam pressure in front of LV needs to be monitored, especially under low load conditions. The steam entering the LPC would fail to meet its cooling demand when the pressure is too low.

B. Safe Operation Range of CHP Unit

This paper takes a 330 MW CHP unit of a power plant in Jilin, China, as the research object. The CHP unit is equipped with a subcritical primary-reheating natural circulation boiler and a subcritical primary-reheating water-cooled steam turbine. The design parameters of the boiler and turbine are shown in Table I and Table II, respectively, which involve a variety of working conditions such as the boiler maximum continue rate (BMCR), boiler rated load (BRL), turbine heat acceptance (THA), heater out of service (HTO), turbine maximum continue rate (TMCR), turbine rated load (TRL), turbine rated extraction (TRE), and turbine maximum extraction (TME).

TABLE I
DESIGN PARAMETERS OF BOILER

Item	Superheated steam flow (t/h)	Superheated steam pressure (MPa)	Superheated steam temperature (°C)	Drum pressure (MPa)	Reheated steam flow (t/h)	Reheated steam pressure (MPa)	Reheated steam temperature (°C)	Feed water temperature (°C)	Boiler efficiency (%)
BMCR	1100.00	17.50	541.0	19.00	909.19	3.833	541	284.2	91.90
BRL	1043.30	17.41	541.0	18.77	865.47	3.443	541	276.2	92.00
THA	997.56	17.34	541.0	18.59	829.81	3.498	541	277.8	91.68
HTO	775.27	17.05	541.0	17.83	761.85	3.263	541	173.1	93.30
75% THA	714.46	16.98	541.0	17.65	606.49	2.542	541	257.1	92.20
40% THA	400.01	8.08	530.1	8.62	349.74	1.402	503	226.6	93.80

TABLE II
DESIGN PARAMETERS OF TURBINE

Item	Unit load (MW)	Main steam flow (t/h)	Main steam pressure (MPa)	Main steam temperature (°C)	First-stage pressure (MPa)	Reheated steam flow (t/h)	Reheated steam pressure (MPa)	Reheated steam temperature (°C)	Heating extraction steam flow (t/h)	Heat rate (kJ/kWh)	Steam rate (kg/kWh)	Turbine thermal efficiency (%)
TMCR	356.481	1100.00	16.70	538.0	13.935	909.19	3.799	538.0	0	7835.9	3.086	45.90
TRL	330.000	1043.26	16.70	538.0	12.269	865.47	3.430	538.0	0	8217.2	3.161	43.80
THA	330.000	997.56	16.70	538.0	12.550	829.81	3.476	538.0	0	7828.2	3.023	46.00
HTO	300.003	775.27	16.70	538.0	9.290	761.85	3.247	538.0	0	8100.6	2.584	44.40
75% THA	247.505	722.00	13.49	538.0	9.167	613.81	2.582	538.0	0	7938.8	2.917	45.30
40% THA	132.007	400.01	7.85	527.1	5.189	349.74	1.452	500.2	0	8600.9	3.030	41.90
TRE	256.220	1043.26	16.70	538.0	13.887	860.27	3.699	538.0	500	5741.5	4.071	62.70
TME	262.747	1100.00	16.70	538.0	14.702	903.51	3.847	538.0	550	5597.9	4.187	64.30

In addition to the BMCR, TMCR, and boiler stable combustion (BSC) conditions, the impact of heating load on the safe operation of CHP units should also be considered. In this case, the safe operation range of CHP units is actually a two-dimensional area based on the heating load and power generation load [21]. In this paper, the heating load is expressed by the heating steam flow entering the heat-supply network, and the power generation load is expressed by the unit load actually sent to the power system. The safe operation range of the CHP unit is calculated as shown in Fig. 2.

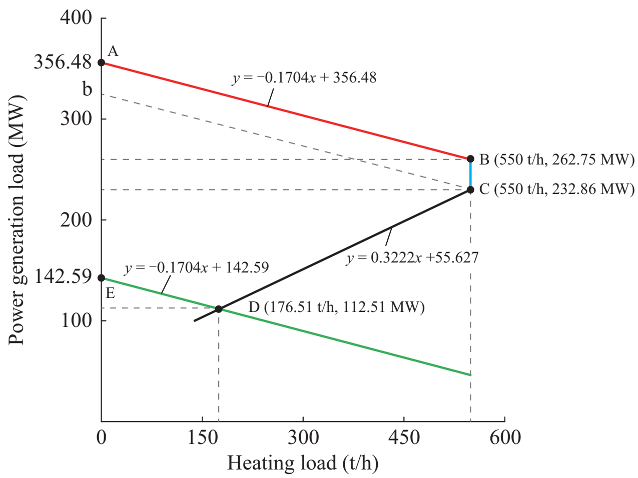

Fig. 2. Calculation of safe operation range for CHP unit.

1) Determine the boundary line (AB) of the BMCR condition. It can be observed from Table I that the superheated steam flow under the BMCR condition is 1100 t/h. If all the steam are sent to the steam turbine, the heating and power generation loads would be 0 and 356.48 MW, respectively (TMCR in Table II), i. e., the coordinate of point A is (0, 356.48 MW). On the other hand, they would be 550 t/h and 262.747 MW, respectively, under the TME condition in Table II, i. e., the coordinate of point B is (550 t/h, 262.747 MW). The straight line AB can be fitted as:

$$\text{AB: } N_e = -0.1704 D_h + 356.48 \tag{1}$$

where N_e is the power generation load; and D_h is the heating load.

2) Determine the boundary line (DE) of the BSC condition. Based on the boiler operation procedures, the minimum stable combustion load of the boiler is 40% BMCR (142.59 MW), i. e., the coordinate of point E is (0, 142.59 MW). Since the thermoelectric conversion efficiency of a steam turbine is basically the same under any operation conditions, the slope of DE is the same as that of AB. Therefore, the equation of line DE is:

$$\text{DE: } N_e = -0.1704 D_h + 142.59 \tag{2}$$

3) Determine the boundary lines BC and CD. The safe operation of the steam turbine is mainly limited by the cooling steam flow of LPC. Based on the turbine operation procedures, the minimum cooling steam flow is 140 t/h. Since the maximum extraction steam flow is 550 t/h under the TME condition, the exhaust steam flow of the IPC is at least 690 t/h.

Based on Table III, the relationship between the main steam flow and the exhaust steam flow from IPC can be fitted as shown in (3), and that between the main steam flow and the unit load can be fitted as shown in (4).

$$D_{IPC} = 0.6648 D_m + 31.871 \tag{3}$$

$$N_e = 0.3275 D_m + 2.3662 \tag{4}$$

where D_{IPC} is the exhaust steam flow from IPC; D_m is the main steam flow; and D_{LPC} is the inlet steam flow of LPC.

TABLE III
STATISTICS OF STEAM TURBINE OPERATION PARAMETERS

Condition	N_e (MW)	D_m (t/h)	D_{IPC} (t/h)	D_h (t/h)	D_{LPC} (t/h)
TMCR	356.481	1100.00	757.78	0	757.78
THA	330.000	997.56	695.00	0	695.00
75% THA	247.505	722.00	521.68	0	521.68
50% THA	165.004	483.83	357.90	0	357.90
40% THA	132.007	400.01	297.01	0	297.01
30% THA	99.007	314.66	233.49	0	233.49
TRE	256.292	1043.26	726.67	500	226.67
TME	262.747	1100.00	761.40	550	211.40

Substituting $D_{IPC} = 690$ t/h into (3), $D_m = 989.97$ t/h. Further substituting D_m into (4), $N_e = 326.58$ MW, i.e., the coordinate of point b is (0, 326.58 MW). Since the slope of bC and AB are the same, the equation of the straight line bC is:

$$\text{bC: } N_e = -0.1704 D_h + 326.58 \tag{5}$$

Keeping $D_h = 550$ t/h and substituting it into (5), $N_e =$ 232.86 MW, i. e., the coordinate of point C is (550 t/h, 232.86 MW).

Based on (4), the main steam flow under the minimum BSC condition is 428.16 t/h. Substituting it into (3), $D_{IPC} =$ 316.51 t/h. Considering the cooling steam flow of LPC (140 t/h), the actual steam flow entering the heat-supply network is 176.51 t/hour. Substituting $D_h = 176.51$ t/h into (2), $N_e =$ 112.51 MW, i. e., the coordinate of point D is (176.51 t/h, 112.51 MW). Line CD can be fitted as:

$$\text{CD: } N_e = 0.3222 D_m + 55.627 \tag{6}$$

In summary, the boundary lines of safe operation range for the CHP unit is as shown in (7).

$$\begin{cases} y_{AB} = -0.1704x + 356.48 \\ x_{BC} = 550 \\ y_{CD} = 0.3222x + 55.627 \\ y_{DE} = -0.1704x + 142.59 \end{cases} \tag{7}$$

C. Contradiction Between Heating and Peaking

Once the CHP unit supplies heat, it needs to ensure the heating load in priority [22]. In this case, the main problem is to solve the contradiction between heating and peaking.

Assuming that the heating load in each period is D_h, the adjustable range of the power generation load is between F and G, as shown in Fig. 3(b). This adjustable range can meet the power demand of the power system when there is no wind power accommodation. However, when the wind power is integrated to the power system, the power demand for the CHP unit is reduced and lower than the adjustable range during some periods (c-d-e in Fig. 3(a)). If the unit is still operated in the manner of "ordering power by heat", the CHP unit would fail to meet the power demand, and the abandonment of wind power is mandatory (area enclosed by the c-d-e in Fig. 3(a)). On the contrary, the CHP unit would fail to meet the heating demand of the heat supply network.

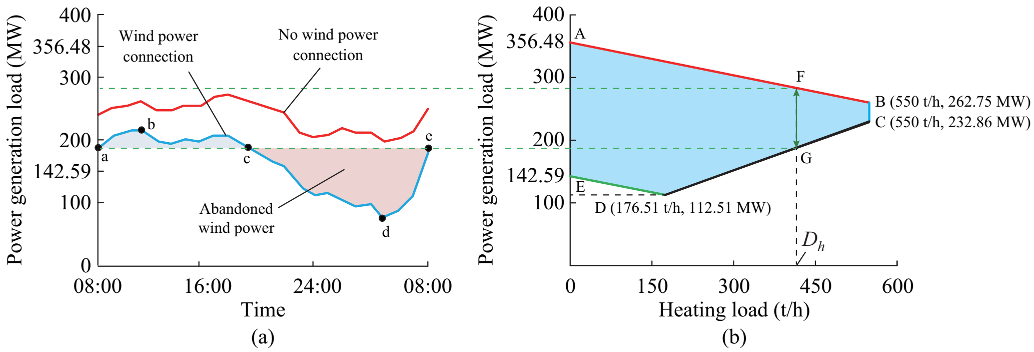

Fig. 3. Contradiction between heating and peaking.

III. Several Flexibility Modifications of CHP Unit

A. Two-stage Bypass

It can be observed from Fig. 4 that: ① part of the main steam is desuperheated and depressurized by high-pressure bypass (HPB), mixed with the exhaust steam from the HPC, and then enters the reheater; ② part of the reheated steam is desuperheated and depressurized by low-pressure bypass (LPB), mixed with the extraction steam from the IPC, and then enters the heater in heat supply network. The HPB and LPB can be put into operation when the heating capacity of CHP unit is insufficient.

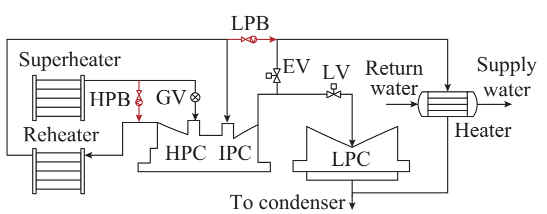

Fig. 4. Principle of extraction-type CHP unit with two-stage bypass.

The design parameters of the bypass system are shown in Table IV and the calculation process is shown in Fig. 5.

1) Theoretically, based on the first law of thermodynamics, the boundary lines AB′ and D′E coincide with AB and DE:

$$\text{AB}': N_e = -0.1704 D_h + 356.48 \tag{8}$$

$$\text{D}'\text{E}: N_e = -0.1704 D_h + 142.59 \tag{9}$$

In this case, 175 t/h of main steam is desuperheated and depressurized by 33.5 t/h of desuperheating water when the high-stage bypass is put into operation, which forms 208.5 t/h of reheated steam. And then, this part of the reheated steam is further desuperheated and depressurized by 37.21 t/h of desuperheating water, and eventually forms 245.71 t/h of heating steam. Thus, the maximum steam flow entering the HPC is 1100 t/h − 175 t/h = 925 t/h, which corresponds to the 646.81 t/h of exhaust steam from IPC in (3).

TABLE IV
Design Parameters of Two-stage Bypass

Item	Value
Steam pressure of HPB	16.7 MPa
Steam temperature of HPB	538 ℃
Steam flow of HPB	175.00 t/h
Desuperheating water pressure of HPB	9.5 MPa
Desuperheating water temperature of HPB	222.6 ℃
Desuperheating water flow of HPB	33.50 t/h
Steam pressure of LPB	3.476 MPa
Steam temperature of LPB	538 ℃
Steam flow of LPB	208.50 t/h
Desuperheating water pressure of LPB	2 MPa
Desuperheating water temperature of LPB	36.1 ℃
Desuperheating water flow of LPB	37.21 t/h

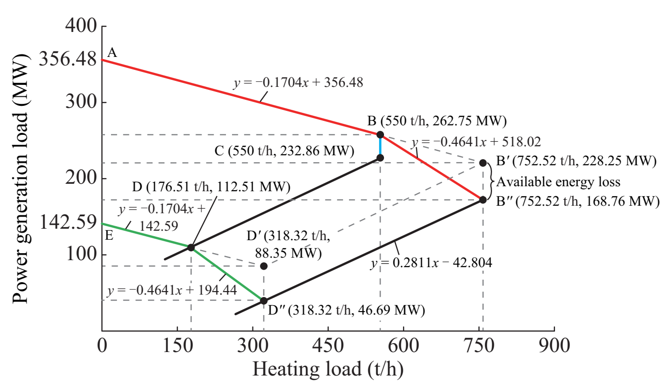

Fig. 5. Calculation of safe operation range for CHP unit with two-stage bypass.

Considering that at least 140 t/h of steam is required to cool the LPC, the steam that can be extracted for heating is 506.81 t/h. With the addition of 245.71 t/h of the heating steam formed by the two-stage bypass, the actual heating capacity is 752.52 t/h. Substituting $D_h = 752.52$ t/h into (8), the maximum power generation load is 228.25 MW, i.e., the coordinate of point B′ is (752.52 t/h, 228.25 MW).

The operation of the bypass systems has decreased the maximum extraction heating steam from 550 t/h to 506.81 t/h. If the power generation load were further reduced, the heating capacity of the unit would continue to decrease. In this case, point C′ has coincided with point B′, and the coincident point is represented by B′ in Fig. 5.

Considering that the slope of B′D′ is the same as that of BD, based on point B′, the equation of the line B′D′ is:

$$\text{B}'\text{D}'\text{: } N_e = 0.3222 D_m - 14.212 \tag{10}$$

Point D′ is actually the intersection of line B′D′ and line D′E. Combining (9) and (10), the coordinate of point D′ can be obtained as (318.32 t/h, 88.35 MW).

2) However, according to the second law of thermodynamics, the energy is graded, which is determined by the steam pressure and temperature. The higher the steam pressure and temperature, the higher the grade of energy, and the greater the available energy. If the high-grade energy is artificially converted into low-grade energy, the available energy would be lost. The efficiency of bypass system can be calculated as [23]:

$$\eta = 1 - \frac{\Delta E}{D_1 E_1} \tag{11}$$

$$\Delta E = D_1 E_1 - D_2 E_2 \tag{12}$$

$$E_1 = \left(h_1 - h_0\right) - T_0\left(S_1 - S_0\right) \tag{13}$$

$$E_2 = \left(h_2 - h_0\right) - T_0\left(S_2 - S_0\right) \tag{14}$$

where η is the efficiency of bypass system; ΔE is the lost available energy; D_1 is the high-grade steam flow; D_2 is the low-grade steam flow; E_1 is the available energy of high-grade steam; E_2 is the available energy of low-grade steam; h_1 is the enthalpy of high-grade steam; h_2 is the enthalpy of low-grade steam; S_1 is the entropy of high-grade steam; h_0 is the steam enthalpy in environmental state, $h_0 = 2618$ kJ/kg; S_0 is the steam entropy in environmental state, $S_0 = 7.323$ kJ/(kg·K); and T_0 is the steam temperature in environmental state, $T_0 = 298$ K.

Based on Table IV, it can be calculated that the efficiency of HPB is $\eta_{HPB} = 0.7398$, while that of LPB is $\eta_{LPB} = 0.4961$. In this case, the total efficiency is $\eta_{total} = 0.3670$. Based on the second law of thermodynamics, it can be observed that more power generation load needs to be sacrificed to meet the same heating load, then the ordinates of B″ and D″ can be calculated as:

$$B''_y = B_y - \left(B_y - B'_y\right)/\eta_{total} \tag{15}$$

$$D''_y = D_y - \left(D_y - D'_y\right)/\eta_{total} \tag{16}$$

Based on the calculation, the coordinate of point B″ is (752.52 t/h, 168.76 MW), and that of D″ is (318.32 t/h, 46.69 MW).

Fitting BB″, B″D″, and DD″, the boundary lines of safe operation range for the CHP unit with two-stage bypass is shown in (17).

$$\begin{cases} y_{AB} = -0.1704x + 356.48 \\ y_{BB''} = -0.4641x + 518.02 \\ y_{B''D''} = 0.2811x - 42.804 \\ y_{DD''} = -0.4641x + 194.44 \\ y_{DE} = -0.1704x + 142.59 \end{cases} \tag{17}$$

B. LPC Removal

It can be observed from Fig. 6 that: ① the sealing performance of the LV is improved, so that the power generation load of the LPC can be switched between "zero" and "non-zero". When the power demand for the CHP unit is low, the LV can be closed to cut off all the steam entering the LPC, thereby reducing the power output and allowing more steam to enter the heater in heat supply network; ② the cooling valve (CV) is added to send a certain amount of cooling steam into the LPC, thereby taking away the heat generated by the rotation and ensuring the safe operation of the unit.

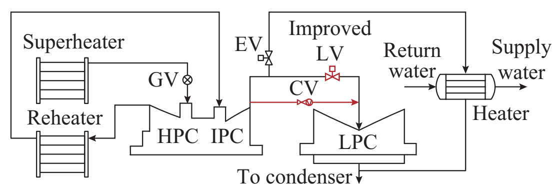

Fig. 6. Principle of extraction-type CHP unit with LPC removal.

The design parameters of the LPC is shown in Table V, and the calculation process is shown in Fig. 7. Ignoring steam leakage and heat loss, the power generation load of LPC N_{LPC} can be calculated according to (18), and the results are shown in the last column of Table V, where P_e is the rated unit load.

$$N_{LPC} = D_{in}\left(h_{in} - h_{out}\right) - \sum_{j=6}^{8} D_j\left(h_j - h_{out}\right) \tag{18}$$

where D_{in} is the inlet steam flow of LPC; h_{in} is the inlet steam enthalpy of LPC; h_{out} is the exhaust steam enthalpy of LPC; D_j is the j^{th} stage extraction steam flow of LPC; and h_j is the j^{th} stage extraction steam enthalpy of LPC.

TABLE V
DESIGN PARAMETERS OF LPC

Item	D_{in} (t/h)	h_{in} (kJ/kg)	h_{out} (kJ/kg)	D_6 (t/h)	h_6 (kJ/kg)	D_7 (t/h)	h_7 (kJ/kg)	D_8 (t/h)	h_8 (kJ/kg)	N_{LPC} (MW)
100% P_e	695.00	3020.2	2313.2	39.13	2817.7	30.78	2628.7	33.48	2478.7	126.770
75% P_e	521.68	3029.6	2331.3	27.61	2825.3	21.54	2633.5	19.58	2485.2	94.758
50% P_e	357.90	3009.8	2363.3	17.78	2810.3	13.84	2622.6	8.81	2478.9	60.785
40% P_e	297.01	2983.0	2378.2	14.39	2789.3	11.24	2607.7	5.43	2466.8	47.404
30% P_e	233.49	2955.3	2403.2	11.01	2767.8	8.61	2592.0	2.38	2454.7	34.208

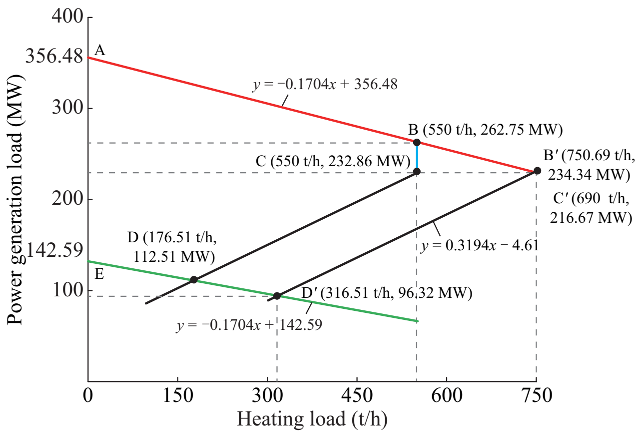

Fig. 7. Calculation of safe operation range for CHP unit with LPC removal.

The relationship between the power generation load of LPC N_{LPC} and its inlet steam flow D_{in} can be linearly fitted as:

$$N_{LPC}=0.2014D_{LPC}-12.01 \tag{19}$$

1) Considering that the LPC removal does not affect the BMCR and BSC conditions, the boundary lines AB′ and D′E coincide with AB and DE, respectively:

$$\text{AB}': N_e=-0.1704D_h+356.48 \tag{20}$$

$$\text{D}'\text{E}: N_e=-0.1074D_h+142.59 \tag{21}$$

2) Determine the coordinate of point B′. Firstly, substituting $N_e=356.48$ MW into (4), $D_m=1081.26$ t/h. Substituting it into (3), $D_{IPC}=750.69$ t/h. Considering the maximum extraction steam flow 550 t/h, the heating steam flow obtained by LPC removal is 200.69 t/h. Substituting it into (19), the power generation load can be reduced by 28.41 MW. In this case, the actually power generation load is 234.34 MW, and the coordinate of point B′ is (750.69 t/h, 234.34 MW).

3) Determine the coordinate of point C′. Substituting the minimum steam flow of LPC 140 t/h into (19), the power generation load can be reduced by 16.19 MW. In this case, the actually power generation load of the unit is 216.67 MW, i. e., the coordinate of point C′ is (690 t/h, 216.67 MW). It can be observed that point C′ is actually on the line B′D′.

4) Determine the coordinate of point D′. Since 140 t/h of steam flow is cut off, the power generation load of the unit can be reduced by 16.19 MW under the BSC condition. In this case, the coordinate of point D′ is (316.51 t/h, 96.34 MW).

5) Determine the boundary line (B′D′) under the TME condition. Based on the coordinates of point B′, C′, and D′, the straight line B′D′ can be fitted as:

$$\text{B}'\text{D}': N_e=0.3194D_m-4.61 \tag{22}$$

In summary, the boundary lines of safe operation range for the CHP unit with LPC removal are as shown in (23).

$$\begin{cases} y_{AB}=-0.1704x+356.48 \\ x_{BC}=550 \\ y_{CD}=0.3222x+55.627 \\ y_{DE}=-0.1704x+142.59 \end{cases} \text{or } y_{B'D'}=0.3194x-4.61 \tag{23}$$

C. Heat Storage Tank

In Fig. 8, a heat storage tank is added to the pipeline in the heat supply network. The tank can be started to release or store heat when the heating capacity of CHP units is insufficient or surplus. The heat storage tank is equivalent to a controllable-virtual heat user, which can make use of time difference to shift part of the heating capacity from day to night.

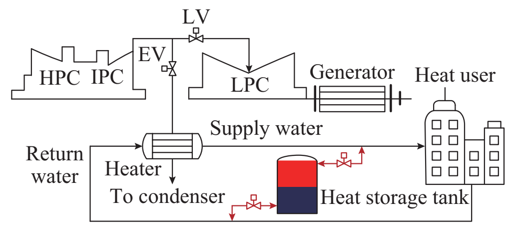

Fig. 8. Principle of extraction-type CHP unit with heat storage tank.

This paper calculates the increased heating capacity by the heat storage tank as shown in (24), and expands the safe operation range of the CHP unit. The design parameters of heat storage tank is shown in Table VI, and the calculation process is shown in Fig. 9.

$$\Delta D_h=\frac{c_p\left(t_h-t_c\right)}{h_{IPC}-h_s}D_{tank} \tag{24}$$

where c_p is the specific heat capacity of water; t_h is the hot water temperature; t_c is the cold water temperature; D_{tank} is the circulating water flow of the tank; h_{IPC} is the exhaust steam enthalpy from IPC; and h_s is the saturated water enthalpy corresponding to the exhaust steam pressure of IPC.

TABLE VI
DESIGN PARAMETERS OF HEAT STORAGE TANK

Item	Value
Diameter of tank	26 m
Total height of tank	48.6 m
Volume of tank	25864.9 m^3
Effective volume of tank	22000 m^3
Design pressure of tank	0.107 MPa
Hot water temperature	91 ℃
Cold water temperature	38 ℃
Maximum circulating water flow	3600 t/h

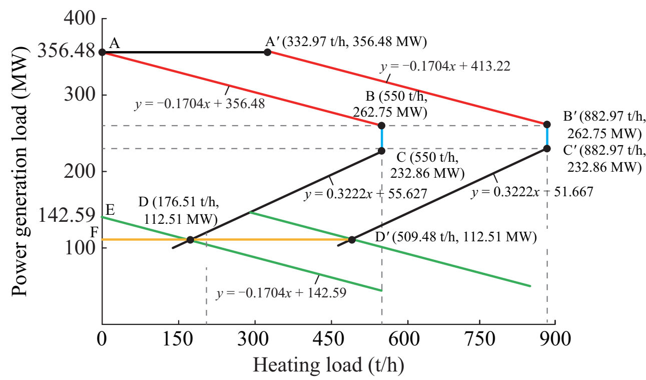

Fig. 9. Calculation of safe operation range for CHP unit with heat storage tank.

Taking $c_p = 4.1882$ kJ/(kg·°C), $t_{out} = 91$ °C, $t_{in} = 38$ °C, $D_{tank} = 3600$ t/h, $h_{IPC} = 2992.6$ kJ/kg, and $h_s = 548.35$ kJ/kg, the increased heating capacity is $\Delta D_h = 332.97$ t/h.

The safe operation range of the CHP unit with heat storage tank should be shifted to the right by (332.97 t/h, 0) during the heat release process. In this case, the coordinates of points A′, B′, C′, and D′ are (332.97 t/h, 356.48 MW), (882.97 t/h, 262.75 MW), (882.97 t/h, 232.86 MW), and (509.48 t/h, 112.51 MW), respectively. Similarly, it should be shifted to the left by (332.97 t/h, 0) during the heat store process. Considering that the heating load of point D is only 176.51 t/h, it can be stored completely. Therefore, point D can be translated to the y-axis as point F with coordinates of (0, 112.51 MW).

In summary, the boundary lines of safe operation range for the CHP unit with heat storage tank is shown in (25).

$$\begin{cases} y_{AA'} = 356.48 \\ y_{A'B'} = -0.1704x + 413.22 \\ x_{B'C'} = 882.97 \\ y_{C'D'} = 0.3222x - 51.667 \\ y_{D'F} = 112.51 \end{cases} \tag{25}$$

D. Electric Boiler

In Fig. 10 [24], an electric boiler is added to the pipeline in the heat-supply network, and part of the power generation load is used to heat the water in the heat supply network. The electric boiler can be started to heat the return water when the power generation load decreases, thereby making up for the insufficient heating capacity of the CHP unit. Since a large part of the power generation load is consumed by the electric boiler, the unit load actually sent to the power system is greatly reduced, which solves the contradiction between heating and peaking.

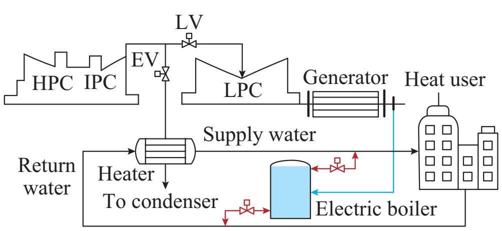

Fig. 10. Principle of extraction-type CHP unit with electric boiler.

The increased heating capacity of the electric boiler can be calculated by (26). The design parameters of the electric boiler are shown in Table VII and the calculation process is shown in Fig. 11.

$$\Delta D_e = \frac{3600}{h_{IPC} - h_s} \eta_{e2h} \eta_{h2h} P_{eboiler} \tag{26}$$

where η_{e2h} is the electricity-heat conversion efficiency; η_{h2h} is the heat exchanger efficiency; and $P_{eboiler}$ is the rated load of electric boiler.

Taking $h_{IPC} = 2992.6$ kJ/kg, $h_s = 548.35$ kJ/kg, $\eta_{e2h} = 99\%$, $\eta_{h2h} = 95\%$, and $P_{eboiler} = 125$ MW, the increased heating capacity of the electric boiler is $\Delta D_e = 173.15$ t/h.

TABLE VII
DESIGN PARAMETERS OF ELECTRIC BOILERS

Item	Value
Rated load of electric boiler	5 × 25 MW
Electricity-heat conversion efficiency	99%
Heat exchanger efficiency	95%

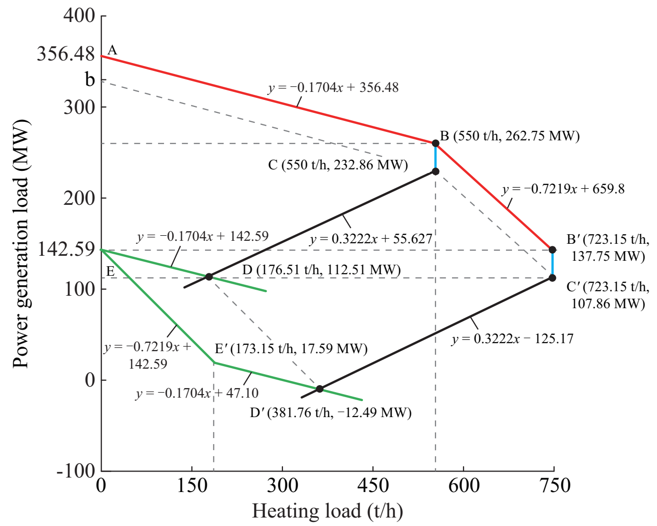

Fig. 11. Calculation of safe operation range for CHP unit with electric boiler.

The safe operation range of the CHP unit with electric boiler should be shifted to the right by (173.15 t/h, 125 MW). In this case, the coordinates of points B′, C′, D′, and E′ are (723.15 t/h, 137.75 MW), (723.15 t/h, 107.86 MW), (381.76 t/h, −12.49 MW), and (173.15 t/h, 17.59 MW), respectively.

In summary, the boundary lines of safe operation range for the CHP unit with electric boiler is shown in (27).

$$\begin{cases} y_{AB} = -0.1704x - 356.48 \\ y_{BB'} = -0.7219x + 659.8 \\ x_{B'C'} = 723.15 \\ y_{C'D'} = 0.3222x - 125.17 \\ y_{D'E'} = -0.1704x + 47.10 \\ y_{E'E} = -0.7219x + 142.59 \end{cases} \tag{27}$$

IV. COMPARISON OF EACH FLEXIBILITY MODIFICATION

A. Deep Peak Shaving Capability (DPSC)

All flexibility modifications can improve the DPSC of the CHP unit to some extent, as shown in Table VIII. The DPSC is given in (28).

$$DPSC = 1 - \frac{N_e}{330} \tag{28}$$

1) Since the two-stage bypass modification fails to affect the BSC condition, the DPSC of the CHP unit with the two-stage bypass remains unchanged when the heating load varies from 0 to 100 t/h. However, it is significantly increased

when the heating load varies from 200 t/h to 700 t/h. In particular, when the heating load reaches 600 t/h, the DPSC of the CHP unit with the two-stage bypass is increased from 0% to 61.86%. Therefore, the two-stage bypass modification can greatly improve the DPSC of the CHP unit. In addition, the minimum power generation load of the CHP unit with two-stage bypass can be reduced as low as 55.21 MW, thereby freeing up more space for wind power accommodation.

TABLE VIII
DPSC OF EACH FLEXIBILITY MODIFICATION

D_h (t/h)	CHP unit		CHP unit with two-stage bypass		CHP unit with LPC removal		CHP unit with heat storage tank		CHP unit with electric boiler	
	N_e (MW)	DPSC (%)	N_e (MW)	DPSC (%)	N_e (MW)	DPSC (%)	N_e (MW)	DPSC (%)	N_e (MW)	DPSC (%)
0	142.59	56.79	142.59	56.79	142.59	56.79	112.51	65.91	142.59	56.79
100	125.55	61.95	125.55	61.95	125.55	61.95	112.51	65.91	70.40	78.67
200	120.07	63.62	101.62	69.21	108.51	67.12	112.51	65.91	13.02	96.05
300	152.29	53.85	55.21	83.27	91.47	72.28	112.51	65.91	–4.02	101.22
400	184.51	44.09	69.64	78.90	123.19	62.67	112.51	65.91	3.71	98.88
500	216.73	34.32	97.75	70.38	155.10	53.00	112.51	65.91	35.93	89.11
600			125.86	61.86	187.01	43.33	141.65	57.08	68.15	79.35
700			153.97	53.34	218.92	33.66	173.87	47.31	100.37	69.58
800							206.09	37.55		

2) Same as the two-stage bypass, LPC removal modification has almost the same effect, which can also improve the DPSC of the CHP unit and reduce the minimum power generation load.

3) Although the heat storage tank modification fails to affect the BSC condition, it can still reduce the minimum power generation load when the heating load varies from 0 to 100 t/h. This is because the heat storage tank can also play the role of a controllable-virtual heat user to store heat under the low load condition. The safe operation range of the CHP unit with heat storage tank has been greatly expanded, which improves its DPSC in a large scale. However, the heat storage tank modification fails to further reduce the minimum power generation load (112.51 MW).

4) The electric boiler uses part of the power output to heat the return water, which not only increases the heating capacity, but also reduces the power generation load of the unit. In this case, the electric boiler modification can greatly reduce the minimum power generation load of the unit, even below zero. Compared with the other flexible modifications, the electric boiler significantly improves the DPSC of the CHP unit.

B. Effect on Wind Power Accommodation

From the above subsection, the flexibility modification can improve the DPSC of the CHP unit to varying degrees. What are their effects on wind power accommodation? This paper has conducted a detailed analysis as follows.

1) Two-stage Bypass

From Fig. 12, with the heating load demand D_h, the adjustable range of the CHP unit with two-stage bypass is increased (green two-way arrow in Fig. 12(b)). In this case, the CHP unit can accommodate all wind power (area enclosed by c-d-e-f-g in Fig. 12(a)).

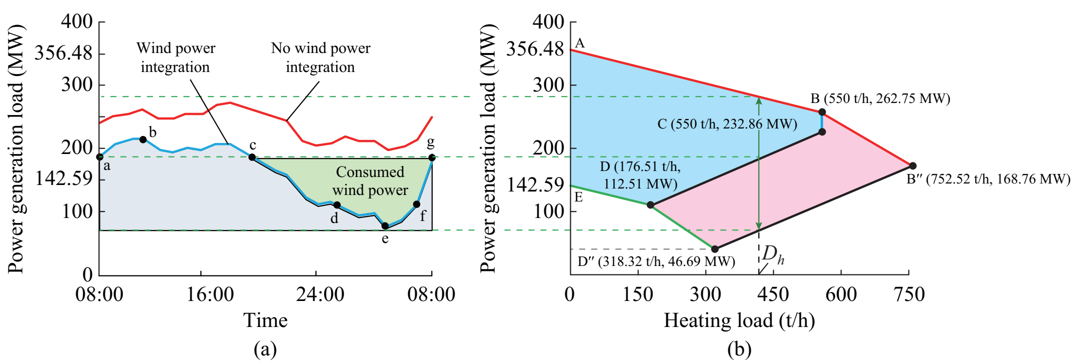

Fig. 12. Effect of two-stage bypass modification on wind power accommodation. (a) Daily power generation load demand. (b) Safe operation range.

2) LPC Removal

From Fig. 13, with the heating load demand D_h, the adjustable range of the CHP unit with LPC removal is increased. In this case, the CHP unit can consume more wind power (area enclosed by d-e-g-h in Fig. 13(a)). Since the power generation load of the LPC can only be switched between "zero" and "non-zero", the increased heating capacity is limited, and as a result, three parts of wind power (areas enclosed by c-d-e, e-f-g, and h-g-i in Fig. 13(a)) are abandoned.

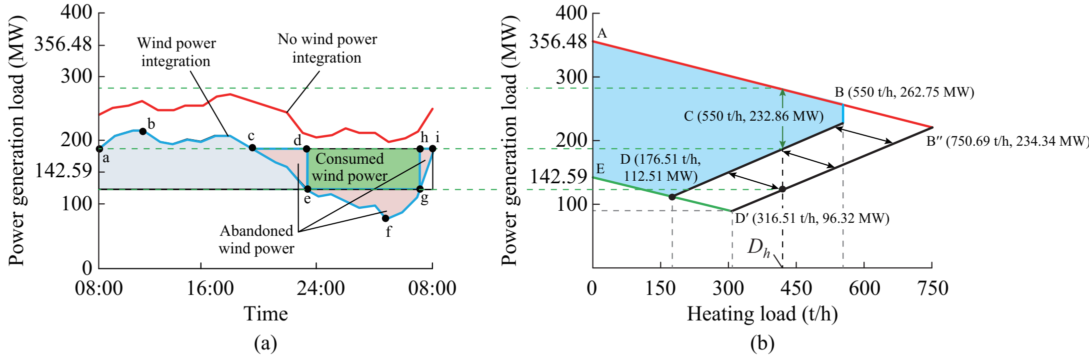

Fig. 13. Effect of LPC removal modification on wind power accommodation. (a) Daily power generation load demand. (b) Safe operation range.

3) Heat Storage Tank

As shown in Fig. 14, although the heat storage tank modification greatly expands the safe operation range, the actual wind power consumption capacity is related to the heat stored during the daytime. Since the surplus heating capacity of the CHP unit is small during the daytime (Fig. 14(a)), the heat stored in the heat storage tank is less, resulting in poor auxiliary heating capacity during the nighttime. In this case, the CHP unit can only consume the wind power enclosed by c-d-e-j in Fig. 14(a), and most of it is abandoned (area enclosed by e-f-g-h-i-j).

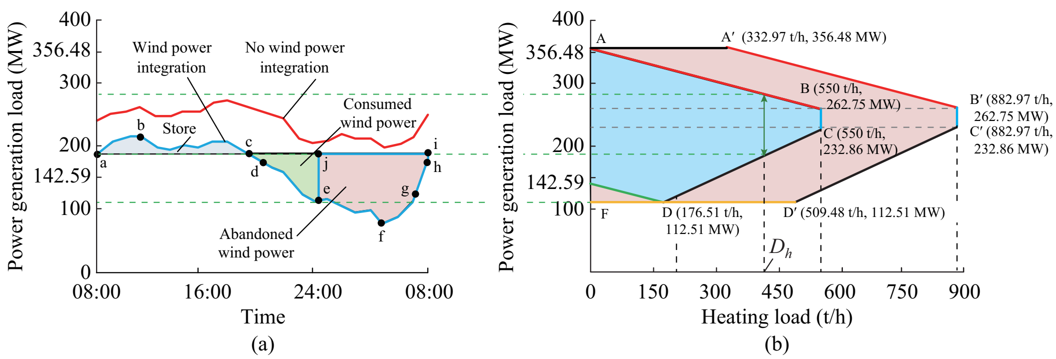

Fig. 14. Effect of heat storage tank modification on wind power accommodation. (a) Daily power generation load demand. (b) Safe operation range.

4) Electric Boiler

From Fig. 15, with the heating load demand D_h, the adjustable range of the CHP unit with electric boiler is greatly increased (green two-way arrow in Fig. 15(b)). In this case, the CHP unit can accommodate all wind power (area enclosed by c-d-e-f-g-h-i in Fig. 15(a)). Therefore, proper electric boiler modification can completely decouple the constraints of "ordering power by heat".

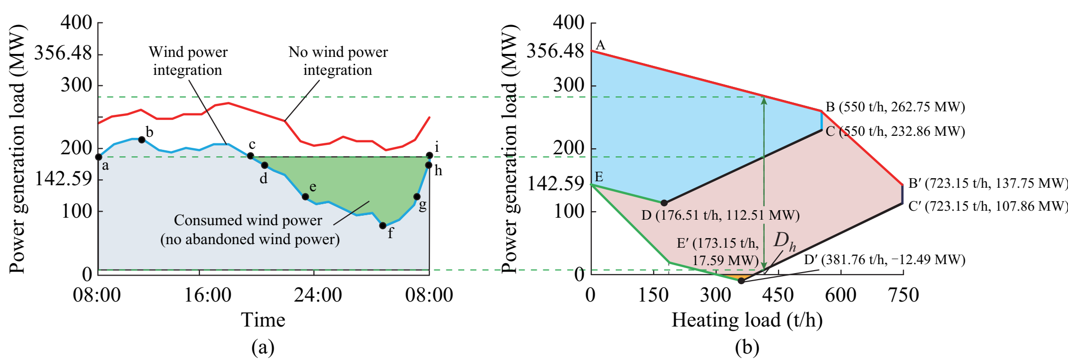

Fig. 15. Effect of electric boiler modification on wind power accommodation. (a) Daily power generation load demand. (b) Safe operation range.

C. Adaptability Analysis in Different Wind Scenarios

All flexibility modification can accommodate wind power to varying degrees. However, there are differences in adaptabilities to wind power accommodation. This paper further simulates and analyzes their adaptabilities in different wind scenarios. If the daily average load rate is less than $50\%P_e$, it would be regarded as a strong wind scenario; otherwise, it would be regarded as a small wind scenario. The following variables are defined: D_h^{DMD} is the heating load demand; D_h^{CHP} is the heating load output from the CHP unit; D_h^{AUX} is the auxiliary heating load output from the flexible devices; D_h^{ACT} is the actual heating load sent to the heat-supply network; N_e^{DMD} is the power generation load demand; N_e^{CHP} is the power generation load output from the CHP unit; N_e^{ABD} is the abandoned wind power load; and N_e^{ACT} is the actual power generation load sent to the power system.

From Figs. 16 and 17, the bypass and electric boiler modifications can adapt to both strong and small wind scenarios, and as a result, they can meet the heating load demand without abandoning any wind power (Figs. 16(a), 16(d), 17(a), and 17(d)).

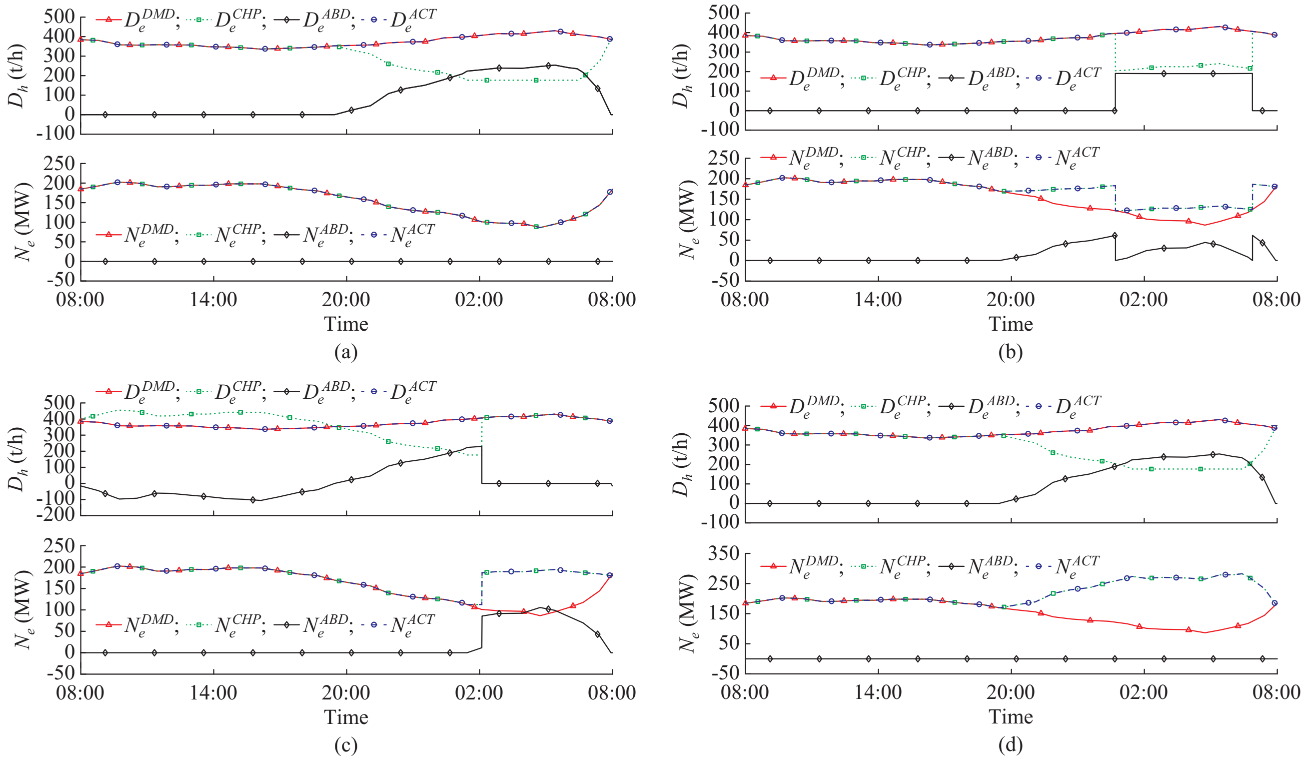

Fig. 16. Adaptabilities to strong wind scenario. (a) Two-stage bypass. (b) LPC removal. (c) Heat storage tank. (d) Electric boiler.

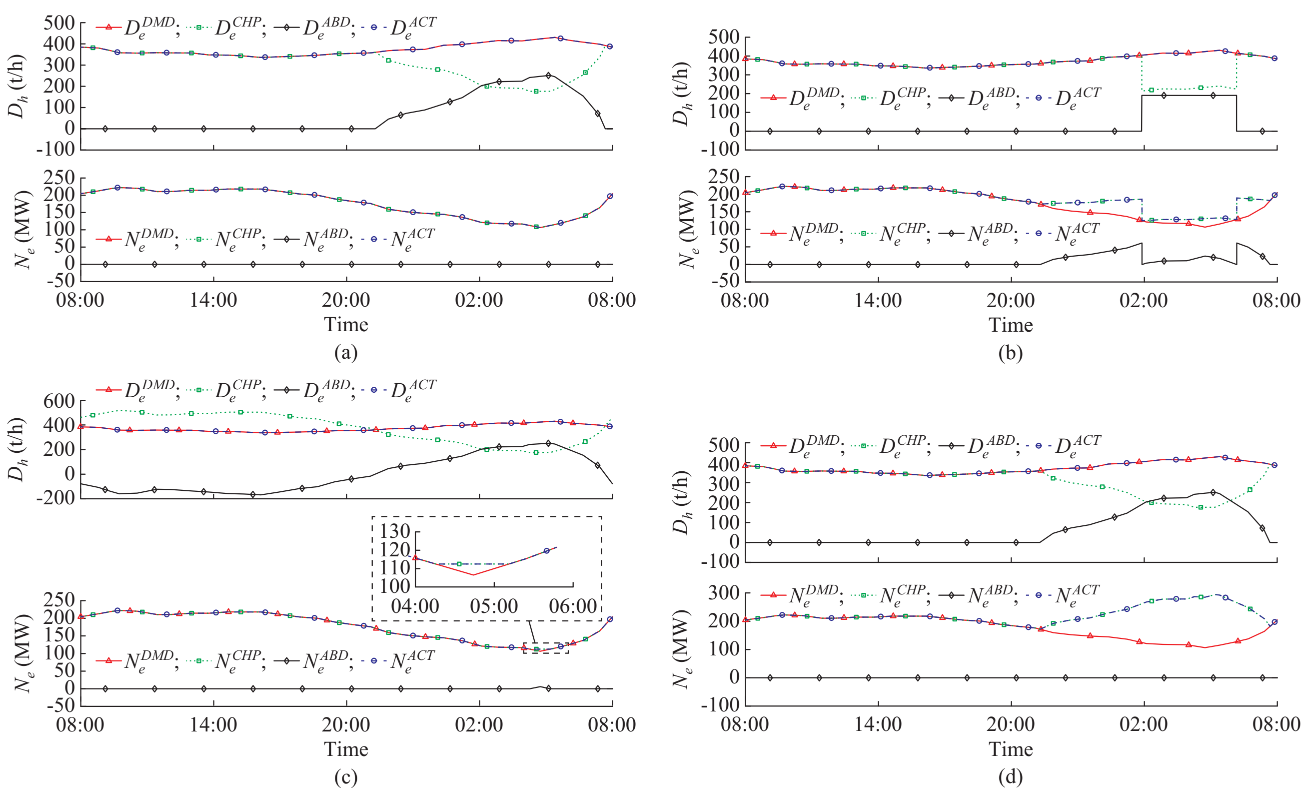

Fig. 17. Adaptabilities to small wind scenario. (a) Two-stage bypass. (b) LPC removal. (c) Heat storage tank. (d) Electric boiler.

However, the LPC removal fails to adapt to neither strong nor small wind scenarios, resulting in a large part of abandoned wind power (Fig. 16(b) and Fig. 17(b)). The heat storage tank modification is extremely unstable for wind power accommodation. Due to the low power demand during the daytime, the surplus heating capacity is small, and as a result, the tank stores less heat and the unit exits the peak shaving condition early during the nighttime (Fig. 16(c)).

In order to further illustrate the adaptability of these flexibility modifications, this paper calculates the abandoned wind power in different scenarios as shown in Table IX.

TABLE IX
ABANDONED WIND POWER IN DIFFERENT SCENARIOS

Scenario	Abandoned wind power (MWh)				
	CHP unit	Bypass	LPC removal	Storage tank	Electric boiler
Small wind	520.41	0	250.29	2.79	0
Strong wind	776.66	0	359.41	474.96	0

From the table, the bypass and electric boiler modifications can realize the full accommodation of wind power. The LPC removal modification can reduce abandoned wind power to some extent, but most of the wind power is still abandoned. The heat storage tank modification is unstable in wind power accommodation. Only 2.79 MWh of wind power is abandoned under small wind scenario, while 474.96 MWh of wind power is abandoned under strong wind scenario. Since the electric boiler can convert electricity to heat, the full accommodation of wind power can be realized.

V. CONCLUSION

All flexibility modifications can improve the DPSC of the CHP unit to varying degrees. Among them, the effect of the electric boiler is the most significant, and the proper electric boiler modification can completely decouple the constraints of "ordering power by heat" for the CHP unit. Compared with other flexibility modifications, the heat storage tank modification fails to further reduce the minimum power generation load of the CHP unit.

All flexibility modifications can consume wind power to varying degrees. Among them, the electric boiler can achieve full accommodation of wind power. Although the heat storage tank modification greatly expands the safe operation range, its actual effect on wind power accommodation is limited by the surplus heating capability during the daytime. The more heat stored in the heat storage tank during the daytime, the stronger the wind power accommodation capability during the nighttime.

The electric boiler and bypass modifications can adapt well to both strong and small wind scenarios, especially for the electric boiler modification, which can realize the full accommodation of wind power. The LPC removal modification can reduce the abandoned wind power to some extent, but most of the wind power is still abandoned. The heat storage tank modification is unstable in wind power accommodation, which can only adapt to small wind scenario.

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