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Improved Ramping and Reserve Modeling of Combined Heat and Power in Integrated Energy Systems for Better Renewable Integration

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***Abstract*—With the largest installed capacity of wind power and solar PV in the world, China is experiencing an approximately 10% curtailment in major northern provinces. The combined heat and power (CHP) units account for over 50% of the local thermal generation capacity, hardly making contributions to ancillary services due to complex coupling of heat and power constraints, and thus are the major barriers for renewable energy integration. This paper explores opportunities for increasing the flexibility of CHP units by improving modeling of ramping and reserve constraints. Reformulated ramping constraints are proposed via analyzing the internal mechanical structure and introducing the regulation of heat exchange rate controlled by heating butterfly valve. A reformulated available reserve capacity model is put forward based on heating compensation mechanism between CHP units and heat storages. The reformulated models are examined in a 6-bus test system and the results show that the reformulated ramping constraint model improves notably the ramping capability of CHP units, especially operating in parallel with heat storages, facilitating the renewable integration during morning hours; whereas the reformulated reserve constraints release the hidden capability of heat storages to supply power reserves, enabling the system integration of additional renewable energy.**

***Index Terms*—Combined heat and power, heat storage, ramping constraints, reserve capacity constraints, curtailment.**

NOMENCLATURE

p^c / q^c	Total power/heat production of CHP units.
p_1 / p_2	Power output of integrated HP and MP cylinder/LP cylinder of CHP units.
R_i^d / R_i^u	Ramp-down/ramp-up limits of i^{th} unit.
$\triangle p^c$	Change of power output of CHP units.
G_t	Steam volume entering into HP cylinder at time t.
α_t	Ratio of steam flow entering into heating network.
$p_{i,t}^c / q_{i,t}^c$	Power/heat production of i^{th} CHP unit at time t.
η_1 / η_2	Ratio of steam to power of integrated HP and MP cylinder/LP cylinder.
η_h	Efficiency of heat exchange.
$I_{i,t}^c$	Binary variable representing online/offline of i^{th} CHP unit at time t.
S_i^d / S_i^u	Start up/shut down ramping limits of i^{th} unit.
$\bar{P}_i^c$	Maximum power production of i^{th} CHP unit.
$\bar{p}_{i,t}^c$	Maximum available power production of i^{th} CHP unit at time t.
$\underline{q}_{i,t}^c$	Minimum necessary heat production of i^{th} CHP unit at time t.
M_i^{AB} / N_i^{AB}	Constant coefficients of boundary AB of i^{th} CHP unit.
rs_t	Reserve capacity of i^{th} CHP unit at time t.
$q_{i,t}^{hs}$	Heating output of i^{th} heat storage at time t.
$\bar{q}_{i,t}^{hs}$	Maximum available heating output of i^{th} heat storage at time t.
$N_p / N_q / N_c$	Number of conventional thermal units/heating boilers/CHP units.
$C_{i,t}^p / C_{i,t}^q / C_{i,t}^c$	Fuel cost of i^{th} conventional thermal units/heating boilers/CHP units at time t.
$\xi_w / \xi_{pv} / \xi_{hs}$	Penalty on wind power/PV/heat storage.
$\omega_1 / \omega_2 / \omega_3$	Penalty factors of curtailment of wind power/PV/daily energy recovery of heat storages.
$N_w / N_{pv} / N_{hs}$	Number of wind farms/PV farms/heat storages.
$p_{i,t}^w / p_{i,t}^{pv}$	Actual power production of i^{th} wind farm/PV farm at time t.
$\bar{p}_{i,t}^w / \bar{p}_{i,t}^{pv}$	Maximum available power production of i^{th} wind farm/PV farm at time t.

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$\varphi_{i,t}$	Slack variable of i^{th} heat storage at time t.
$p_{i,t}^{p}$	Power production of i^{th} conventional thermal unit at time t.
$p_{i,t}^{eb}$	Power consuming of i^{th} electrical boiler at time t.
N_{eb}	Number of electrical boilers.
P_t	System power load at time t.
p_t^{EV}	Electrical vehicles power load at time t.
$q_{i,t}^{hb} / q_{i,t}^{eb}$	Heat production of i^{th} heating boiler/electrical boiler at time t.
N_{hb} / N_{hs}	Number of heating boilers/heat storages.
$Q_{i,t}$	Heat demand in i^{th} district at time t.
$\bar{P}_i^p$	Maximum available power production of i^{th} conventional thermal unit.
$I_{i,t}^p$	Binary variable representing online/offline of i^{th} conventional thermal unit at time t.
UT_i / DT_i	Minimum up/down time of i^{th} CHP unit.
G_i / L_i	Initial time periods when i^{th} CHP unit is online/offline till the start time.
$Q_{i,t}^{hs}$	Total available heat energy of i^{th} heat storage at time t.
$q_{i,t}^{loss}$	Heat loss of i^{th} heat storage at time t.
η^{hs}	Expanding rate of hot-cold-mixing water of heat storages.
Δt	Time duration.
η_i^{eb}	Conversion efficiency of i^{th} electrical boiler.
$\bar{p}_{i,t}^p$	Maximum available power production of i^{th} conventional thermal unit at time t.
RES_t	Required reserve capacity of system at time t.

I. Introduction

The installed capacity for wind power and photovoltaics in China reached 414GW till the end of 2019 [1][2], accounting for 33% of the global installation [3][4]. However, the curtailment rate of wind power ranged from 7% to 14% in the Northern and Northwestern provinces [2] and that of photovoltaics reached at maximum 24.1% in the Northwestern provinces [1] in China, incurring $1.4 billion financial losses annually [5][6].

In the Northeastern provinces in China, the wind tends to be strongest in the early morning, putting pressure on the ramping requirement during the upcoming morning peak. Similarly, with large installed capacity of PV in the Northwestern provinces, the “duck curve” effect leads to significant ramping deficit during sunset. In Guangdong province, the ramping problem is especially serious from approximately 8 a.m. to 11 a.m. (maximum 4.9 GW in 15 minutes) due to its power consumption characteristics. Flexibility requirements, especially fast ramping and reserves, are essential to deal with the variability of renewables.

Combined heat and power (CHP) units are major contributor in the generation mix for providing heat in China. In the Northern provinces, CHP units account for more than 50% of the thermal generation capacity. Even in southern Guangdong province, considerable number of CHP units are installed for central heat supply in industrial parts. Meanwhile, CHP units operate 120-210 days per year to meet the heat and power demands [7], making CHP plants an important role in energy supply.

However, CHP units lack flexibility because of the special operational mode, where the heat supply is pre-set and the power production could only be changed restrictedly with the influence of heating level. Also, the CHP units make less contribution to reserve capacity in the ancillary services market.

A promising method to relieve the constraints between a high level of power production of CHP units and consuming much wind power and photovoltaics is installing electrical boilers and heat storages [8][9]. Electrical boilers can provide heat by consuming power, coordinating with CHP units to meet the heat demand. Heat storages can store and release heat by exchanging the hot and cold water, making total energy keep a dynamic balance. Although electrical boilers and heat storages play a part in improving the ability of consuming wind power and photovoltaics, there is less advance on the flexibility of CHP units in terms of ramping and reserve requirements.

Several electrical options, such as battery energy storage systems, could provide fast ramping and reserve capabilities [10]-[13]. However, such equipment requires significant additional investments. Meanwhile, electrical boilers, heating boilers and heat storages have been installed in some regions in Chins for several years, with the purpose of decoupling the internal constraints of power and heat production from CHP units and reducing the minimum power output of CHP units when wind is strong. Based on the installed heating-supply equipment, it is more economical to explore the auxiliary benefits of CHP units on fast ramping and reserve, which are only limited by the existing mathematical formulation of operation and control model.

Important research has been conducted on integrated energy systems incorporating CHP units [14]-[22]. Efficient operation of the system is demonstrated in the heating system with CHP units and storages [14][15]. The integrated energy system optimized operation could bring CO_2 emission decreasing and social welfare increasing [16][17]. In [18], biogas plants with CHP systems are integrated to conduct long-term supply-demand adjustments. An economic dispatch model for power and heating systems are developed in [19] considered the detailed modeling of CHP units, heat boilers, electrical boilers and heat storages, with the result of reducing wind curtailment and saving energy by installing electrical boilers and heat storages. Wind power is further absorbed based on a district heating network in an integrated energy system [20]. In [21], a bilevel market equilibrium model for integrating solar-powered heat pumps into CHP systems is simulated to demonstrate the investment of solar-powered heat pumps. A regional energy system (Jing-Jin-Tang) is simulated in [22], considering the ramping constraints of the CHP units and showing the less wind

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curtailment rate and investment. However, the ramping requirements in the previous literature are either omitted or simply borrow the form of conventional thermal units. The interaction between power and heat output has not been considered for the modeling of ramping requirement of CHP explicitly.

Several researches on ancillary services that CHP units could supply are listed in [23]-[31]. The reserve flexibility of conventional units is illustrated and extended considering the electricity and heat coupling characteristics [23][24]. The integrated community energy system has the ability to participate in a joint energy and ancillary service market [25]. Dynamic operability of CHP units is analyzed in [26] to better attend the Automatic Frequency Restoration Reserve market. An operational and financial analysis on CHP units, PV systems and energy storages based on both energy and ancillary services markets is studied in [27]. A two-layer control method to coordinate CHP with district heating energy sources is put forward in [28], bringing CHP the ability to provide frequency response persistently in the GB Firm Frequency Response market. An optimal bidding model is built in [29] for energy companies owning CHP units and heat storage devices to allocate the capacity considering the predicted load level. The strategy of making solar, wind and CHP participate in the Ancillary Services market in a microgrid is studied in [30]. The feasibility of integrating heat pumps with CHP plants to participate in reserve power markets is discussed in [31]. However, there is less research on detailed reserve capacity models of CHP units based on heating compensation. Meanwhile, the application to the service market of CHP units is limited.

This paper developed an improved model for integrated power and heating systems for both economic dispatch and unit commitment problems, with a special focus on the ramping and reserve constraints for CHP units. We start with analyses of the internal mechanical structure of the CHP unit, especially the heating butterfly valve with its actuator and control mechanism. Then we model the reformulated ramping constraints considering not only the change of steam volume at the steam inlet, but also the alter of volume for heat exchange controlled by the valve before the low pressure cylinder. We also model the reformulated available reserve capacity constraints of CHP units, coordinating with the heat storages for heat compensation and operational point optimization. Next, we structure a small test system, including conventional thermal units, CHP units, wind farms, PV farms, heat boilers, electrical boilers and heat storages, and five different scenarios, with the target of optimizing the production from all power and heat sources to balance the demands in each district at all time periods.

Based on simulations on the test system, with improved modeling of ramping and reserve constraints, we find that the application of heat storages is crucial: the abilities of rapid ramping and reserve supply of CHP units are advanced, the amount of necessary online units reduces, and the curtailment of wind power and PV can be decreased.

The main contributions that this paper makes are as follows.

1) We analyze the internal mechanical structure of the CHP unit and the steam flow in detail, and establish the heat and power output models. By analyzing and deriving the coupling relationship between heat and power, we put forward the reformulated ramping constraints considering the heating exchange controlled by the heat valve, extending the ramping ability of CHP units.
2) Based on the CHP typical feasible operational area, we analyze the details of the operating point and illustrate the varying reserve capacity. By analyzing the heating compensation mechanism of heat storages and CHP units, we put forward the reformulated available reserve capacity constraints, enabling the additional reserve supply of CHP units.
3) We structure a case system with conventional thermal units, CHP units, wind farms, PV farms, heat boilers, electrical boilers and heat storages and five scenarios for simulation hourly for a typical day. The results show that the application of the reformulated ramping constraints can efficiently reduce the wind power and PV curtailment, compared to that when adopting the conventional ones. Also, the reformulated reserve capacity constraints could reduce the fuel cost of the conventional power units by consuming more wind and PV power.

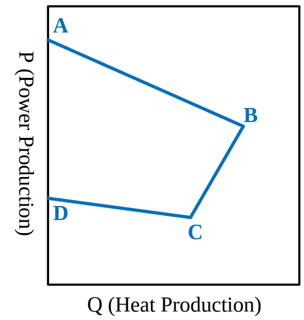

Fig 1. Typical feasible operational area of CHP units.

The ramping models and reserve capacity of CHP units combined with heat storages are formulated in Section II. The system model including objective function and numerous constraints is formulated in Section III. The designed case with conventional thermal units, CHP units, wind power, photovoltaic, electrical boilers, heating boilers and heat storages is described in Section IV, as well as contrastive scenarios and test results. Conclusions are presented in Section V.

II. Modeling of Flexibility of CHP Units

In this section, we firstly present the general description of the combined heat and power units. Then the internal steam flow of the CHP unit is analyzed, including its structure and the control mechanism of the valve. Next, the power and heat production of the CHP unit is formulated, followed by reformulated ramping constraints. The advanced expression of reserve capacity of the CHP unit is given, coordinating with heat storage devices.

A. General Description of CHP Units

CHP units can simultaneously produce power and heat, playing an important role in both power and heat system. The

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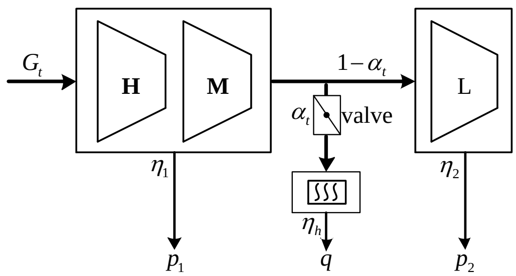

Fig 2. Steam flow and power and heat output of CHP units.

typical feasible operational area of a CHP unit is shown in Fig. 1. The operational area is surrounded by four boundaries of AB, BC, CD and DA, which represent the maximum limit of power production, the maximum limit of fuel injection, the maximum heating rate and the minimum limit of steam injection respectively [32].

A few constraints impose restrictions on the operation of the CHP units and previous researches had formulated relatively comprehensive constraints, such as generation limits, ramping constraints and minimum up and down time constraints.

B. Improved Formulation of Ramp Rates

1) Internal Steam Flow

A CHP unit generally consists of high pressure (HP) cylinder, medium pressure (MP) cylinder, low pressure (LP) cylinder and other mechanical components as shown in Fig. 2. The high-temperature and high-pressure steam first enters into the HP cylinder and the MP cylinder successively, doing work and producing power. A part of the steam flow which is relatively low-temperature and low-pressure from the MP cylinder enters into the LP cylinder and similarly does work and produces power, while another part enters into heating network, driving heat exchange and producing heat.

The total power production and heat production of the CHP unit are expressed as follows:

$$\begin{cases} p^c = p_1 + p_2 \\ q^c = q \end{cases} \tag{1}$$

The conventional ramping constraint is expressed as:

$$-R_i^d \le \triangle p^c \le R_i^u \tag{2}$$

The conventional ramping constraint only considers the change of input steam volume which is controlled by the main steam butterfly valve. However, the ratio of the steam entering into heating network can also be regulated by the heating butterfly valve, which would affect the total power production as well.

The heating butterfly valve installed between the MP cylinder and heating network, shown in Fig. 2, has the characteristic of remote control by oil motor, the same as the main steam butterfly valve. The valve actuator with high-pressure fire-resistant oil as its power oil consists of hydraulic servo-motor, connector and spring, thus the valve works as hydraulic opening and spring closing.

For typical CHP units, the maximum limit rate of the increasing or decreasing heat supply is 4 to 5 ton per minute controlled by the heating butterfly valve for a few mechanical restrictions.

2) Modeling of Power and Heat Production

The power and heat production of a CHP unit at time t would be given by

$$p_{i,t}^c = \eta_1 \cdot G_t + \eta_2 \cdot (1-\alpha_t) \cdot G_t \tag{3}$$

$$q_{i,t}^c = \eta_h \cdot \alpha_t \cdot G_t \tag{4}$$

Considering that G_t ranges from 30% to 100% of the rated value, η_2 and η_h would be constants whether the CHP unit operates in a constant-pressure or sliding-pressure mode.

Similarly, we could also model the power and heat production, $p_{i,t-1}^c$ and $q_{i,t-1}^c$, at time $t-1$. By subtracting $p_{i,t}^c$ and $p_{i,t-1}^c$, as well as $q_{i,t}^c$ and $q_{i,t-1}^c$, the expressions of power and heat change between time t and $t-1$ could be calculated respectively:

$$\begin{aligned} p_{i,t}^c - p_{i,t-1}^c = &\eta_1 \cdot (G_t - G_{t-1}) + \eta_2 \cdot (G_t - G_{t-1}) \\ &- \eta_2 \cdot (\alpha_t \cdot G_t - \alpha_{t-1} \cdot G_{t-1}) \end{aligned} \tag{5}$$

$$q_{i,t}^c - q_{i,t-1}^c = \eta_h \cdot (\alpha_t \cdot G_t - \alpha_{t-1} \cdot G_{t-1}) \tag{6}$$

By combining (5) and (6), and then eliminating the same part $(\alpha_t \cdot G_t - \alpha_{t-1} \cdot G_{t-1})$, the following equation would be satisfied:

$$\begin{aligned} p_{i,t}^c - p_{i,t-1}^c = &\eta_1 \cdot (G_t - G_{t-1}) + \eta_2 \cdot (G_t - G_{t-1}) \\ &- \eta_{2h} \cdot (q_{i,t}^c - q_{i,t-1}^c) \end{aligned} \tag{7}$$

where η_{2h} is equal to the result of η_2 divided by η_h.

The equation (7) illustrates the coupling relationship between the difference of power production and that of heat supply at time $t-1$ and t. The first two terms on the right side, $\eta_1 \cdot (G_t - G_{t-1}) + \eta_2 \cdot (G_t - G_{t-1})$, reflect the effect of input steam volume change on ramping, and therefore are the same as $\triangle p^c$ in the equation (2). The last term illustrates the influence of heat-production changing solely due to η_{2h} being a constant.

3) Reformulated Ramping Constraints

By combining Equation (2) with (7), and eliminating $\triangle p^c$ and $\eta_1 \cdot (G_t - G_{t-1}) + \eta_2 \cdot (G_t - G_{t-1})$, the reformulated ramping constraints would be given by:

$$p_{i,t}^c - p_{i,t-1}^c \le \mathrm{R}_i^u - \eta_{2h} \cdot (q_{i,t}^c - q_{i,t-1}^c) \tag{8}$$

$$p_{i,t-1}^c - p_{i,t}^c \le \mathrm{R}_i^d + \eta_{2h} \cdot (q_{i,t}^c - q_{i,t-1}^c) \tag{9}$$

Compared to the conventional ramping constraint (2), the advanced formulations take the change of heat production into consideration additionally. The advanced models result in that the available increasing or decreasing rate of power production of the CHP units would be higher than that of conventional thermal units.

For example, when the CHP units are requested to improve the power supply, the steam volume would be increased and heat production be decreased simultaneously, giving rise to rapid power production increasing.

The reformulated ramping constraints expand the rate limit of increasing and decreasing power production, improving the

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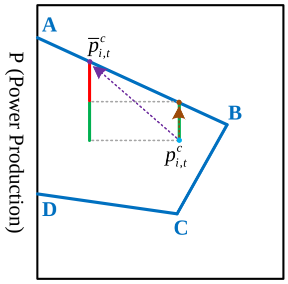

Fig 3. Change of operating point of the CHP unit.

flexibility of CHP units.

When considering further the unit commitment models, which are the extension and generalization of (8)(9) for economic dispatch problems, the ramping constraints of a CHP unit employ the following forms, containing the change of heat production in addition based on the form as in [22]:

$$p_{i,t}^{c}-p_{i,t-1}^{c}\le \mathrm{R}_{i}^{u}\cdot I_{i,t-1}^{c}+S_{i}^{u}\cdot(I_{i,t}^{c}-I_{i,t-1}^{c}) + \overline{P}_{i}^{c}\cdot(1-I_{i,t}^{c})-\eta_{2h}\cdot\left(q_{i,t}^{c}-q_{i,t-1}^{c}\right) \tag{10}$$

$$p_{i,t-1}^{c}-p_{i,t}^{c}\le \mathrm{R}_{i}^{d}\cdot I_{i,t}^{c}+S_{i}^{d}\cdot(I_{i,t-1}^{c}-I_{i,t}^{c}) + \overline{P}_{i}^{c}\cdot(1-I_{i,t-1}^{c})+\eta_{2h}\cdot\left(q_{i,t}^{c}-q_{i,t-1}^{c}\right) \tag{11}$$

By conducting the coordinated heat supply, the flexibility of CHP units would be improved, making the CHP units a more important role in ancillary services.

C. Reserve Capacity

1) Change of CHP Operating Points

For economic reasons, the operating point of the CHP unit $(q_{i,t}^{c}, p_{i,t}^{c})$ is mostly located near the upper boundary, as shown in Fig. 3. This feature would result in limited reserve capacity as the green line segment that the CHP unit can supply during most operational periods, when the brown arrow represents the movement of operating point.

For a part of the CHP units, the upper boundary AB has the characteristic of negative slope, which means that the unit can produce more power by decreasing its heat output. Hence, by means of heating compensation, the reserve capacity can be increased.

For the i^{th} CHP unit, the maximum available power production $\overline{p}_{i,t}^{c}$ at time t is shown in Fig. 3.

Given that the line segment AB has the expression of linear function, $\overline{p}_{i,t}^{c}$ would be determined by $\underline{q}_{i,t}^{c}$. The following equation would be satisfied:

$$\overline{p}_{i,t}^{c}=M_{i}^{AB}\cdot\underline{q}_{i,t}^{c}+N_{i}^{AB} \tag{12}$$

More reserve capacity can be supplied when the CHP unit decreases its heat production with operating point moving as the purple arrow. As shown in Fig. 3, the red line segment is the extra reserve capacity, compared with the general one, the green line segment, when heat production is fixed.

2) Reserve Capacity of CHP & Heat Storage

Given that heating demand is fixed at time t and the heat storage has remaining heat, reserve capacity of the integrated CHP unit and heat storage would be given by:

$$rs_{t}=\overline{p}_{i,t}^{c}-p_{i,t}^{c} \tag{13}$$

Considering the fixed heat demand, the following equation would be satisfied:

$$\overline{q}_{i,t}^{hs}=q_{i,t}^{hs}+\left(q_{i,t}^{c}-\underline{q}_{i,t}^{c}\right) \tag{14}$$

III. System Model

In this section, the objective function of the system is firstly described which includes fuel cost and penalties. Then a few operational constraints in the system are modelled, involving system power and heat balance, thermal units, CHP units, heat storage, electrical boilers and system reserve capacity, as well as other common constraints.

A. Objective Function

The model proposed in this paper is designed to minimize the fuel consumption, as well as the wind power and PV curtailment:

$$\min\ f=\sum_{t=1}^{n}\sum_{i=1}^{N_p}C_{i,t}^{p}+\sum_{t=1}^{n}\sum_{i=1}^{N_q}C_{i,t}^{q}+\sum_{t=1}^{n}\sum_{i=1}^{N_c}C_{i,t}^{c}+\xi_{w}+\xi_{pv}+\xi_{hs} \tag{15}$$

where ξ_w , ξ_{pv} and ξ_{hs} are determined by

$$\xi_{w}=\omega_{1}\cdot\sum_{t=1}^{n}\sum_{i=t}^{N_w}\left(\overline{p}_{i,t}^{w}-p_{i,t}^{w}\right) \tag{16}$$

$$\xi_{pv}=\omega_{2}\cdot\sum_{t=1}^{n}\sum_{i=t}^{N_{pv}}\left(\overline{p}_{i,t}^{pv}-p_{i,t}^{pv}\right) \tag{17}$$

$$\xi_{hs}=\omega_{3}\cdot\sum_{t=1}^{n}\sum_{i=t}^{N_{hs}}\varphi_{i,t} \tag{18}$$

The objective function (15) includes fuel cost and penalty. The coal consumption of the conventional thermal plants, the heating plants and the CHP plants, employing the forms as in [19], is considered in total fuel cost, when penalty contains daily energy recovery of heat storage and wind power and PV curtailment.

B. Operational Constraints

1) Power and Heat Balance

Given the set power and heat demand, the power load needs to be equal to the sum of the power production from all the conventional thermal units, CHP units, wind farms, PV farms and electrical boilers hourly, when the power production sign of the electrical boiler is negative.

The equation of power balance can be expressed by

$$\sum_{i=1}^{N_p}p_{i,t}^{p}+\sum_{i=1}^{N_c}p_{i,.t}^{c}+\sum_{i=1}^{N_w}p_{i,t}^{w}+\sum_{i=1}^{N_{pv}}p_{i,t}^{pv}-\sum_{i=1}^{N_{eb}}p_{i,t}^{eb}=P_{t}+p_{t}^{EV} \tag{19}$$

Meanwhile, the heat load needs to be equal to the sum of the heat supply from all the heating boilers, CHP units, electrical boilers and heat storages hourly in each district, when the heat supply sign of the heat storage depends on the operating status (storage or supply).

In each district, the heat balance satisfies the following equation:

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$$\sum_{i=1}^{N_{hb}} q_{i,t}^{hb} + \sum_{i=1}^{N_c} q_{i,t}^{c} + \sum_{i=1}^{N_{hs}} q_{i,t}^{hs} + \sum_{i=1}^{N_{eb}} q_{i,t}^{eb} = Q_{i,t} \tag{20}$$

2) Constraints on Conventional Thermal Units

The ramping constraints for the conventional thermal units are formulated for a UC model as follows:

$$\begin{cases} p_{i,t}^{p} - p_{i,t-1}^{p} \le R_i^u \cdot I_{i,t-1}^{p} + S_i^u \cdot (I_{i,t}^{p} - I_{i,t-1}^{p}) + \bar{P}_i^p \cdot (1 - I_{i,t}^{p}) \\ p_{i,t-1}^{p} - p_{i,t}^{p} \le R_i^d \cdot I_{i,t}^{p} + S_i^d \cdot (I_{i,t-1}^{p} - I_{i,t}^{p}) \end{cases} \tag{21}$$

3) Constraints on CHP Units

Besides the ramping constraints (8) ~ (9) or (10) ~ (11) in section II, the minimal up and down time constraints also limit the operation of CHP units:

$$\begin{cases} \sum_{t=1}^{G_i} (1 - I_{i,t}^{c}) = 0 \\ \sum_{n=t}^{t+UT_i-1} I_{i,n}^{c} \ge UT_i \cdot (I_{i,t}^{c} - I_{i,t-1}^{c}) \quad t = G_i + 1, \ldots, \mathrm{T} - UT_i + 1 \\ \sum_{n=t}^{T} (I_{i,n}^{c} - (I_{i,t}^{c} - I_{i,t-1}^{c})) \ge 0 \quad t = T - UT_i + 2, \ldots, \mathrm{T} \end{cases} \tag{22}$$

$$\begin{cases} \sum_{t=1}^{L_i} I_{i,t}^{c} = 0 \\ \sum_{n=t}^{t+DT_i-1} (1 - I_{i,n}^{c}) \ge DT_i \cdot (I_{i,t-1}^{c} - I_{i,t}^{c}) \quad t = L_i + 1, \ldots, \mathrm{T} - DT_i + 1 \\ \sum_{n=t}^{T} (1 - I_{i,n}^{c} - (I_{i,t-1}^{c} - I_{i,t}^{c})) \ge 0 \quad t = T - DT_i + 2, \ldots, \mathrm{T} \end{cases} \tag{23}$$

The total power and heat production limits of the CHP unit depend on the corner coordinates of the feasible operational area and employ the forms as in [22].

4) Constraints on Heat Storages

Based on the linear control model for heat storage tanks with three layers of water of different temperature [19], the heat exchange $q_{i,t}^{hs}$ should satisfy the following equation:

$$Q_{i,t}^{hs} - Q_{i,t-1}^{hs} = -q_{i,t}^{hs} - q_{i,t}^{loss} \tag{24}$$

where the sign of $q_{i,t}^{hs}$ is positive or negative when the heat storage tank is in the discharging or charging process.

The heat loss is determined by

$$q_{i,t}^{loss} = \eta^{hs} \cdot \Delta t - \varphi_{i,t} \tag{25}$$

where $\varphi_{i,t}$ is from (18).

For the convenient management on heat storages, we also set a constraint that the total available heat energy at the beginning of a day should be equal to that of the next day.

$$Q_{i,24 \cdot t}^{hs} = Q_{i,24 \cdot (t+1)}^{hs} \tag{26}$$

where $Q_{i,24 \cdot t}^{hs}$ and $Q_{i,24 \cdot (t+1)}^{hs}$ are the initial available heat energy in two continuous days.

5) Constraint on Electrical Boilers

For the i^{th} electrical boiler, the heat production and power consuming should satisfy the following equation:

$$q_{i,t}^{eb} = \eta_i^{eb} \cdot p_{i,t}^{eb} \tag{27}$$

where η_i^{eb} is taken as 0.96 in the following analysis.

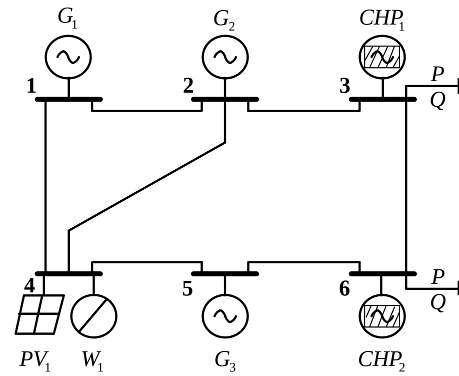

Fig 4. Modified standard 6-bus system.

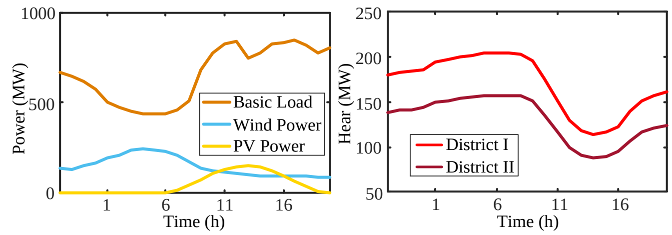

Fig 5. Power and heat demand.

6) Reserve Constraint

In a unit commitment model, the system reserve constraint is expressed as

$$\sum_{i=1}^{N_p} I_{i,t}^{p} \cdot \bar{p}_{i,t}^{p} + \sum_{i=1}^{N_c} I_{i,t}^{c} \cdot \bar{p}_{i,t}^{c} + \sum_{i=1}^{N_w} \bar{p}_{i,t}^{w} + \sum_{i=1}^{N_{pv}} \bar{p}_{i,t}^{pv} - \sum_{i=1}^{N_{eb}} p_{i,t}^{eb} \ge P_t + p_t^{EV} + RES_t \tag{28}$$

7) Other Constraints

Other constraints include maximum and minimum power production limits of the conventional thermal units, wind farms and PV farms, maximum and minimum heat supply limits of heating boilers, electrical boilers and heat storages.

DC power flow and heating flow constraints are also considered according to the topology of system, which employ the form as in [19], [32] and [33].

IV. RESULTS

In this section, we test the reformulated models and analyze the results compared to the conventional formulations. Ramping and reserve capacity constraints are emphasized and simulated in dispatch and unit commitment model respectively. Based on the 6-bus test system, the reformulated ramping and available reserve capacity models of CHP units increase the system's ability to consume PV and wind power especially.

A. Introduction of the Test System

As shown in Fig. 4, a modified 6-bus system is used to test the effect of reformulated ramping constraints and reserve supply of CHP units. The system consists of three 169MW conventional thermal units (G_1, G_2 and G_3), two 247MW CHP units (CHP_1 and CHP_2), a wind power farm (W_1) and a photovoltaic power farm (PV_1).

The profiles of hourly power and heat demand with wind and

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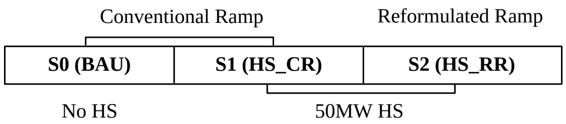

Fig 6. Scenarios of different heating sources and CHP ramping constraint models.

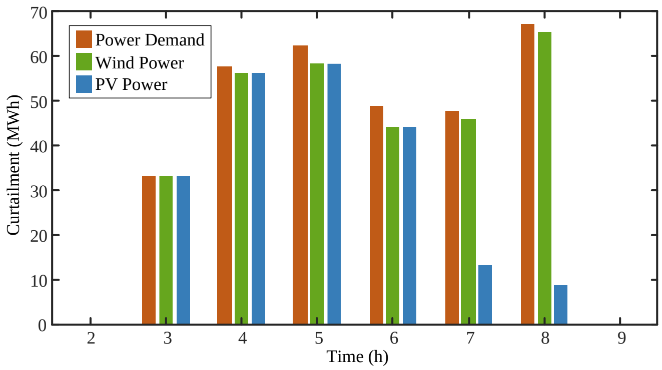

Fig 7. Hourly wind and PV power curtailment.

photovoltaic power generation are shown in Fig. 5. The basic load and capacity factor for PV and wind power are derived from actual data in China. The peaking power load in the morning reaches up to 840MW, with merely 507MW power demand four hours ago, putting huge pressure on the system for ramping. The supply of wind power accounts for 20% of the basic total power demand with its peaking value around 242MW at 4 a.m., while PV generates maximum 146MW at 1 p.m. The total power demand is distributed equally at bus-3 (district I) and bus-6 (district II).

The heat demand in district I is 1/3 more than that in district II, as presented in Fig. 5. The CHP units provides heat for districts independently, with CHP_1 and CHP_2 serves district I and district II respectively.

B. Operational Benefits for Improving Ramping Formulation

1) Scenarios

Besides adopting CHP units for heat production, a 120MW coal-fired heating boiler is equipped in district I, while a 50MW electrical boiler and a 50MW heat storage are applied in district II. Among the heating source, the heat storage is optional.

By applying the conventional and reformulated ramping constraints respectively, we structure the following scenarios:
Scenario S0 (BAU):

Conventional ramping constraints without heat storage.
Scenario S1 (HS_CR):

Conventional ramping constraints with heat storage.
Scenario S2 (HS_RR):

Reformulated ramping constraints with heat storage.

The description and comparison of different scenarios above are concluded in Fig. 6

2) Wind and PV Power Curtailment

The hourly wind and PV power curtailment in periods from 2 a.m. to 8 a.m. is shown in Fig. 7. In other periods of the day, the curtailment is zero in all scenarios.

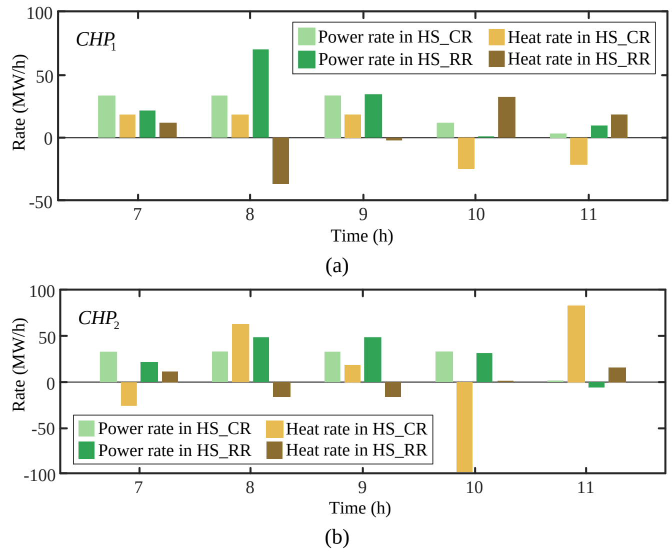

Fig 8. Rates of CHP heat and power production change.

On the whole, the HS_RR scenario shows the greatest ability to consume PV and wind power, while the curtailment is highest in the BAU scenario.

In periods from 2 a.m. to 3 a.m., the curtailment is almost the same in the three scenarios due to the minimal power production constraints of conventional thermal units and CHP units. However, the advantage of applying the heat storage reveals with less PV and wind curtailment from 4 a.m. to 8 a.m. because of its ability to transform and store energy. Moreover, with reformulated ramping constraints of CHP units applied in the HS_RR scenario, the curtailment further decreases drastically from 6 a.m. to 8 a.m., which reaches 13.2MWh and 8.9 MWh respectively. Especially at 7-8 a.m. period, the curtailment in the HS_RR scenario is 1/8 of that in the BAU scenario.

3) Rates of production change of CHP units

Fig. 8 shows the hourly rate of change of CHP heat and power production. The model of the reformulated ramping constraints works at periods from approximately 7 a.m. to 10 a.m. with the results that the heat production of the CHP unit decreases and the power supply increases rapidly.

The ramping ability of the CHP_1 unit are increased extremely. Especially at period 8 a.m., the heat production decreases 36MW and corresponding power supply rapidly increases 70MW in the HS_RR scenario, 2 times rapider than that (33MW/h) of the CHP_1 unit power supply in the HS_CR scenario.

For the CHP_2 unit, the heat production decrease about 15MW/h at periods from 7 a.m. to 9 a.m. when the power supply increases 49MW/h approximately in the HS_RR scenario, which is more rapid than that of 33MW/h at the same periods in the HS_CR scenario.

C. Operational Benefits for Improving Reserve Capacity Formulation

1) Scenarios

The results above demonstrate the advantage of applying the heat storage and reformulated ramping constraints of CHP units.

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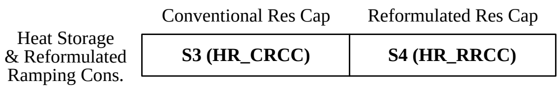

Fig 9. Scenarios of different modeling of reserve capacity CHP units can supply.

TABLE I
ON/OFF STATUS OF THE CONVENTIONAL THERMAL UNITS

Thermal Units On/Off Status	HR_CRCC	HR_RRCC
G_1 G_2 G_3	1 1 1	1 1 0

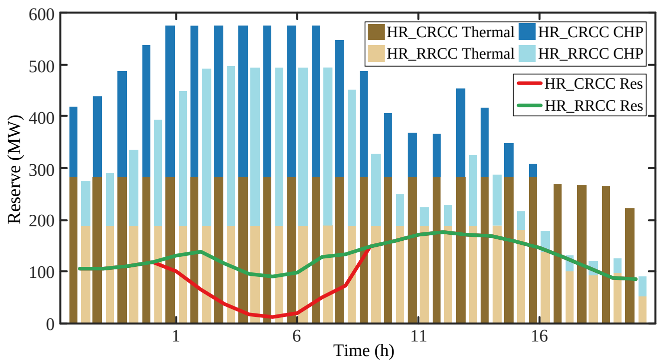

Fig 10. Reserve capacity and system requirement.

Based on that, when taking system reserve constraints into consideration, we structure another two scenarios:

Scenario S3 (HR_CRCC):

Conventional reserve capacity constraints.

Scenario S4 (HR_RRCC):

Reformulated reserve capacity constraints.

The description and comparison of different scenarios above are concluded in Fig. 9.

2) Units On/Off Status and Reserve Capacity

After adding the reserve constraints to the system, the test system converses from a dispatch model to a unit commitment model. The results of on/off status of the conventional thermal units G_1, G_2 and G_3 in different scenarios are represented in TABLE I.

In order to meet the requirement of the reserve capacity, three conventional thermal units must be online for the whole day in the HR_CRCC scenario, while G_3 could be offline in the HR_RRCC where the reformulated available reserve capacity of the CHP unit is applied.

The reserve supply of the conventional thermal units and CHP units is shown in Fig. 10. Because of one more online unit in the HR_CRCC scenario, the reserve supply of the conventional thermal units is approximately 3/2 times than that in the HR_RRCC scenario within the first 18 periods.

With high power demand and less wind power in the afternoon, CHP units must produce more power to meet the demand, leading to less available reserve capacity. In the HR_CRCC scenario, the reserve capacity that CHP units could supply gradually decrease to 0 MW at 16 p.m. and the situation lasts for 4 hours. By applying the reformulated available reserve capacity models in the HR_RRCC scenario, however, CHP units could always supply more than 26MW reserve capacity.

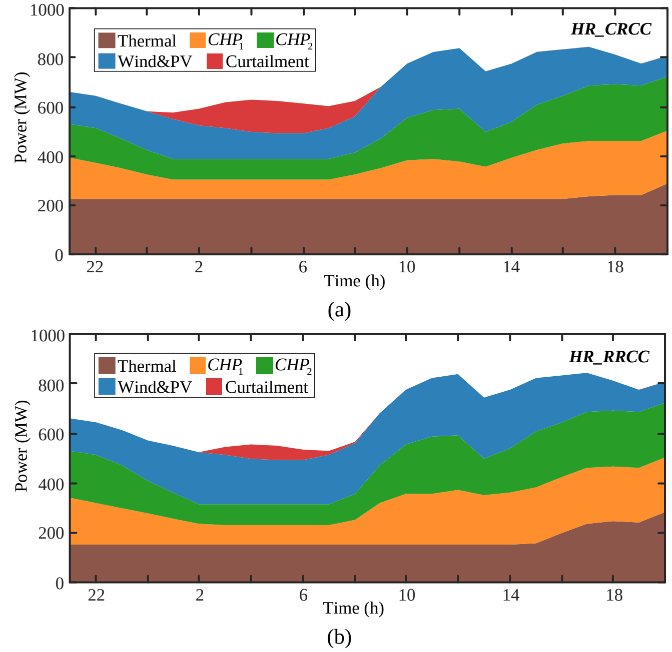

Fig 11. Hourly power balance and curtailment.

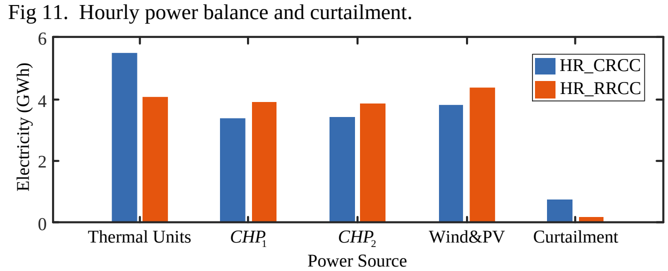

Fig 12. Power production and curtailment.

3) Hourly Power Balance

The hourly power balance and curtailment are represented in Fig. 11. Because of the constraints of minimal power production, the online conventional thermal units occupy a large part of the total power supply. The total power production of the three conventional thermal units reaches about 225MW at the first 18 periods in the HR_CRCC scenario, 3/2 times more than that (150MW) in the HR_RRCC scenario, where only G_1 and G_2 are online.

Due to the different online number of the conventional thermal units in the scenarios, the wind and PV power curtailment varies. The operation of the third conventional thermal unit G_3 occupies the capacity for consuming wind power and PV, causing huge curtailment from 0 a.m. to 8 a.m. in the HR_CRCC scenario. Especially at the periods of 0-1 a.m. and 1-2 a.m., the curtailment reaches up to 27.5MWh and 70.1MWh respectively, when there is no curtailment in the HR_RRCC scenario.

4) Power Production

The total power production of every energy source and curtailment is shown in Fig. 12. The difference of power production of the conventional thermal units is 1.44GWh between the two scenarios. This difference is compensated by CHP_1, CHP_2 and wind and PV power. The CHP units in the HR_RRCC scenario produce 0.49GWh and 0.41GWh more power than that in the HR_CRCC scenario respectively. The

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total wind and PV power curtailment in the HR_CRCC scenario is 744.5MWh, approximately 3.5 times more than that (214.0MWh) in the HR_RRCC scenario.

The applying of the reformulated available reserve capacity of CHP units improves the consuming of wind and PV power and it is also useful and meaningful to determine the quantity and capacity of the energy sources for the system.

V. Conclusion

In this paper, we analyze the internal mechanical structure and put forward the power and heat production models. By deriving the relationship between power and heat supply and comparing the conventional ramping constraints of the conventional thermal units, we propose the reformulated ramping constraints of the CHP units. The reformulated ramping constraint model can improve the ramping ability of the CHP unit by controlling the heat valve. It is the key part to improve the flexibility of the CHP unit, so that the system could accommodate additional wind and PV power.

We also analyze the heating compensation mechanism between CHP units and heat storages and propose the reformulated available reserve capacity constraints of the CHP units. The reformulated available reserve capacity model can release the ability of heat storages: not only provide heat reserve, but also supply power reserve when coordinated with CHP units. With increased reserve capacity from CHP units, fewer online conventional thermal units could supply enough capacity. Additional wind and PV power could be integrated into the system during off-peak periods.

The improved flexibility modeling of CHP units can release the hidden capacity from both CHP and heat storage, facilitating the accommodating of higher penetration of renewable energy and the participation of ancillary services.

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