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Multi-area combined heat and power coordinated operation considering the heat storage of buildings

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Abstract.

During the winter heating period in the northern area of China, the traditional operation mode that heating supply determines the electricity generation leads to the limitation of regulation ability of the combined heat and power (CHP) units, resulting in a large number of wind power curtailment. This paper decouples the strong coupling between electric power and heating supply of CHP units by considering the heat storage of buildings, and extends it to coordinated dispatching of multi-area connected by tie lines. Taking the lowest cost of power generations as the objective, an optimization model of CHP coordinated operation considering the heat storage of buildings is established. On this basis, a model of the multi-area CHP coordinated operation is established considering the tie-line constraints. The results of the example show that, the regulation range of the CHP units increases and the peak-shaving ability of the system enhances after considering the thermal storage of the building. When applying the thermal storage of the building to the coordinated operation of multi-area CHP system, it can achieve a wider range of coordination of electricity and heat, and fully excavate the flexibility of CHP system, and provide more space for wind power access to power grid.

Keywords: Heat storage of buildings, combine heat and power, tie line, multi-area interconnection, wind power consumption

1. Introduction

The problem of wind abandonment and power limitation has become the main contradiction, which is affecting the sustained and healthy development of wind power in China. The phenomenon of wind abandonment is more serious in the North China, Northeast and Northwest China, especially during the time of low load in winter heating period. This is because the heating mode in these areas is centralized heating with CHP units as heat source. The traditional operation mode of CHP units that heating supply determines the electricity generation results in that CHP units occupies a larger space of the power grid and wind power cannot access to the power grid on a large scale. In order to solve the problem of wind abandonment, the peak shaving capacity of the system can be improved by breaking the strong coupling of power and heat under the traditional operation mode of CHP units [1].

Many scholars have proposed a variety of decoupling methods, including installing electric boilers, heat pumps, heat storage tanks and other heat storage devices in the CHP system as compensated heating [2-4], in order to reduce the output of CHP units when there is excess wind power. The establishment of a storage power station including pumped storage can also play an effective role in wind power utilization [5].Although these methods can achieve the purpose of peak shaving capacity promotion, they need additional investment and comprehensive consideration of economy and practicability.

The research shows that the heating system, including pipeline network and building, has thermal dynamic characteristics. Decoupling power and heat can be achieved to a certain extent by utilizing this

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characteristic in the CHP system operation. This method needs no additional investment and can be given priority. [6-8] make a thorough study on the thermal dynamic characteristics of the heating network of central heating system, which verifies the feasibility of the heat storage characteristics of the pipeline network participating in peak shaving of the system. [9] regards heating buildings and heat networks as a whole, and the overall heat capacity as the peak shaving capacity. [10] assumes that the building is in a constant outdoor temperature environment and studies the influence of coordinated dispatching of electricity and heat on promoting wind power access to grid considering the thermal load demand of a single building and room temperature comfort. [11] synthetically considers the thermal dynamic characteristics of buildings and heat networks, and establishes a simple dynamic characteristic equation. [12] takes into account the flexibility of building thermal storage, describes the thermal dynamic characteristics of buildings by using equivalent thermodynamic parameters, and simplifies them into discrete difference equations. [13] regards the heating area as a first-order inertia link, obtains the discretized difference equation describing the thermal inertia of the building, and increases the heat dissipation of the radiator as an optimal control variable.

The above researches on decoupling power and heat relationship, improving peak shaving ability of CHP system and enhancing the grid-connected capability of wind power are all shown by the power and heat coordination in the same region. Due to the extensive interconnection of modern power, it will be an inevitable trend to study the operation of the CHP system from a single region to the multi-area. The problem of wind power absorption in winter heating period can be alleviated by transmitting the abandoned wind power through the tie lines outward [14-15]. [16] establishes a multi-area CHP dispatch coordinated model including thermal storage boiler devices, and the interregional power exchange through tie lines, which has a positive impact on wind power grid-connected. [17] introduces distributed heat pump and electric boiler to share heat load and establishes an integrated dispatching model considering the restriction of tie-line interaction, so as to improve the ability of wind power absorption. [18] establishes a multi-area integrated energy system model of combined cooling heating and power with equations of describing heat transfer state of heat network. But this model only allows one-way transmission of electric energy from each region to the power grid, and there is no power transmission between regions.

In summary, most of the existing research on coordinated dispatching model of multi-area CHP system adopted installing heat pumps, electric boilers and regenerators to decouple the power and heat connection and improve the regulation ability of the system, but have not taken into account the use of thermal storage characteristics of the thermal system. Therefore, this paper will establish a multi-area combined heat and power coordinated operation model considering the heat storage of buildings. And considering the existing dispatching modes in China, the transmission power on the tie-line is equivalent to the electric load and generator in the transmission area and the receiving area respectively.

2. Model of the Building Inertia Thermal Energy Storage

The building envelope makes it have great thermal inertia, which can storage heating energy. The heat gain and heat consumption of buildings are always in a dynamic equilibrium state.

2.1. Heat consumption of the building

Heat consumption of buildings mainly includes three parts: heat consumption of building envelope, infiltration heat loss and ventilation heat loss:

1) Heat consumption of building envelope

Building envelope including doors, windows, floors, walls, roofs and other parts of the building that can contact with the outdoor air. The heat consumption of building envelope is divided into basic heat consumption and modified heat consumption. The heat consumption of envelop can be expressed as:

$$Q_{1,k} = (1 + x_{g,k})\sum \alpha_k K_k F_k (T_{bin,k} - T_{bout})(1 + x_{ch,k} + x_{f,k}) \tag{1}$$

2) Infiltration heat consumption

The heat consumed that heating the outdoor cold air that seeps into the room through the cracks of doors and windows to the indoor temperature is called cold air infiltration heat consumption:

$$Q_{2,k} = 0.278V_k \rho c(T_{bin,k} - T_{bout}) \tag{2}$$

3) Ventilation heat consumption

The heat consumed by heating the cold air that seeps into the room through the open doors and windows for air change to the indoor temperature is called the heat consumed by the cold air intrusion:

$$Q_{3,k} = 0.278V_{w,k} \rho c(T_{bin,k} - T_{bout}) \tag{3}$$

In summary, the total heat consumption of a building can be expressed as the sum of the three:

$$Q_{b,k} = Q_{1,k} + Q_{2,k} + Q_{3,k} \tag{4}$$

2.2. Thermal dynamic characteristics of the building

The heat change of a building is the difference between the heat transferred from the heat source to the building through the heat network and the heat consumption of the building. The dynamic change of the building's heat can be expressed as follows:

$$I_{b,k} \frac{dT_{bin,k,t}}{dt} = H_{r,k,t} - Q_{b,k} \tag{5}$$

where the left side of the equation (5) represents the dynamic change of building's indoor temperature and the right side represents the heat change of the building. If the derivative expression is greater than zero, it means that the heat is increased and the building is storing heat. On the contrary, it means that the heat is reduced and the building stored heat is being released.

Put the equations (1)-(4) into the equation (5), thermal dynamic constraints of the building can be obtained by integral calculation [10-11]:

$$\begin{aligned} T_{bin,k,t+1} = {} & (T_{bin,k,t} - T_{bout,t} - \frac{H_{r,k,t}}{X_{b,k}})\exp(-\frac{\Delta t}{t_{b,k}}) \\ & + T_{bout,t} + \frac{H_{r,k,t}}{X_{b,k}} \end{aligned} \tag{6}$$

$$\begin{aligned} X_{b,k} = {} & (1 + x_{g,k})\sum \alpha_k K_k F_k (1 + x_{ch,k} + x_{f,k}) \\ & + 0.278V_k \rho c + 0.278V_{w,k} \rho c \end{aligned} \tag{7}$$

where the $X_{b,k}$ is the heat transfer coefficient of the building, indicates the heat transfer capacity of building envelopes per unit area and the $t_{b,k}$ is the equivalent heat storage time coefficient, indicates the time required for the indoor temperature to rise or fall by 1℃ under a certain building envelope structure. The relationship between them and the total heat capacity $I_{b,k}$ of the building is as follows:

$$X_{b,k} t_{b,k} = I_{b,k} \tag{8}$$

2.3. Indoor temperature of the building

In order to ensure heating to meet the normal production and living needs of indoor people, indoor temperature of the building should be set in a reasonable comfortable range:

$$T_{bin}^{\min} \le T_{bin} \le T_{bin}^{\max} \tag{9}$$

3. Model of the District Heating Network

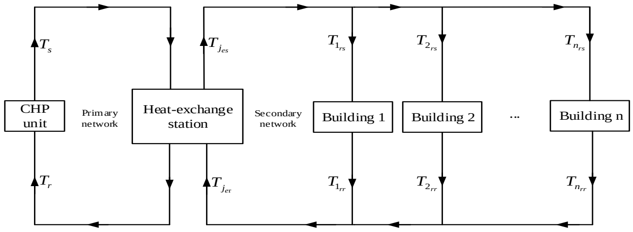


Fig. 1. Structural chart of district heating system.

3.1. Heat storage characteristics of pipeline network

As shown in Fig. 1, in the district heating system, the heat generated is transferred from the heat source CHP unit to the heat load through the primary network, the heat exchange station and the secondary network. In this process, there are heat delays and attenuations, which are manifested as delay in heat transfer time and temperature losses of water in the pipeline network during the transmission process [6-8, 11]:

$$T_{pout,j,t+\mu_j} = T_{soil,t} + (T_{pin,j,t} - T_{soil,t})\exp(-\frac{\mu_j \Delta t}{t_{p,j}}) \tag{10}$$

$$\mu_j = round(\frac{t_{p,j}}{\Delta t}) \tag{11}$$

3.2 Mixing temperature and flow of the node

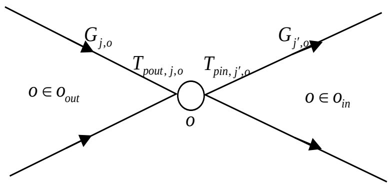


Fig. 2. Node structure diagram of heating network.

As shown in Fig. 2, the structure of heating network is complex and there are many nodes. The temperature and flow of these nodes should satisfy certain constraints. For the supply water pipeline, the water temperature of the pipeline connecting the same heat network node should be consistent. While the return water pipeline should satisfy the algebraic sum of mass flow after temperature mixing in the pipeline is zero [11]:

$$T_{pout,j,t} = T_{pin,j',t} \tag{12}$$

$$\sum_{o \in o_{out}} G_{j,o} = \sum_{o \in o_{in}} G_{j',o} \tag{13}$$

$$c_w T_{pout,j,t} \sum_{o \in o_{out}} G_{j,o} = \sum_{o \in o_{in}} (c_w G_{j',o} T_{pin,j',t}) \tag{14}$$

where j and j' are two different pipes connecting the same node o .

3.3. Heating transfer

In the district heating network, the thermal power of the pipeline is related to the flow speed and temperature of the water in the pipeline:

$$H_{pin,j,t} = c_w G_j T_{pin,j,t} \tag{15}$$

$$H_{pout,j,t} = c_w G_j T_{pout,j,t} \tag{16}$$

The heat power output of CHP unit is transferred to the secondary network through the primary network and heat-exchange station as shown in Fig. 1. The water temperature in the pipeline of the secondary network is heated. A certain amount of heat loss will occur in this process:

$$H_{chp,i,t} = (1-\lambda_{e,i})(H_{pin,j_{es},t} - H_{pout,j_{er},t}) \tag{17}$$

The heat energy is transferred to the radiator in the building through the secondary network and then the heat is transferred from the radiator to the indoor air to ensure that the heat load meets the demand. In this process, a certain amount of heat loss will occur:

$$H_{r,k,t} = (1-\lambda_{r,k})(H_{pout,j_{rs},t} - H_{pin,j_{rr},t}) \tag{18}$$

4. Model of Power System

4.1. CHP units

There is a certain coupling relationship between heat power output and electric power output of CHP units, and its operational feasible region is within the polygon ABCDA as is shown in Fig. 3.

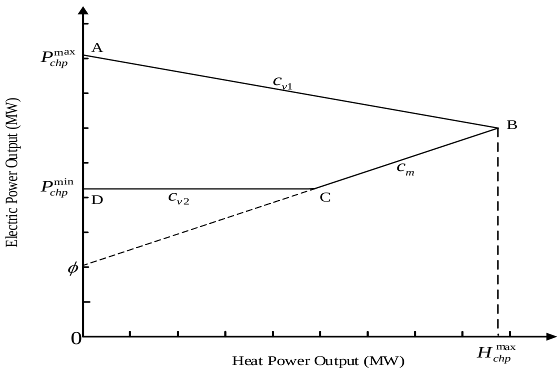


Fig. 3. Electric and heat power characteristics of CHP units.

Therefore, the electric and heat power output constraints of CHP units are as follows:

$$\begin{aligned} &\max\{P_{chp,i}^{\min} - c_{v2,i}H_{chp,i,t}, \varphi_i + c_{m,i}H_{chp,i,t}\} \\ &\le P_{chp,i,t} \le P_{chp,i}^{\max} - c_{v1,i}H_{chp,i,t} \end{aligned} \tag{19}$$

$$0 \le H_{chp,i,t} \le H_{chp,t}^{\max} \tag{20}$$

The electric power output of CHP units is limited by the ramping constraints in each unit dispatching time Δt :

$$-\Delta P_{chp.i}\Delta t \le P_{chp,i,t+1} - P_{chp,i,t} \le \Delta P_{chp.i}\Delta t \tag{21}$$

4.2. Condensing power (CON) units

The electric power output of CON units should be controlled within the upper and lower limits and it is also constrained by ramping rate:

$$P_{con,m}^{\min} \le P_{con,m,t} \le P_{con,m}^{\max} \tag{22}$$

$$-\Delta P_{con,m}\Delta t \le P_{con,m,t+1} - P_{con,m,t} \le \Delta P_{con,m}\Delta t \tag{23}$$

4.3. Wind power farms

The output of wind power should be less than the maximum capacity of the wind power farm:

$$0 \le P_{wind,n,t} \le P_{wind,n,t}^{\max} \tag{24}$$

4.4. Power reserve

In order to ensure the normal operation of the CHP system, the system in each region needs to provide a certain amount of power reserve:

$$\sum_{i=1}^{I}(P_{chp,i}^{\max} - P_{chp,i,t}) + \sum_{m=1}^{M}(P_{con,i}^{\max} - P_{con,i,t}) \ge R_{r,t} \tag{25}$$

5. Model of Multi-Area CHP Coordinated Operation

5.1. Fundamentals of multi-area CHP coordinated operation

Wind power has spatial and temporal distribution characteristics. It takes a certain time for wind to propagate from wind source to outside according to its wind direction. Therefore, according to the wind direction passing through the regions, the wind power is different at the same time, which shows that the wind power in area A is higher than that in area B. In order to avoid wind abandonment in Area A, we can consider sending wind power to area B and using the heat storage characteristics of the buildings in Area B to help Area A absorb the wind power, so as to realize the complementarity of area A and area B, as shown in Fig. 4 .

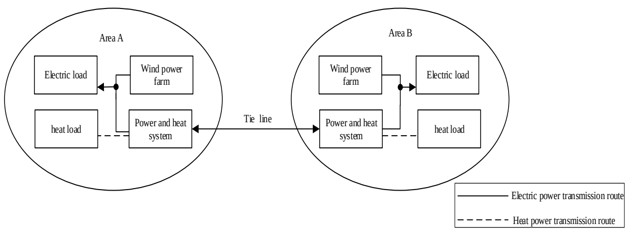


Fig. 4. Schematic diagram of multi-area power and heat system coordination for tie line connection.

The power system of China implements multi-level hierarchical dispatching mode including national dispatching, grid dispatching and provincial dispatching, etc. Grid dispatching is responsible for the safe operation of inter-provincial lines and the formulation of provincial power generation plans. While provincial dispatching is mainly responsible for the safe operation of provincial power grids. In order to meet the actual dispatching situation of China's power grid and avoid the inter-provincial dispatching work and cross-management between provinces, the power of inter-regional tie lines should be split up equivalently. As shown in Fig. 5, the tie-line power in the transmission area is equivalent to adding an equivalent load so that the area A can consume more electric energy; the tie-line power in the receiving area is equivalent to adding an equivalent generator so that the area B can generate more electric energy. Thus, it can be transformed into the coordinated operation of the internal CHP system in each region after dividing the power of tie line into two parts, so as to achieve the purpose of provincial dispatching can dispatch in each region by itself.

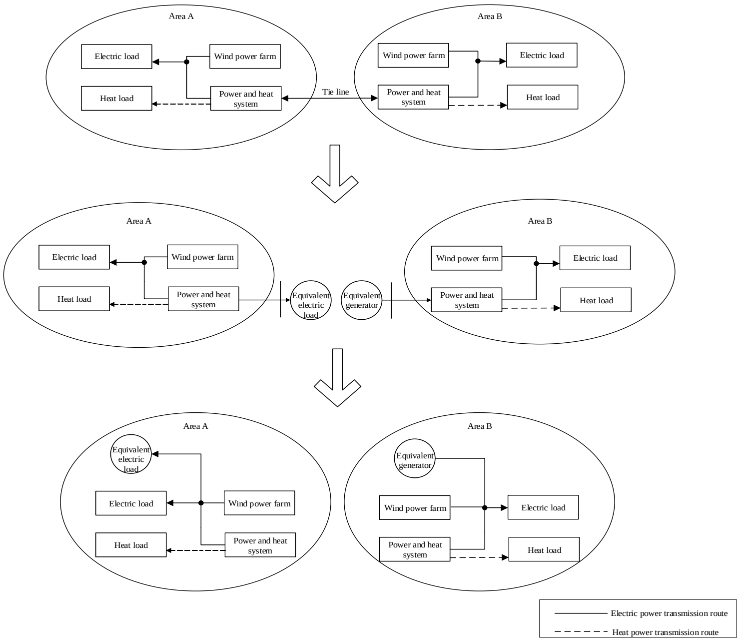


Fig. 5. Equivalent schematic diagram of multi-area power and heat system coordination.

5.2. Power balance

The normal operation of the power and heat coordinating system in each region should satisfy the active power balance constraints:

$$\sum_{i=1}^{I} P_{chp,i,t} + \sum_{m=1}^{M} P_{con,i,t} + \sum_{n=1}^{N} P_{wind,i,t} + \sum_{l=1}^{L} P_{line,l,t} = P_{load,r,t} \tag{26}$$

where $P_{line,l,t}$ means the transmitted power through the tie line l ,specifying that the transmission of electric power from area A to area B is in the positive direction.. If $P_{line,l,t} > 0$, it means the tie line inputs electric power to the inner part of the area at time t , whereas the tie line transport the electric power to the outer part of the area at time t . The equivalent electric load in the transmission area is negative and the equivalent generator in the receiving area is positive.

5.3. Tie line

The tie lines between regions have some limitations in the process of transmitting electric energy that there are upper and lower limits:

$$P_{line,l}^{\min} \le P_{line,l,t} \le P_{line,l}^{\max} \tag{27}$$

6. Multi-area Combined Heat and Power Coordinated Operation Considering the Heat Storage of Buildings

6.1. Objective function

In this paper, taking the minimum total operation cost as objective function that establishing the model of combined heat and power dispatch coordinated operation considering the heat storage of the buildings:

$$\begin{aligned}&\min \sum_{l=1}^{L}[a_{chp}(P_{chp,i,t}+c_{v1}H_{chp,i,t})^2+b_{chp}(P_{chp,i,t}+c_{v1}H_{chp,i,t})+c_{chp}]\\&+\sum_{m=1}^{M}(a_{con}P_{con,m,t}^2+b_{con}P_{con,m,t}^2+c_{con})+\sum_{n=1}^{N}(P_{wind,n,,t}^{\max}-P_{wind,n,t})^2\end{aligned} \tag{28}$$

where the objective function includes three parts: operation cost of CHP units, operation cost of CON units and penalty term about the cost of wind abandonment.

6.2. Constraints

The constraints in the model of combined heat and power dispatch coordinated operation considering the heat storage of the buildings mainly include the constraints of heat system and electric power system. Relevant constraints of the heat system include the characteristics of building thermal storage and the range of indoor temperature expressed by equations (6)-(9), pipeline and nodal constraints represented by equations (10)-(14), and heat transfer constraints expressed by equations (15)-(18). Relevant constraints of power system include those of CHP units, CON units and wind farms, as well as power reserve constraints of systems in different regions, which are equations (19)-(25). The transmission power limit, equivalent electric load and generator constraints of the inter-area tie-line are formulated from (26) to (27).

7. Results Analysis

7.1. Basic data

This section constructs a regional dispatching model of CHP system with taking 300 MW and 200 MW CHP units commonly used in the northern area of China as an example. Take 15 minutes as a dispatching cycle and observe the operating conditions 24 hours a day. Use CPLEX commercial software to solve the dispatching model, and make comparative analyses of the results.

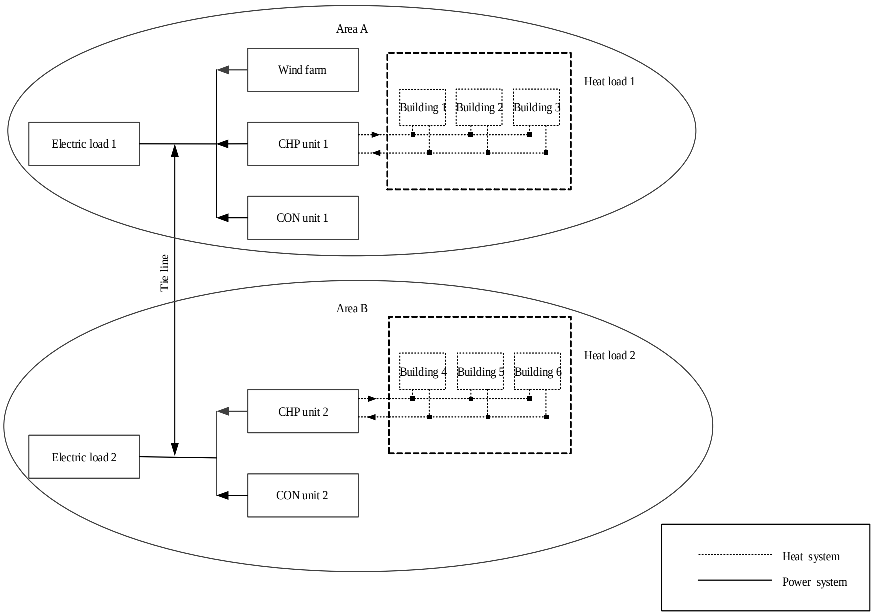
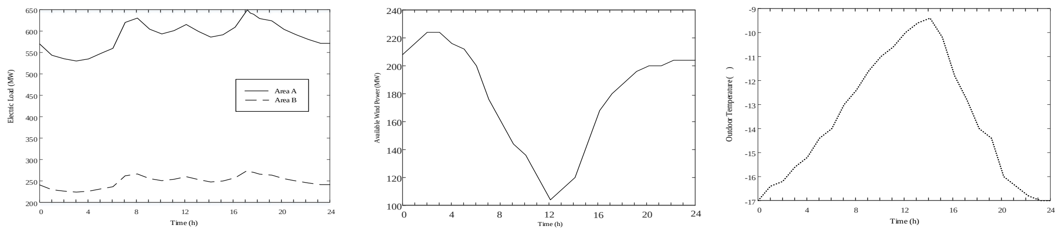


Fig. 6. Structural chart of multi-area power and heat system.

The multi-area CHP system is constructed as shown in Fig. 6. Area A includes a 300 MW CHP unit, a 500 MW CON unit, a heat-exchange station, three buildings and several pipes. Area B includes a 200 MW CHP unit, a 200 MW CON unit, a heat-exchange station, three buildings and several pipes. The regulation process can not affect the heating quality, so the buildings’ indoor temperature fluctuates in the range of 18℃-22℃.

The electric load prediction curve of area A and B are shown in Fig.7(a). It is assumed that the trend of electric load in the two regions is basically the same. The power generation prediction curve of area A's wind farm is shown in Fig. 7(b). The available capacity of wind power generation is large during the time of low electric load at night, but contrary in the day, which conforms to the characteristics of "reverse peak regulation" of wind power. Outdoor temperature is selected as a typical daily temperature in winter in a city of the northern China, as shown in Fig. 7(c).

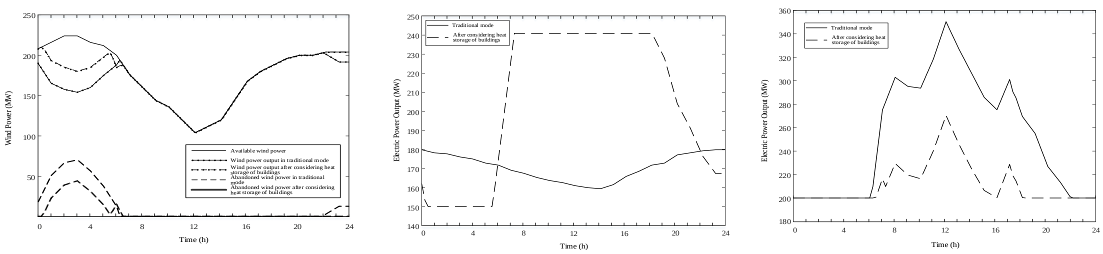


(a) (b) (c)

Fig. 7. Basic data prediction curve: (a) electric load prediction curve (b) power generation prediction curve.

7.2. Effect of building heat storage characterist-ics on CHP system

In order to explore the influence of building thermal storage characteristics on the power and heat system, an example is analyzed by only using the relevant parameters of area A without considering the regional interconnection. The effect of the CHP dispatching mode with considering building thermal storage characteristics of the system is compared with that of the traditional mode of determining the power by heat. The results are shown in Fig. 8.



(a) (b) (c)

Fig. 8. Electric power output curve: (a) Wind power output and abandoned power (b) CHP units (c) CON units.

Fig. 8 compare the operation of CHP units and CON units before and after considering building thermal storage characteristics and the wind power output of the system in area A. The solid line shows the traditional mode without considering building thermal storage characteristics, and the dotted line shows the coordinated operation of CHP system after considering building thermal storage characteristics.

As can be seen from Fig. 8, in the traditional mode, the period of wind abandonment is mainly from 10 p.m. to 6 a.m., which is due to the decrease of outdoor temperature at night and in order not to reduce the quality of heat supply and maintain the indoor temperature of buildings, the CHP units are required to produce more heat because of the coupling characteristics of it. The electric power output of CHP units increases with the increase of the heat power output in this period. However, this period is during the night sleep, the total electric power load in the region is low, which leads to the wind power cannot integrate into grid. Before considering the thermal storage characteristics of buildings, CHP units operate strictly according to the mode that the power output determined by heat. The heat power output and electric output operate consistent operational trends so that the regulation range of the system is limited and a large amounts of wind power curtailment

After considering the thermal storage characteristics of buildings, the strict restrictions between power and heat are decoupled of the traditional mode is broken. Starting around 5:30 a.m., the heat power output of CHP units increases, and the electric output also increases. The buildings begin to store heat and the heat output of CON units decreases with the constant electric load. After 6 p.m., the heat and electric power output of CHP units decreases, and the building releases the heat stored during the day. That can provide more space for wind power into the grid. After considering the heat storage of buildings, the regulation range of the CHP units in the system has been expanded by 33.3% upward and 5.7% downward, respectively. The peak shaving ability of the system has been improved, and the power of abandon wind has decreased by 52.3%.

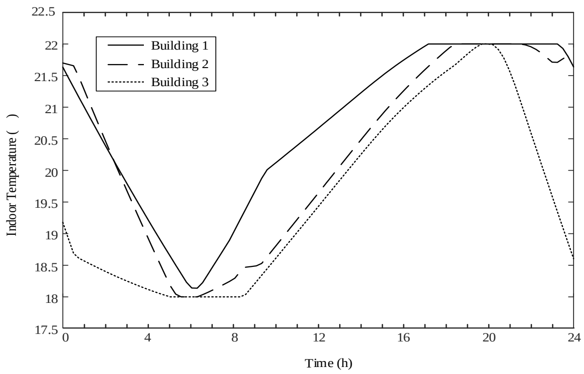


Fig. 9. Indoor temperature curve of buildings in area A.

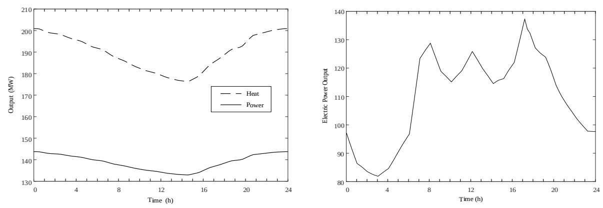
The thermal storage characteristics of buildings increase the range of electric and heat power output of CHP units, which is also reflected in the change of buildings' indoor temperature. After considering the heat storage, the temperature changes of buildings 1-3 are shown in Fig. 9. With the increase of heat power output of CHP units, the temperature of buildings starts to rise from about 6 a.m. to store heat. When the room temperature reaches 22℃, the building's thermal storage capacity reaches its limit. After 8 p.m., wind power begin to grow rapidly and the buildings released the heat stored in the daytime so that the indoor temperature begin to drop. The power and heat output of the CHP units decreased and the in-grid wind power increased. The rise and fall time of building indoor temperature are delayed compared with the increase and decrease time of CHP units' output, which fully reflects the delay characteristics of thermal inertia in thermal system.

7.3. Multi-area combined heat and power coordinated operation considering the heat storage of buildings

Area A and B are electrical interconnected by tie lines. There is no thermal pipeline between the two regions. Heat is supplied by CHP units in their respective regions. Equivalent of the electric power of tie line makes area A as the power transmission area that tie-line power is equivalent to adding equivalent electric load. And area B is the power receiving area that tie-line power is equivalent to adding an equivalent generator. Two cases of area A and B before and after considering the transmission of power by tie-line are discussed respectively.

Case 1: Both area A and B take into account the heat storage of buildings in their respective regions, but the transmission power on the tie-line is 0, that is, there is no power transmission between two areas.

Case 2: On the basis of considering the heat storage of buildings in A and B regions respectively, power transmission is carried out through the tie line between two areas and the transmission power of tie-line has been dealt with equivalently. Equivalent electric load and equivalent generator are added to the transmission area A and the receiving area B respectively.



(a) (b)

Fig. 10. Power output curve in area B in case 1: (a) CHP units (b) CON units.

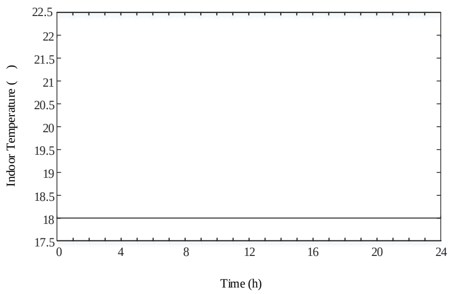
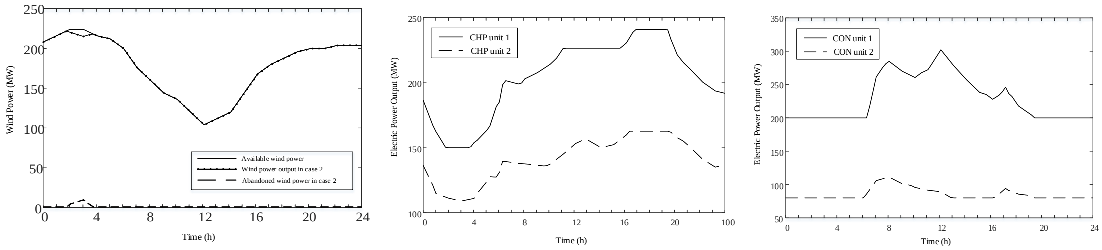


Fig. 11. Indoor temperature curve of buildings in area B in case 1.

In case 1, the electric power output curves in area A are the same as the dotted line in Fig.8. The electric and heat output of CHP units and the power output of the CON units in area B are shown in Fig.10. There is no wind farm in area B so that under the condition of the lowest operating cost of the system, the output of the CHP unit is fixed because of the determined electric load of the system. Therefore, the buildings' heat storage capacity in area B cannot work. The temperature of No. 4-6 buildings can only be maintained at the lowest temperature of 18℃, as shown in Fig.11.



(a) (b) (c)

Fig.12. Electric power output curve in case 2: (a)Wind power output (b)CHP units (c)CON units.

In case 2, area A and area B are electrical connected by tie line. Area A can transfer excess wind power to area B through the tie line, and use the heat storage characteristics of the buildings in area B to help absorb the remaining wind power in area A. Assuming that the transmission power capacity of the tie line is 35 MW and the allowable transmission power is 50%~100% of the capacity, the wind power output and abandonment and the output of CHP units and CON units in Area A and B are shown in Fig. 12. The solid line represents the operation status of the system in area A, and the dotted line represents the operation status of the system in area B in Case 2. In case 2, the regulation range of CHP units in area B is widened up and down by 13.3% and 18.2%, respectively comparing with Case 1. The output range of CON units is reduced by 19.0% and the wind power absorption capacity is stronger. This means that the heat storage capacity of the buildings in area B helps the electric and thermal regulation in area A. After connecting the two areas with the tie line, the abandoned wind in area A will be transferred to area B for absorption. The generating capacity of unit in area B will be reduced and the operating cost will be reduced, which achieve the win-win situation in both area A and area B.

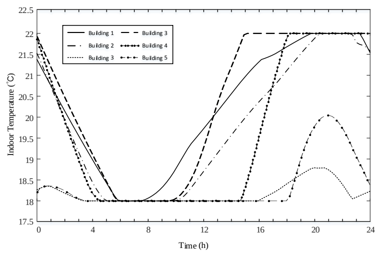


Fig. 13. Indoor temperature curve of buildings in area A and B in case 2.

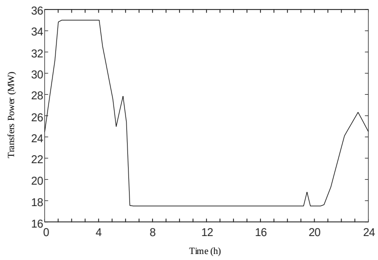


Fig. 14. Transfers power curve from area A to area B through the tie line.

As can be seen from Fig.13, the indoor temperature of No.4-6 Buildings in area B in Case 2 increased, that means the heat storage of the buildings has played a role. Fig.14 shows the transmission capacity of the tie line from area A to area B. It can be seen that during the period of large wind power generation from 10 p.m. to 6 a.m., the transmission power from area A to area B increases. While the transmission power capacity of the tie line only keeps at the minimum during 6 a.m. to 10 p.m. when wind power generation is not large. If the allowable transmission power capacity of the tie line is increased, the complete absorption of wind power can be realized under certain conditions.

Table 1. Operation cost of the system in two case

Dispatch mode	**Participating dispatching area**	**Operation cost ($)**	**Cost savings of Case 2 base on Case 1**
Case 1	Area A	301363.9	3.04%
	Area B	158573.3	
Case 2	Area A and B	445953.8	

Table 1 shows the comparison of the operation cost of the power and heat system in two cases. It can be seen that the operation cost of the system in case 2 is lower than the sum of that in case 1 in both area A and B after considering the power transmission of the inter-regional tie line. The inter-regional tie line can give full play to the thermal storage performance of the buildings in the two regions and the wind power into the grid has been greatly increased, which has considerable economic benefits.

7. Conclusion

This paper establishes a multi-area CHP coordinated operation model considering the heat storage of buildings. The following conclusions are drawn from the analysis of an example:

1) Considering the heat storage characteristics of buildings can break the traditional production mode that heating determines power, decouple the coupling relationship between heat and power, increase the

output range of CHP units, and improve the peak shaving capacity of the system.

2) Establishing the multi-area power and heat system connected by tie lines, which provides the power interconnection between regions and the heat supply respectively. Through the dual regulation of power coordination and heat coordination, it provides more space for wind power into grid and has obvious effect on enhancing the peak shaving capacity of the system. Considering the actual power grid dispatching situation in China, it is feasible to divide the transmission power of tie line into the equivalent electric load of the transmission area and the equivalent generator of the receiving area for modeling.

Dispatch of multi-area power and heat system considering buildings' heat storage characteristics can expand the range of unit output and participate in the depth peak shaving of the system on the premise that the building indoor temperature fluctuates within a reasonable range. Utilizing the heat storage characteristics of buildings, no additional investment is needed to add other equipment, which has significant economic and social significance.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors discussed and put forward the main idea of the research together; Haixia Wang, Yutong Han wrote the paper and analyzed the data; all authors had approved the final version.

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Nomenclature

K	heat transfer coefficient of building envelope
F	area of building envelope
α	correction coefficient of temperature difference of building envelope
x_g	high additional rate
x_f	wind additional rate
x_{ch}	orientation correction percent
V	infiltration air volume
V_m	ventilation air volume
ρ	density of indoor air in buildings
c	specific heat capacity of cold air
$H_{r,k}$	thermal power of radiator in the building k
$Q_{b,k}$	total heat consumption of the building k
T_{bout}	outdoor temperature
T_{soil}	soil temperature outside pipeline
$t_{p,j}$	thermal reserve coefficient of the pipeline j
Δt	scheduling cycle
G_j	mass flow rate of the pipeline j
$T_{bin}^{min}/T_{bin}^{max}$	the lower/upper limit of indoor temperature
$T_{pin,j}/T_{pout,j}$	water temperature at entrance/exit of the pipeline j
$\lambda_{e,i}$	heat loss coefficient of the heat-exchange station connected with the CHP unit i
$\lambda_{r,k}$	heat loss coefficient the radiator of the building k
$H_{pin,j}/H_{pout,j}$	thermal Power of water at entrance/ exit of the pipeline j
j_{es} / j_{er}	supply/return pipeline of heat- exchange station
j_{rs} / j_{rr}	supply/return pipeline of radiator
$P_{chp,i}^{min}/P_{chp,i}^{max}$	minimum/maximum electric output of the CHP Unit i
$H_{chp,i}^{max}$	maximum heat output of the CHP Unit i
$\Delta P_{chp,i}$	ramping rate of the CHP Unit i
$P_{con,m}^{min}/P_{con,m}^{max}$	minimum/maximum electric output of the CON Unit i
$\Delta P_{con,m}$	ramping rate of the Con Unit i
$P_{wind,n}^{max}$	maximum capacity of the wind power farm n
R_r	reserve power capacity of the area r
$P_{line,l}^{min}/P_{line,l}^{max}$	minimum/maximum transmission power of the tie line l
$P_{load,r}$	electric load of the area r