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Application of Heat Storage in Heating Network for Surplus Wind Power Consumption

Shuang Rong*,[1], Xiaoguang Chen*, Wanlin Guan*, Yuanting Hu*, Kexin Zhang*, Yang Lin*, and Chao Wang*

Abstract – *Among northern China, CHP is the main electric and heating source to provide electricity and heat. While, with the increasing integration of wind power, the peak regulation capacity is lacking. Wind power curtailment occurs frequently because of the contradiction between heating and electric load. District heating system plays the majority role in heating supply because of its efficiency and cleanness. There are enormous heat storage capacity contained in district heating system, if the stored heat energy could be utilized efficiently the contradiction between heating and electric load could be relieved and the wind power curtailment could be avoided considerably. This study presents an approach that takes advantage of the heat in the primary heating circuit to absorb surplus wind power. The expressions of the components in heating system are given to establish the mathematical model. Followed, the thermodynamic properties of heating pipelines are analyzed, the heat storage capacity and heat transmit delay characters are studied. Then, the consumption capacity of surplus wind power is discussed, and the temperature changes are also considered. The economic benefits are also analyzed. Finally, a case study was undertaken to prove the effectiveness. The results show that by utilizing the heat in heating network, the wind power curtailment rate could be reduced by 20.6% which means about 219.4MWh surplus wind energy could be consumed during a valley electric load period.*

Keywords – *combined heat and power, heat storage capacity, heating system, primary heating circuit, wind power consumption.*

1. INTRODUCTION

The blossom of wind power provides a clean, sustainable and accessible energy source to relieve the environmental issues led by the burning of fossil fuel [1]–[4]. However, the mass integration of wind power, an intermittent, volatility and anti-peak regulation energy source at the same time, increases the difficulty of peak load regulation, especially at the valley load period during the heating season because of the requirement of heating from combined heat and power (CHP) units [5]–[10]. Thus, wind power curtailment occurs frequently in high wind penetration rate grid. One of the main causes is that the control mode of heating network connects the need of heating load and the output of heating source rigidly. Also, the CHP units almost work as a back pressure units and their heating output and electric output show a linear relationship which restricts the peak regulation capacity of CHP units during the valley load period. What is more, a negative correlation is found between the electric load and heating load and an "Ordering Electricity by Heat" (OEBH) policy shrink the capacity of CHP units to participate in peak regulation at valley load period during heating season [11]–[12].

At present, the research interests on wind power consumption by heat storage system are mainly focused on heat storage facilities and energy transform equipment such as electric boiler [13]–[15]. On the premise of the stable heat transmission between the primary circuit and the secondary circuit of heating network, the solid connection between heating load and heating source could be softened and decrease the heating need from CHP units by utilizing the internal energy of the heat medium in primary heating circuit (PHC). Reason from the lowered heating output, the electric output of CHP units could be depressed that creates a considerable room for wind power to interspace [16]–[17]. On account of the less additional equipment and facilities, the utilization of heat storage character of heat network expresses a better investment economy compare with adding electric boilers and/or heat storages. References [18] and [19] believe that the CHP unit could actively respond the short-time load disturbance from the power grid by utilizing the heat storage capacity of distributed heating system, based on that those papers present a coordinating control designing scheme which increases the feed-forward compensation of CHP unit. References [20]–[23] argue that the wind power consumption could be promoted by using the heat storage capacity of the pipe network, heat exchangers and heat radiators within heating system, also, the author strives for shrinking the wind power curtailment by optimizing the operation of AGC units. But all those papers only focus on one or some heating equipment, the articles that consider the whole heating system as an organic integrity to analyze its heating storage capacity are relatively less.

This paper will introduce the mathematical model of heating system, firstly. Then, we analyze the heat storage capacity of the PHC by a single-source-single-load heating system. Followed, a research will undertake to illustrate the temperature changes. Also, the influence on the electric output of CHP units by using storage heat

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from the PHC will be calculated to demonstrate the availability of wind power consumption. Then, the economic benefits of utilizing extra wind power for heat supply are analyzed. Finally, the case studies will further verify the effectiveness of this approach.

2. HEATING SYSTEM AND ITS MATHEMATICAL MODEL

2.1 The Contents and Operating Principle of Heating System

A heating system is composed by heating source, heating network and heating load. Also, a heating system could be split into PHC and the secondary heating circuit (SHC), the former transmits heat energy from heating source to sub-regions and the other distributes heat to each end-user. For the PHC, heating sources are CHP units or heating boilers and the heating loads are the heat exchange station between primary and secondary circuit. As for SHC, the heat exchange station and the various kinds of heating users are the heating source and load. The operating principle of heating system is illustrated as Figure 1.

2.2 The Mathematical Model of Heating System

2.2.1 The mathematical model of heating source

The heating energy supply from heating source is co-determined by the circular flow of heating source output, the supply water temperature and the return water temperature, which could be obtained by Equation 1.

$$Q_h = G_h \cdot c\left(t_{hc} - t_{hr}\right) \tag{1}$$

Where, Q_h is the heating load of heating source (kW), G_h is the outlet circuit flow of heating source (kg/s), c is the specific heat of heat medium (kJ/kg•°C), t_{hc} and t_{hr} are the outlet and inlet temperature of heating source (°C), respectively.

2.2.2 The mathematical model of heating line

The schematic diagram of heating line is shown as Figure 2. According to the assumptions, the heat balance equations of the tube wall and heat medium could be formulated as below:

$$\frac{\partial t_p(\tau,x)}{\partial \tau} = H_1[t(\tau,x) - t_p(\tau,x)] + H_2[t_e - t_p(\tau,x)] \tag{2}$$

$$\frac{\partial t(\tau,x)}{\partial \tau} + u\frac{\partial t(\tau,x)}{\partial x} = H[t_p(\tau,x) - t(\tau,x)] \tag{3}$$

where, $t(\tau,x)$ and $t_p(\tau,x)$ are the radial temperature distribution of heat medium and tube wall (°C), *L* is the length of pipeline (m), u is the flow velocity of heat medium in pipeline (m/s), H, H1 and H2 are the heat transmission ratios of the different layers of pipeline.

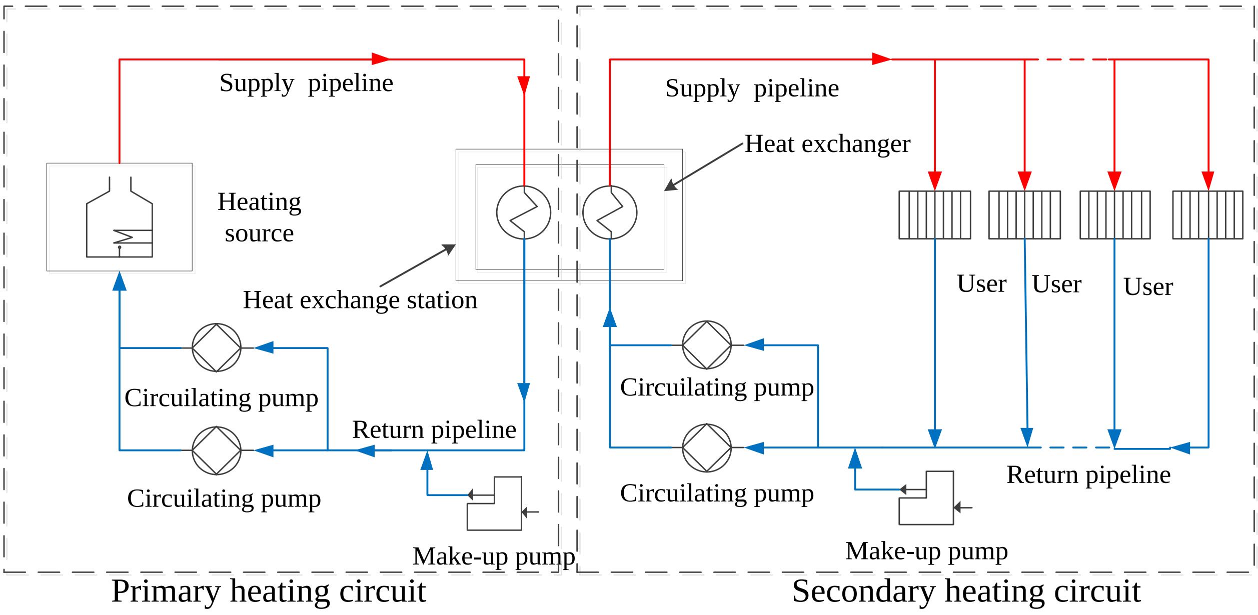

Fig. 1. The schematic diagram of heating system.

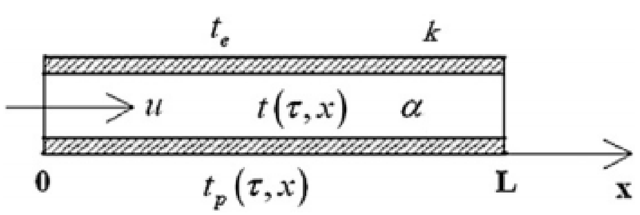

Fig. 2. The schematic diagram of heating line.

2.2.3 The mathematical model of heat exchanger

Heat exchanger is the equipment that transfers a partition of thermal energy from high temperature fluid to low temperature fluid. In heating system, heat exchangers are usually located in heat exchange stations to compete for the heat transmission between PHC and SHC. This paper chooses water-water plate heat exchanger (PHE) as the target because of its high transfer coefficient, wide applicability, compact structure, low scaling factor and easy maintainability that make it become the dominating type in heat exchange station in heating system. Figure 3 presents the schematic diagram of PHE.

The heat transfer equation of PHE could be described as below:

$$Q_{\mathrm{HE}} = \varepsilon_e \cdot W \cdot \left(t_{g1} - t_{g2}\right) \tag{4}$$

where, Q_{HE} is the transferred heating energy from PHC to SHC (kW), W is the heat equivalent (W/°C), ε_e is the effective coefficient, t_{g1} and t_{g2} are the inlet and outlet water temperature of PHE at primary side (°C).

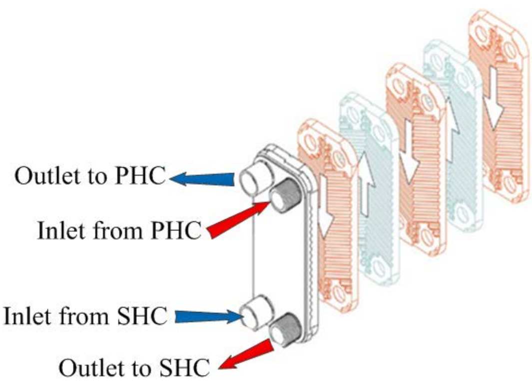

Fig. 3. The schematic diagram of PHE.

2.2.4 The mathematical model of heating load

Radiator is the main heating load in heating system, especially for commercial and residential buildings. Most of the radiators are located in room that take charge of the release of heat to indoor air for the compensation of heat loss and the stabilization of indoor ambient temperature. As for PHC, the PHEs between PHC and SHC could be considered as the heating load. The mathematical expression of heating load could be stated as below:

$$Q_r = \varepsilon_r W_{rs} \left(t_g - t_n\right) \tag{5}$$

where, Q_r is the heating load of heat user (W), W_{rs} is the equivalent heating flow (kJ/ (h·°C), ε_r is the effective coefficient, t_g and t_n are the temperature of supply and return water of heating load (°C).

2.3 The Thermodynamical Characters of Heating Pipeline

The heating network is constituted by pipelines and the heating medium. During the process of heat transmission, the thermal character of heating pipeline has a great influence on temperature drop to heating medium, thus, this section will analyze the heating loss characters and heat transmission delay of pipelines and the temperature drop of heating medium.

2.3.1 The heating loss of pipeline

The water temperature in the PHC is relatively high, thus, most of the pipelines are pressure-bearing. In order to maintain enough pressure bearing capacity, high strength steel pipes are mainly chosen as the inner layer of the heating pipes. To minimize the heating loss, the steel pine would be wrapped by insulation layer with a certain thickness, moreover, the outermost layer is the protective layer that protects the pipeline from external damage. The cross section sketch view of a typical heating pipeline presents in Figure 4.

The heating resistance of metallic pipe is rather small and could be treated as a negligible quantity in engineering calculation. Therefore, the per meter heating loss of supply and return pipe could be defined as follow.

$$q_{\mathrm{spl}} = \frac{(t_{\mathrm{spl}} - t_{\mathrm{air}})(R_{\mathrm{rtn}} + R_{\mathrm{soil}}) - (t_{\mathrm{rtn}} - t_{\mathrm{air}})R_{\mathrm{add}}}{(R_{\mathrm{spl}} + R_{\mathrm{soil}})(R_{\mathrm{rtn}} + R_{\mathrm{soil}}) - R_{\mathrm{add}}^2} \tag{6}$$

$$q_{\mathrm{rtn}} = \frac{(t_{\mathrm{rtn}} - t_{\mathrm{air}})(R_{\mathrm{rtn}} + R_{\mathrm{soil}}) - (t_{\mathrm{spl}} - t_{\mathrm{air}})R_{\mathrm{add}}}{(R_{\mathrm{spl}} + R_{\mathrm{soil}})(R_{\mathrm{rtn}} + R_{\mathrm{soil}}) - R_{\mathrm{add}}^2} \tag{7}$$

$$R_{\mathrm{rtn}} = R_{\mathrm{spl}} = R_{\mathrm{isl}} + R_{\mathrm{prt}} \tag{8}$$

where, q_{spl} and q_{rtn} are the heat loss of supply and return line per unit length (W/m), t_{spl}, t_{rtn} and t_{air} are the temperature of supply water, return water and environment (°C), respectively. R_{spl}, R_{rtn}, R_{soil}, R_{isl}, R_{prt} and R_{add} are the heating resistance of supply line, return line, soil, insulating layer, protective layer and additional heating resistance of heating line (m·K/W), respectively.

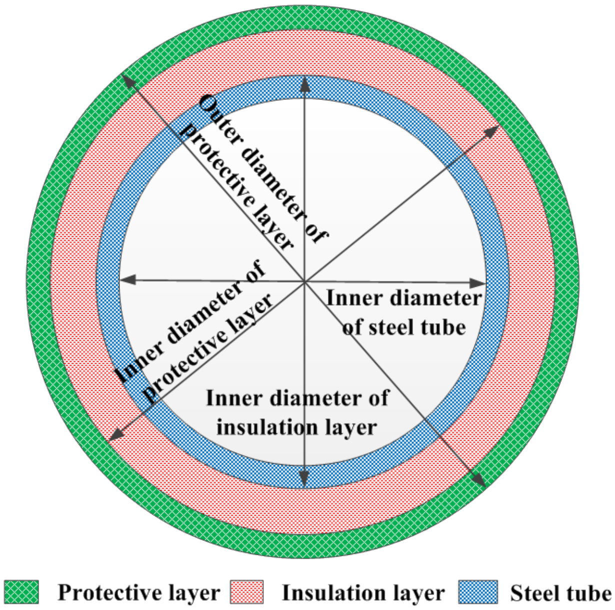

Fig. 4. The sectional view of heating line.

2.3.2 The heat transmission delay of heating pipelines

The heating medium would be pumped into the supply lines after absorbing heat and raising the temperature from heating source. The temperature change at heating load would be later than that at heating source reason from the transmission distance. The heating transmission delay could be defined as below.

$$T_{delay} = \frac{L}{u}\left(1 + \frac{H_1 H_2}{(H_1 + H_2)^2}\right) \tag{9}$$

where, T_{delay} is the heating transmission delay time(s).

Let $K_{delay} = 1 + \frac{H_1 H_2}{(H_1 + H_2)^2}$ and define it as the heating transmission delay coefficient.

2.3.3 Temperature drop of heating medium

Without the consideration of friction between heating medium and pipe, the temperature drop of heating medium could be mainly attributed to the heat exchange to the pipeline. The temperature drop of heating medium after the transition of a certain distance could be presented as follow.

$$\begin{cases} \Delta t_{spl} = \dfrac{q_{spl} \cdot L}{G \cdot c} \\ \Delta t_{rtn} = \dfrac{q_{spl} \cdot L}{G \cdot c} \end{cases} \tag{10}$$

where, Δt_{spl} and Δt_{rtn} are the temperature drop in supply and return lines (°C), respectively. G is the mass flow rate of heating medium (kg/s).

3. THE ANALYSIS OF EXTRA WIND POWER CONSUMPTION OF PHC

3.1 The Heat Storage Capacity Analysis of PHC

The study object of this paper is the heat storage capacity of PHC, thus we make an assumption that the heat transmission between the primary and secondary circuit is fixed and the secondary heating circuit and the changes of heating load could be ignored. The supply line and the return line are laid in parallel and the length of supply line and return line are echo.

In order to facilitate analyzing the heat storage capacity of a heating network, the complex primary heating circuit could be equivalent to a single-source-single-load system which has one CHP unit and one heating load.

A 200MW CHP unit with 250MW heating power output is chosen to be the heating and electric source. The minimum electric heating power output is 100MW and 166.7MW, respectively. The electric to heating power output ratio is 0.75 as a back pressure unit. The working conditions chart of the unit is presented in Figure 5.

The type of heating line is DN1200 with 3km and parallel buried. The parameters and thermodynamic constant of heating line o could be achieved as shown in Table 1. The upper and lower limit of the supply and return water are 120°C and 70°C, respectively.

The heating area of the system is about 3,650,000 m^2 with a heat load index of 55W/m^2 which means the heat load for the CHP unit is 200.75MW. The temperature of outlet water from CHP is 120°C.

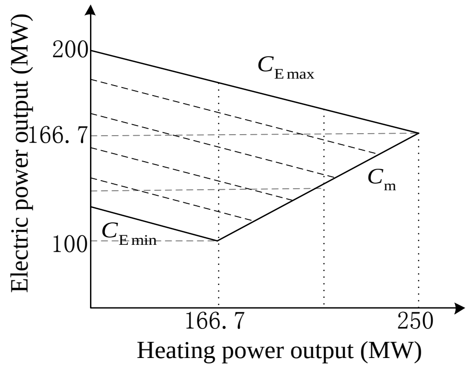

Fig. 5. The working conditions chart of the CHP unit.

Table 1. The parameters of heating line.

The parameters of heating line	Value
Inner diameter of steel pipe (mm)	1200
Tube pitch (mm)	2350
Soil thermal conductivity (W/m·K)	1.5
Heat transfer coefficient of soil (W/m^2· K)	13.5
Insulating layer heat transfer coefficient (W/m· K)	0.0275
Protective layer heat transfer coefficient (W/m· K)	0.0410
Heat resistance	0.5826
Heat resistance of soil (m·K/W)	0.1000
Heat resistance of insulating layer (m·K/W)	0.5039
Heat resistance of protective layer (m·K/W)	0.0787

On the basis of energy conservation in the primary heating circuit, the following equation should be met in each unit time interval.

$$E_{\text{CHP,H}} + E_{\text{HM}} = E_{\text{HE}} + E_{\text{loss}} \tag{11}$$

The parameters in Equation 11 are defined as below.

$$\begin{cases} E_{\text{CHP,H}} = T_{\text{div}} \cdot Q_{\text{CHP,H}} = T_{\text{div}} \cdot G \cdot c \cdot \Delta t_{\text{CHP,H}} \\ E_{\text{HM}} = c \cdot M \cdot \Delta \overline{t_{\text{HE}}} \\ E_{\text{HE}} = T_{\text{div}} \cdot Q_{\text{HE}} = T_{\text{div}} \cdot G \cdot c \cdot \Delta t_{\text{HE}} \\ E_{\text{loss}} = T_{\text{div}} \cdot L \cdot (q_{\text{spl}} + q_{\text{rtn}}) \end{cases} \tag{12}$$

Where, $E_{CHP,H}$, E_{HM}, E_{HE} and E_{loss} are the heating output of CHP, heat transmit to SHC, heat transmit through PHE, heating loss on pipelines during a unit interval (MJ), respectively. M is the mass of heat medium in primary circuit (kg), $\Delta t_{\text{CHP,H}}$, $\Delta \overline{t_{\text{HE}}}$ and Δt_{HE} are the water temperature differences of CHP, water temperature increase/drop of PHC during an interval and water difference of PHE at primary side (°C). T_{div} is the unit interval (s), $Q_{\text{CHP,H}}$ is the heating power output of CHP.

Comparing with the heat transmitted by heating network, the heat loss on the heating network is rather small, thus the heat transmits to SHC by PHE could be approximation measured as the sum of heating source output and the internal energy released by heating medium in PHC. The reduced heating output of CHP could be calculated if the lower limit of the heating medium temperature in the primary heating circuit is clarified, which could be achieved as follow.

$$E_{\text{CHP}_{\text{H,dwn}}} = \min(T_{\text{delay}} \cdot \Delta \text{CHP}_{\text{H}}, \Delta \overline{t_{\text{delay}}} \cdot M \cdot c) \tag{13}$$

Where, $E_{\text{CHP}_{\text{H,dwn}}}$ is the reducible heating output of CHP (MJ), $\Delta \overline{t_{\text{delay}}}$ is the receivable temperature drop (°C), $\Delta \text{CHP}_{\text{H}}$ is the reducible heating power output (MW).

Assuming the supply water temperature of SHC is no lower than 85°C, and should be higher than the return water temperature of PHC. Moreover, the temperature difference between inlet and outlet water at the primary side of PHE should not less than 20°C, therefore, the inlet and outlet water temperature at the primary side of PHE be higher than 105°C and 85°C, respectively.

The temperature changes in different parts of PHC under are presented in Figure 6. From the figure, it could be discovered that the temperature differences between inlet and outlet water of CHP and PHE are stable. The temperature change of PHE is later than CHP outlet water for a heat delay cycle, also the change of average temperature of the heating medium in return lines is later than that in supply lines for a delay cycle, the average temperature of the total heating medium in PHC is approximately linear decreased.

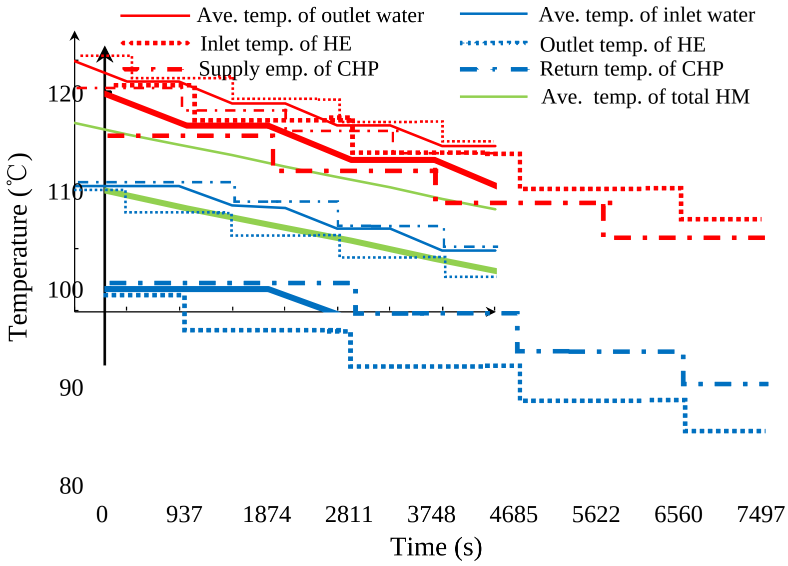

Fig. 6. The temperature changes of PHC.

3.2 The Wind Power Consumption Capacity of PHC

With the additional heat supply, the CHP could bring down the heating output as well as the electric output. Therefore, the increasing capacity of wind power consumption comes from the decreasing electric power output of CHP. This chapter will analyze the promotable capacity of wind power consumption by using the heat storage character of PHC.

Before the beginning of valley electric load period, the heating medium in PHC should stay in a high temperature which could enrich the stored heating energy in the tubes. According to the forecasting of electric load and wind power, the occurrence time, duration and intention of wind power curtailment will be estimated. When electric power exceeds the demand, the heating medium in PHC could release its inner energy and transmit it to heating load through SHC. With the supplement of heating energy from PHC, the CHP could bring down its heating and electric power output, then the wind power could replace the electric power ration give up by CHP. Therefore, the promoting capacity of wind power consumption could approximate equal to the reducible electric power output of CHP, the increasing consumption of wind power could be approximately equivalent to the reducing electric power generation of CHP which directly correlate to the releasable heating energy from the primary heating circuit. The increasable power volume of wind power consumption could be described as follow.

$$P_{\text{W,PHC},t} = \Delta P_{\text{CHP,E},t} = P_{\text{CHP,minE-P}} - P_{\text{CHP,E},t} \tag{14}$$

Where, $P_{\text{W,PHC},t}$ is the increasable consumption of wind power (MW), $\Delta P_{\text{CHP,E},t}$ is the decreased electric power output of CHP, $P_{\text{CHP,minE-P}}$ is the lowest electric power output of CHP according to "OEBH" , $P_{\text{CHP,E},t}$ is the electric power output of CHP after the co-work of PHC. The increasable consumption of wind energy could be calculated by follow equation.

$$E_{\text{W,PHC}} = \int_{\Phi_{\text{EV}}} \Delta P_{\text{CHP,E},t} \tag{15}$$

Where, $E_{\text{W,PHC}}$ is the increasable consumption capacity of wind energy during valley load period (MWh), Φ_{EV} is the integration path of curtailed wind power consumption.

While utilizing the heating storage capacity of heating system, some restricted conditions need to be considered. The temperature of the heating medium needs to keep in a certain range as below.

$$\underline{t_{\text{spl}}} \le t_{\text{spl},t} \le \overline{t_{\text{spl}}} \tag{16}$$

$$\underline{t_{\text{rtn}}} \le t_{\text{rtn},t} \le \overline{t_{\text{rtn}}} \tag{17}$$

Where, $\overline{t_{\text{spl}}}$, $\underline{t_{\text{spl}}}$, $\overline{t_{\text{rtn}}}$ and $\underline{t_{\text{rtn}}}$ are the upper and lower limit of supply and return water temperature of PHC, respectively. $t_{\text{rtn},t}$ and $t_{\text{spl},t}$ are the supply and return water temperature at moment t.

The calculation flow chart of promoting wind power consumption by heating system is illustrated in Figure 7. Firstly, the wind power consuming state should be estimated according to the input real-time data of electric load, heating load and the power output of the power sources. If the wind power could be consumed completely, the stop criterion should be checked to decide the termination of the data sampling. Otherwise, followed, the heating state of PHC should be determined, then estimating whether the extra wind power could be consumed by using the stored heating energy in PHC. If the answer is negative, checking the stop criterion, or else calculating the reducible electric power output of CHP by using the stored heat in PHC. Finally, the stop criterion should be checked to determine the stop of the calculation or keep it in the loop.

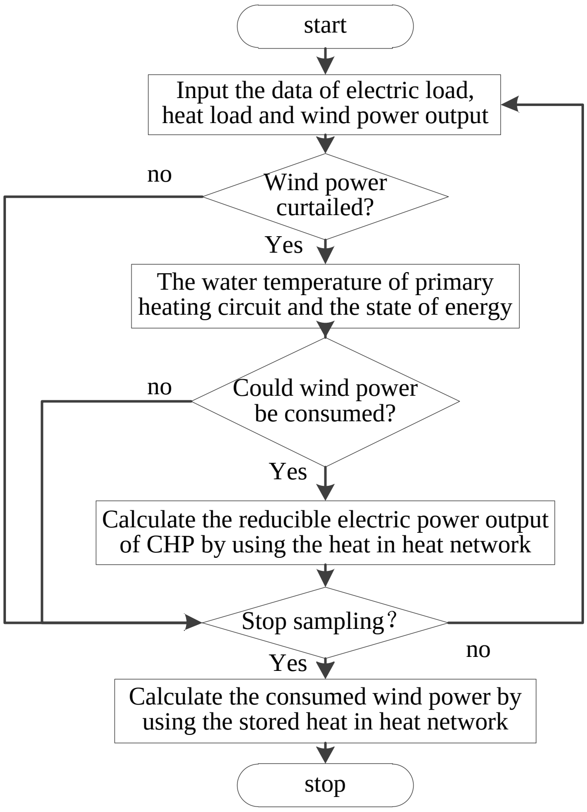

Fig. 7. The flow chart of wind power consumption.

4. ANALYSIS OF ECONOMIC BENEFIT

This paper adopts annual benefits within the design service life as the objective function:

$$P_{\text{annual}} = B_{\text{annual}} - C_{\text{annual}} \tag{18}$$

where, A_{nnual} is the annual benefit by the adoption of stored heat in PHC, B_{annual} is the annual incomes of the adoption of stored heat in PHC and C_{annual} is the annual cost, respectively.

4.1. *The Analysis of Incomes*

The incomes of the TED application mainly comprise operating incomes such as fuel savings, and policy gains, emission reduction subsidies and/or carbon trading earnings, etc. for instance:

$$B_{\text{annual}} = B_{\text{E}} + B_H + B_{\text{policy}} \tag{19}$$

The fuel savings could be divided into savings from lower electric power output, more wind power access and lower heat power output as the participation of outside heat resources.

The equation below is the definition of annual fuel savings by lower electric power output as the participation of TED:

$$B_{\text{E}} = b_{\text{fuel}} \cdot \sum \int_{\Phi} \Delta P_{n,t} \cdot a_n \tag{20}$$

where, respectively, B_{E} is the annual fuel savings by less electricity generation, b_{fuel} is the fuel price per unit mass, $\Delta P_{n,t}$ is the reduced electric power output of CHP n by TED at moment t, a_n is the fuel consumption rate of electricity generation of CHP n, Φ is path of integration for annual fuel savings. The annual fuel savings by reducing heat supply could be defined as follows:

$$B_{\text{H}} = b_{\text{fuel}} \cdot \sum \int_{\Phi} \Delta H_{n,t} \cdot b_n \tag{21}$$

where, B_H is the annual fuel saving by less heat supply, $\Delta H_{n,t}$ is the decreased heat power output of CHP n by TED, b_n is the fuel consumption rate of heat generation of CHP n, respectively.

The annual policy income is defined as:

$$B_{\text{policy}} = b_{\text{policy}} \cdot \Gamma \cdot (a_n \cdot \sum_n \int_{\Phi} \Delta P_{n,t} + b_n \cdot \sum_n \int_{\Phi} \Delta H_{n,t}) \tag{22}$$

where, B_{policy} is the annual policy incomes by the utilization of TED, b_{policy} is the per unit income of emission reduction under relative policy support, Γ is the emission quantity per unit mass fuel burning.

4.2. *The Analysis of Costs*

As the heating system is an existing system, the investment cost could be ignored. The annual cost on utilizing stored heat in PHC could be equal to the sum of annual operation cost and annual cost on electricity utilization:

$$C_{\text{annual}} = C_{\text{op.annual}} + C_{\text{power,annual}} \tag{23}$$

where, $C_{\text{op.annual}}$ is the annual operation cost, $C_{\text{power,annual}}$ is the annual energy cost.

The annual operation cost includes the annual productive labor cost C_{HR}, annual system maintaining and service cost $C_{M\&S}$ which could be described as follow.

$$C_{op.annual} = C_{HR} + C_{M\&S} \tag{24}$$

The labor cost has a direct relationship with the monthly salary per person $_{labor}$ and the number of employees n_{hire}..

$$C_{HR} = 12 \cdot b_{labor} \cdot n_{hire} \tag{25}$$

The annual system maintaining and service cost could be assumed as 15% of the annual income.

The annual energy cost mainly relatives to the electric price for the wind power consumption from wind farms b_{W2C}, and the electric quantity bought from wind farms E_{W2C}. While, as the consumed wind power is the surplus power, the electric price could be relatively low.

$$C_{power,annual} = b_{W2C} \cdot E_{W2C} \tag{26}$$

5. CASE STUDY

5.1 The Parameters of the Case System

The power sources of the study case are consisted by pure condensing steam units, extraction steam CHP units and wind turbines which the rated capacity are 300MW, 200MW and 125MW, respectively. The penetration rate of wind power in this grid is 20%, approximately. The electrical power load cover is calculated from the average value of three running days in Changchun City, Jilin Province, China as shown in Figure 8. The flow cover of wind power is calculated from the average value of a three running days data which gathered from Xiangyang Wind Farm in Taonan, Jilin Province, China shows in Figure 9.

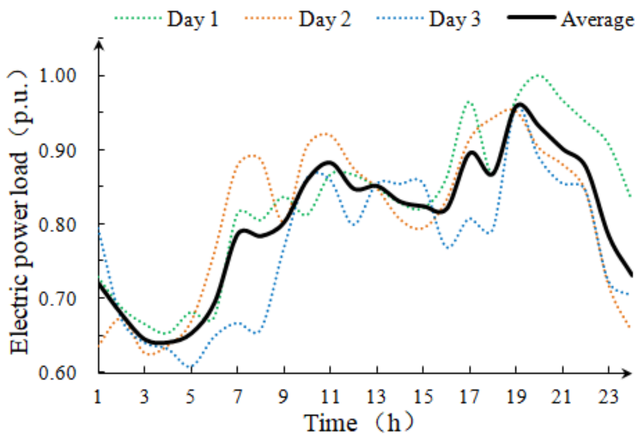

Fig. 8. The curves of electric power load.

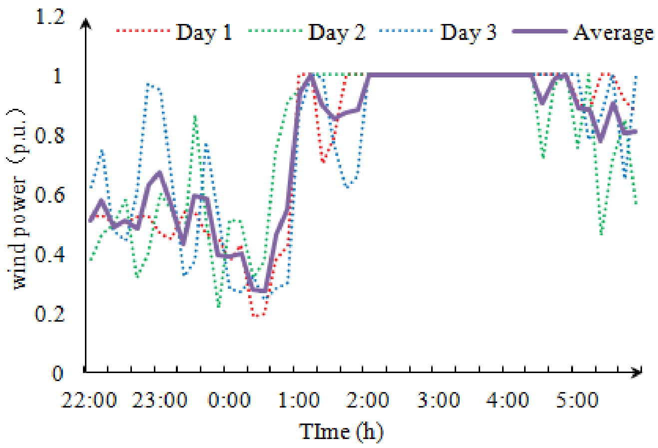

Fig. 9. The curves of wind power output.

This paper collects the outdoor temperature and heating load data of three (3) running days of the No.2 Thermal Power Plant in Changchun (No.2 TPPCC) and calculates their average values as the daily temperature and heating load curve as illustrated in Figure 10 and Figure 11. It could be discovered that the correlation relationship between heating load level and outdoor temperature are negative. Also, compare with Figure 9, the electric power load presents a variation trend of high during the day and low at night, the variation trend of the heating load is opposite which result in the peak-valley contradiction of electric power load and heating load.

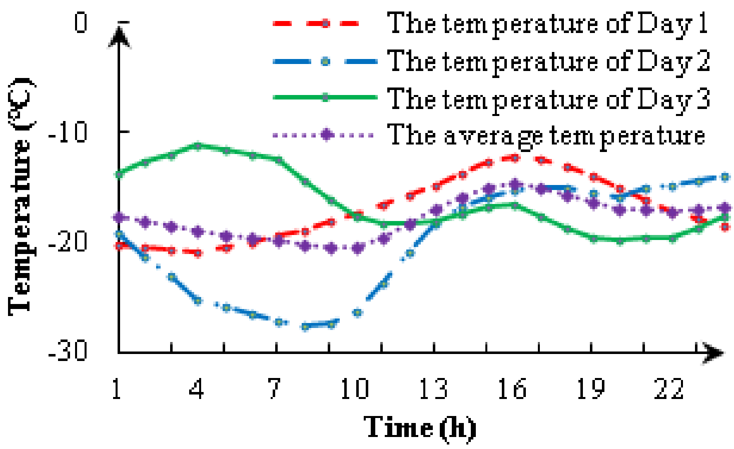

Fig. 10. The curves of outdoor temperature.

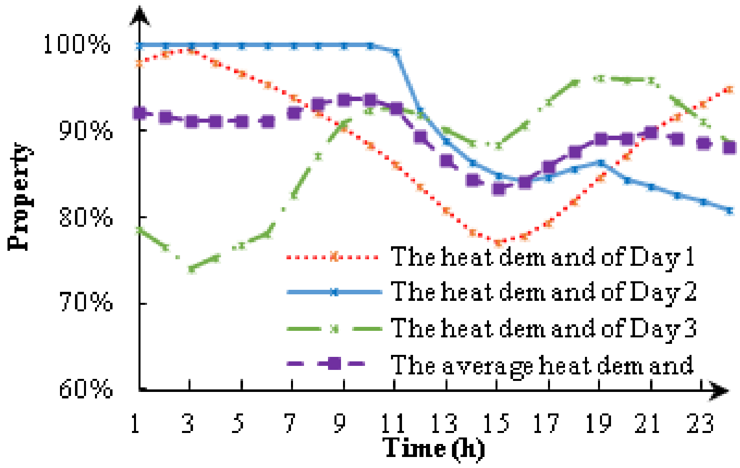

Fig. 11. The curves of heating load level.

The operation mode of CHP plant in the mid-term of heating season is that the heating power output should higher than 220MW which means the adjustment interval of electric power output is between 140MW to 170MW. The electric power output of the CHP and pure condensing steam units in minimum operation mode are 100MW and 120MW, respectively, and the ramp rate of the CHP is ±20MW/10m.The distribution mode of the primary heating circuit system is branched, the heating source is CHP. There are 5 heat exchange stations, with one PHE in each one, and each PHE takes charge of heating service for 7.2×106 m^2. The heating load is 55W/m^2 and the total heat load is 198MW approximately. According to the design standard, the temperature of supply and return water in primary heating circuit are 120°C and 85°C, respectively. The schematic diagram of the PHC as shown in Figure 12 where node ① is the joint between CHP and PHC, node ②, ④, ⑥ and ⑧ are the 3-way joint that change the flow direction of heat medium, node ③, ⑤, ⑦, ⑨ and ⑩ is the joint between PHC and PHE.

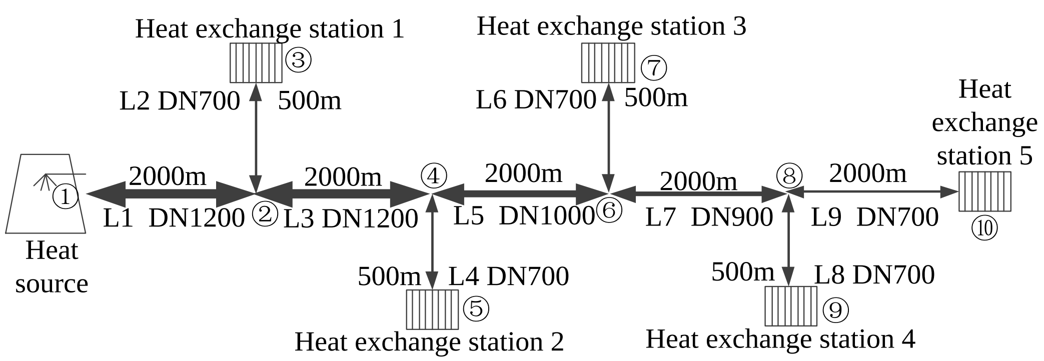

Fig. 12. The schematic diagram of PHC.

According to the difference of runoff volume, the pipes with different diameters are located in different locations. In this case study, 4 types of pipeline are applied which are DN1200, DN1000, DN900 and DN700, the parameters and thermodynamic constants are listed in Table 2.

In order to guarantee the wind power consumption capacity, the heat medium in PHC needs to maintain a high-temperature level when near the valley load period to enlarge its internal energy capacity. Thus, assuming the inlet and outlet temperature of the farthest heat exchange station, heat exchange station 5, are 120°C and 100°C, respectively. The temperature difference between inlet and outlet water of other heat exchange stations are all 20°C. Table 3 illustrates the thermodynamic parameters of the pipelines and heat exchange stations at the beginning of valley electric load period.

Table 4 presents the inlet and outlet water temperature under the initial state when at the beginning of valley electric load period. It could be found that the heat loss on pipelines is higher and higher and the inlet water temperature is lower and lower with the longer distance between the CHP and heat exchange station. At the same time, with the increase of transmission distance, the heat response delay from heat source to heat exchange station is longer and longer.

Table 2. The parameters of heating lines.

Item	DN 1200	DN 1000	DN 900	DN700	Unit
Inner diameter of steel pipe	1200	1000	900	700	mm
Tube pitch	2350	2150	1950	1600	mm
Soil transfer coefficient	13.5	13.5	13.5	13.5	W/m·℃
Insulating layer conductivity	0.028	0.027	0.0275	0.028	W/m·K
Protective layer conductivity	0.041	0.041	0.041	0.041	W/m·K
Heat resistance	0.671	0.672	0.773	0.911	m·K/W
Soil heat resistance	0.049	0.072	0.087	0.114	m·K/W
Insulating layer heat resistance	0.586	0.577	0.677	0.799	m·K/W
Protective layer heat resistance	0.085	0.095	0.097	0.112	m·K/W

Table 3. The thermodynamic constants of the heating lines.

No.	Flow volume kg/s	Total loss kW/km	Supply drop rate ℃/km	Supply drop rate ℃/km	Heat delay s
L1	2291	340.1	0.0192	0.0161	1317
L2	458	237.5	0.0672	0.0562	544
L3	1833	340.1	0.0240	0.0202	1637
L4	458	237.5	0.0672	0.0562	544
L5	1375	327.7	0.0309	0.0259	1396
L6	458	237.5	0.0672	0.0562	544
L7	916	284.4	0.0403	0.0337	1635
L8	458	237.5	0.0672	0.0562	544
L9	458	237.5	0.0672	0.0562	2176

Table 4. The parameters of PHEs under the initial state.

No.	Inlet temperature ℃	Outlet temperature ℃	Flow volume kg/s	Load MW	Delay s
PHE 1	120.29	100.29	458.33	38.50	1861
PHE 2	120.24	100.24	458.33	38.50	3498
PHE 3	120.18	100.18	458.33	38.50	4894
PHE 4	120.10	100.10	458.33	38.50	6529
PHE 5	120.00	100.00	458.33	38.50	8161
CHP	100.12	120.36	2291.67	196.03	N/A

5.2 Analysis of Heat Storage Capacity of Heat Network

When utilizing the stored heat in PHC to supplement the heat need from the SHC, the average temperature of the heat medium in PHC goes down and down, also the temperature of CHP inlet water will decrease as well. The changing trend of CHP inlet water temperature is similar with its heat power output, and result from the continual decrease of its return water temperature, the general variation trend of CHP outlet water temperature during valley electric load period is declined as present in Figure 13.

The inlet water temperature curves during the valley electric load period of the PHEs are illustrated in Figure 14. The inlet water temperature of PHE is mainly determined by the outlet water temperature of CHP, thus the variation trend of the PHE inlet temperature is similar to outlet water temperature of CHP units. Since the different distances from CHP unit to the PHEs, the respond time of temperature variation of the PHEs are basically proportional to their distances. The temperature difference between inlet and outlet water is fixed and the response time could be ignored as the steady flow velocity in PHC.

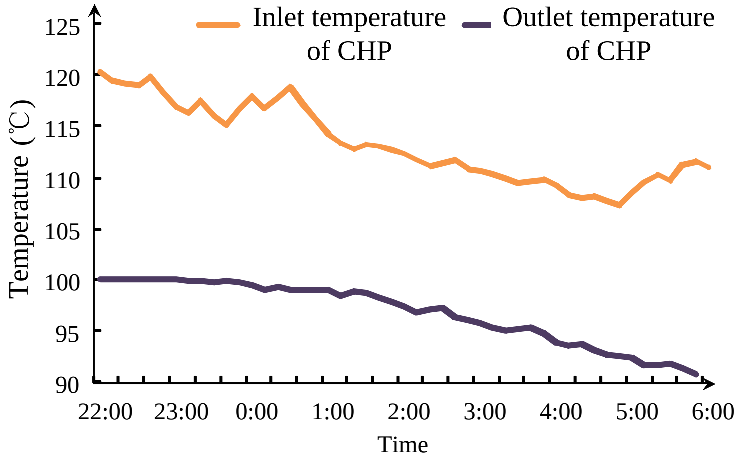

Fig. 13. The supply and return water temperature of CHP.

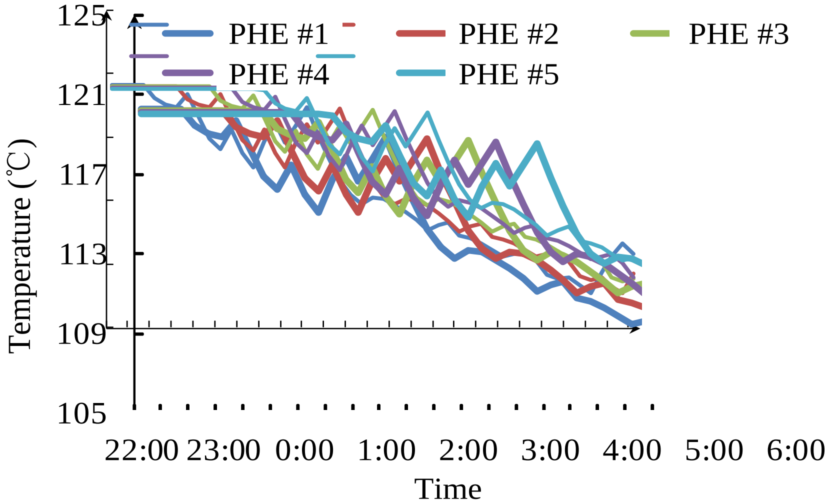

Fig. 14. The supply water temperature of each PHE

The average temperature changes of supply water in different pathways are presented in Figure 15 and Figure 16. Similar variation trend emerges among the average temperature of the supply waters and the outlet water of heating source. However, because of the different distances to heating source, the heat response time of the PHEs are disparate. As the same reason, the average medium temperature in each supply pipeline shows a similar change trend but with different response time. While, the water temperature in return lines is not only determined by the outlet water from the connected PHE, but also the return water from other return lines. The return lines link with different heat exchange stations which have different distances from the heating source, the lasting time of thermodynamic cycle for the heat exchange stations are different. For instance, when the return water from No.1 heat exchange station reaches to No.1 return line, the supply water even not reach to No. 2 heat exchange station, and when the return water from No.5 heat exchange station reaches to No.1 return line, several thermodynamic cycles has accomplished between the CHP and other heat exchange stations, by then the return temperature from each heat exchange station are disparate. In addition, the return water temperature in No. 8 and No.9 return line are only affected by No. 4 and No.5 heat exchange station, respectively, while the water temperature in No.5 return line is affected by No. 3, No. 4 and No.5 heat exchange station, and No.1 return line is affected by all of the heat exchange station. Thus compare with the supply water temperature, the changes of return water in return lines are much more complicated.

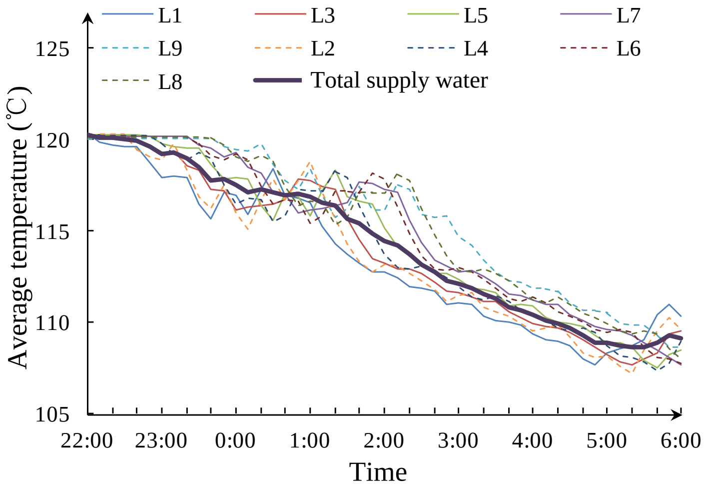

Fig. 15. The temperature of supply in lines.

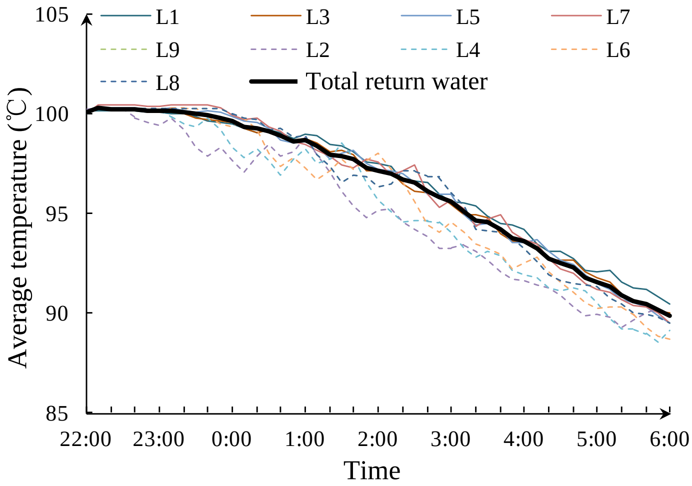

Fig. 16. The temperature of return in lines.

5.3 The Analysis of Wind Power Consumption Capacity

Based on the data and statistics of wind power, electric load and traditional power sources, the wind power consumption, without the participation of heating network, during valley electric load period in a typical heating day could be simulated, which the wind power curtailment rate is about 48.3% and near 383.5MW wind energy has to be abandoned as shown in Figure 17.

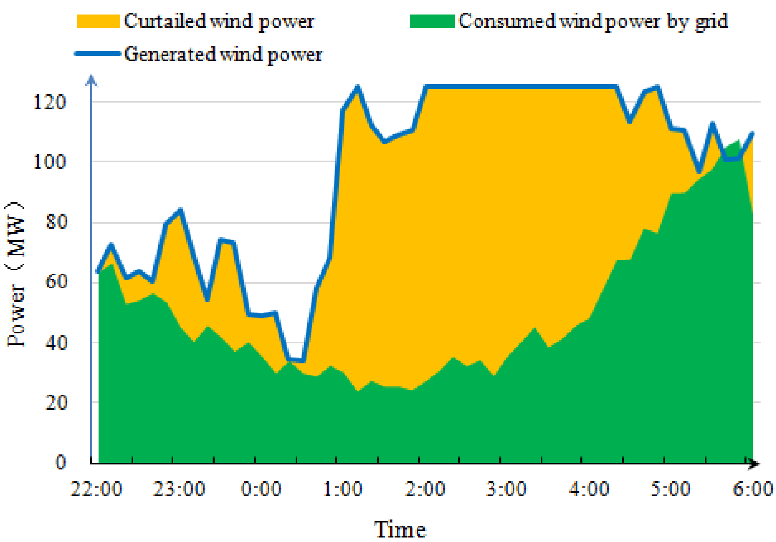

Fig. 17. The wind power consumption during electric load valley.

Without the participation of heating network, by the combined effect of valley electric load and peak wind power generation, the CHP unit have to work as a backpressure unit and its electric power output should be stabilized around the lower limit regulated by the "OEBH" policy. After the co-working of heating network, the heating medium within PHC could release the inner energy to SHC to guarantee the energy transmission stability, the heating power output of CHP could decline with the less heating need and the electric power output could be brought down by the fixed electric-heating power ratio under backpressure working condition. Figure 18 illustrates the electric power output changes before and after the participation of the PHC.

After the participation of the primary heating circuit, the wind energy that about 219.4MWh could be consumed by utilized the stored heating energy in heating network, at the same time, the wind power curtailment rate could be reduced to 27.7%, approximately. Figure 19 shows the consumption of wind power after the participation of the primary heating circuit.

It could be discovered that the wind power curtailment could be relieved by the associate of heating network, but a certain amount of wind power could not be consumed. The main reason for that is the CHP unit has its own technical power output limits, the declining space of power output for consuming wind power is restricted. What is more, the ramp rate of CHP unit and the operating constraint conditions also have an important influence on wind power consumption.

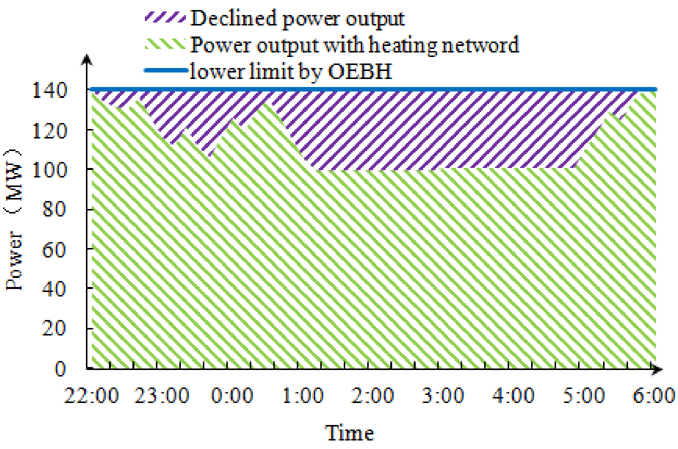

Fig. 18. The electric power output of CHP after co-work of PHC.

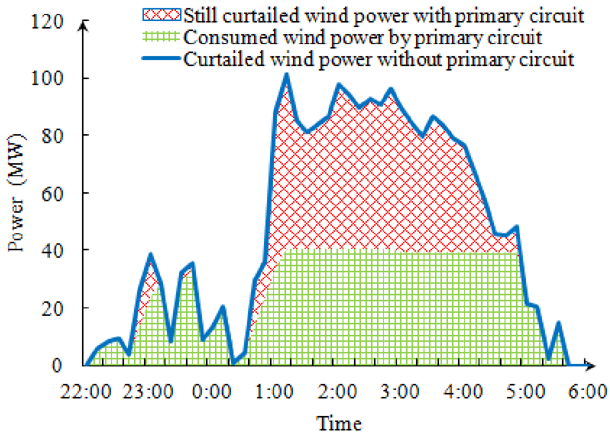

Fig. 19. The surplus wind power consumption after the co-work of PHC.

5.4 The Analysis of Economic Benifits

The economic parameters needed for economic analysis are set as in Table 5. Assuming five (5) persons are hired to operate the system.

By the simulation of a whole heating season, approximate 26.3GWh wind energy could be consumed by utilized the stored heating energy in PHC. By the supplement of wind energy of about 15GWh electric energy and 40.7 trillion Joule heating energy generation of CHP could be reduced, the reduced heating energy is complemented by the surplus wind energy. As the utilization of storage heat in PHC, about 1843.5 tons of coal could be saved and the benefits on fuel saving is US$ 178.81×10^3, the income on carbon trading price is about US$ 13.73×10^3. Thus, the annual income of the utilization of storaged heat in PHC is about US$ 192.54×10^3.

There are five (5) persons employed for 12 month a year and the annual cost on labor force is US$44.78×$10^3$, the annual system maintaining and service cost could be assumed as 15% of the annual incomes which could be US\$ 28.88×10^3. During the heating season, approximate 11.7GW of electric quantity is bought from wind farms for complementing heat supply and the cost on electricity purchase is about US\$ 67.46×10^3.

To sum up, the annual incomes and cost on the utilization of storage heat in PHC are about US\$ 192.54×10^3 and US\$ 141.04×10^3, respectively. The annual economic benefit is US\$ 51.49×10^3.

Table 5. The economic parameters for simulation.

Item	Value	Unit
Coal price	0.10	10^3 US\$/ton
Carbon trading price	7.46	US\$/ton
Coal evaluation on electricity generation	0.1229	ton/MWh
Carbon trading price	7.46	US\$/ton
Employee salary	750	US\$/month
Heat price	3.21	US\$/GJ
Electricity price from wind farm	5.77	US\$/MWh

6. CONCLUSION

This paper establishes the thermodynamic model of PHC, analyzes the heat storage capacity and calculates the wind power consuming ability by utilizing the inner energy of heating medium with a single-source-single-load heating system. Also, this work uses probabilistic production simulation to calculate and analyze study case. The results of the case study proving that the utilization of heat storage capacity of heat network could enhance the wind power consuming ability during valley electric load period, relieve the wind power curtailment caused by the inverse correlation between heating and electric load. The case study presents that without large scale remold of heating system and power grid, the wind power curtailment rate could be reduced by about 28%, and about 219.4MWh surplus wind energy could be consumed by changing the operation and management mode of heating system. This approach spends few funds on the retrofitting of hardware, only a matter of increasing cost on administration, thus, the economic efficiency and the security of this approach is objective.

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