STUDY ON OPTIMAL HEAT-POWER DISPATCH CONSIDERING DISTRICT HEATING SYSTEM THERMAL INERTIA

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ABSTRACT

As the global climate change and increasing requirement for thermal comfort of human, the thermal demand in the heating period is gradually climbing. The district heating system (DHS) with combined heat and power (CHP) units as the heat source is the major heating method in northern China, and exploring the flexibility enhancement way of CHP units is a key issue. The main ways to improve the flexibility of CHP units are heating unit modification and utilization of external energy storage. At the same time, there is a large amount of thermal storage in the DHS, which can be used to achieve the same effect as using hot water tank thermal storage, and can reduce the heating unit's own renovation and lower costs. In the integrated heat and power scheduling optimization, the cost is generally used as the optimization objective, but the amount of coal consumption under different operating conditions of CHP is less considered in the cost of CHP units as heat sources. In this paper, the dynamic model of the system considering the heat storage of the DHS heat network is established, and the coal consumption of CHP unit is added to the system operating cost. The study shows that the costs is negatively correlated with the water temperature of the heat network and positively correlated with the mass flow rate of heating steam, while higher CHP operating conditions increase the total operating cost.

1 INTRODUCTION

According to statistical review of world energy, coal-fired power plants still play an essential role to ensure the energy security and resilience of the power system (Chen *et al.*, 2022), but cogeneration often leads to unnecessary heat-power coupling (Wang *et al.*, 2022). The main ways to improve the flexibility of CHP units are heating unit modification and utilization of external energy storage (Liu *et al.*, 2019, Katulić *et al.*, 2014).

Research (Romanchenko *et al.*, 2018) find that hot water tank heat storage and the thermal inertia of buildings have the same effect on the operation of the central heating system, leading to a boom in research into the effects of heat network thermal storage on DHS. Meanwhile, some studies (Li *et al.*, 2020, Korpela *et al.*, 2017) reveal that using the thermal storage of the DHS can effectively improve the flexibility of the CHP unit and absorb renewable energy. Zheng et al. (2018) proposed an integrated heat-power scheduling model considering thermal inertia and found that the use of thermal storage not only enhances the safety of the scheduling process but also reduces the cost. Sun et al. (2021) found that considering thermal inertia will enhance the thermal storage capacity of the heat network, which has positive benefits for multi-energy system regulation, balances the operating costs and robustness of the system, and facilitates the integration of wind power.

Cost optimization in the scheduling process is complex, and varies for modeling and selecting parameters for costs. Li et al. (2019) combined generating unit fuel costs, thermal storage operating and investment costs, demand response (DR) incentive costs, and wind abandonment costs. Shi et al. (2020) divided the operating costs of heat sources into four components: heating energy costs, equipment depreciation and overhaul costs, and personnel salaries. Li et al. (2023) divided the system's operational

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energy consumption into two components, pump operation and operational heat loss, and converted them into costs. Wang et al. (2022) integrated the operation and maintenance costs, the penalty cost of abandoning renewable energy sources, and the carbon emissions trading cost as the optimization objective, where the operation cost includes the cost of purchasing electricity, the cost of purchasing gas, and the maintenance cost.

However, in the study of optimal scheduling of integrated heat and power, generally for the model of heat source, especially the operation model of CHP units, the operation domain conditions are given to simplify its cost calculation. In this paper, the dynamic model of the system considering the heat storage of the DHS heat network is established, and the coal consumption of CHP unit is added to the system operating cost, and the change of the total operating cost of the system under different electric and heat loads is calculated, so as to do the groundwork for the optimal operation of the DHS under specific electric and heat loads afterwards.

2 SYSTEM DESCRIPTION

The heating system is shown in Figure 1, it mainly composed of heat source, heat network and heat users, respectively. The heat network includes heat exchange stations and water pipes. In this system, the steam is extracted from heat source and exchanged in the primary heat exchange station, then passed through the heat network to ultimately heat the heat users. The primary network water and secondary network water in the heat network are exchanged in the secondary heat exchange station.

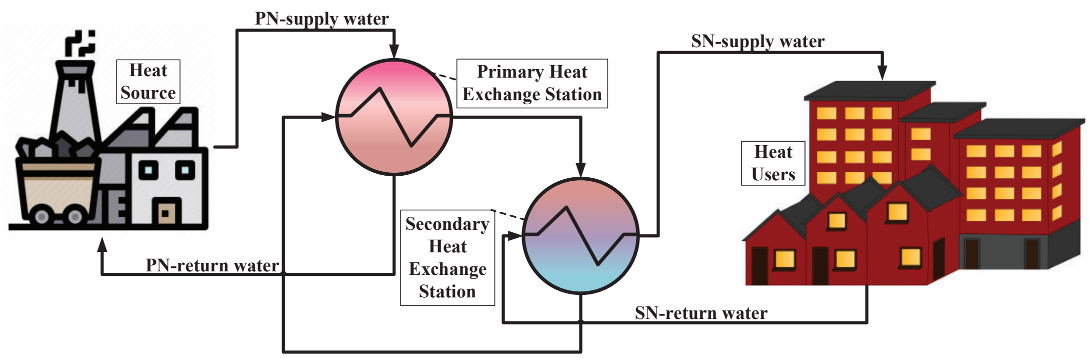

Figure 1: Heating system diagram

2.1 Mathematical Model

In order to fully represent the heat storage within the heat network, the models of the DHS are all built as dynamic models, containing models of both the building and the heat network.

The model of the building is mainly composed of a radiator, room, and envelope structure (Jiang *et al.*, 2018). The heat network model includes water supply and return pipes, mixed water nodes, and heat exchange stations (Zheng *et al.*, 2018) The system model of the building and heat network has been reflected in the previous research (Wang *et al.*, 2024) and will not be described again.

In this paper, the CHP unit, as the main heat source. The calculation model of variable working conditions mainly refers to the calculation process of unit variable working conditions in Ref (Liu *et al.*, 2019). Generally, the electric heating operating domain of the extraction steam heating unit is limited by the main steam flow and the minimum condensate flow of the low-pressure cylinder. The heating unit used in this paper is a 330 MW unit, with a rated steam flow of 420 t/h.

2.2 Evaluation Index

In this paper, the operation cost is adopted as the main evaluation index of the system, which mainly includes the energy consumption cost of the heat source and the energy consumption cost in the operation process. The running cost of whole heating system is calculated using the following formula:

$$C_A = C_{source} + C_{oper} \tag{1}$$

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where C_{source} is the energy consumption cost of the heat source, yuan; C_{oper} is the energy consumption cost in the operation process, yuan.

The energy consumption cost of the heat source is calculated using the following formula:

$$W = \frac{\sum_{i=1}^{r} D_i \cdot (h_0 - h_i) + \sum_{i=r+1}^{n} D_i \cdot (h_0 + \sigma - h_i) + D_c \cdot (h_0 + \sigma - h_c)}{3600} \tag{2}$$

$$Q = D_h (h_{gr} - h_{grh}) \tag{3}$$

$$B^s_{tp,e} = \frac{3600 W_h}{\eta_m \eta_g \eta_{i,h} \eta_b \eta_p q_{net}} + \frac{3600 W_e}{\eta_m \eta_g \eta_{i,e} \eta_b \eta_p q_{net}} \tag{4}$$

$$B^s_{tp,h} = \frac{Q}{\eta_b \eta_p \eta_{hs} q_{net}} \tag{5}$$

$$C_{source} = \frac{(B^s_{tp,e} + B^s_{tp,h}) c_C}{3600000} \tag{6}$$

where W is the output power of the heat source, kW; D_i is the steam mass flow rate at stage i, t/h; D_c is the exhaust steam mass flow rate of the turbine, t/h; h_0 is the enthalpy of main steam, kJ/kg; h_i is the steam enthalpy at stage i, kJ/kg; h_c is the enthalpy of exhaust steam from the turbine, kJ/kg; σ is the enthalpy rise of reheated steam, kJ/kg; Q is the thermal load of heat source, kJ/h; D_h is the mass flow rate of heating steam, t/h; h_{gr} is the enthalpy of heating steam, kJ/kg; h_{grh} is the enthalpy of heating steam backwater, kJ/kg; $B^s{}_{tp,e}$ is the standard coal consumption for co-generation in CHP unit, kg of standard coal/h; W_h is the power generation of the heating steam, kW; W_e is the power generation of the condensate stream, kW; η_m is the mechanical efficiency; η_g is the efficiency of the generator; η_b is the boiler efficiency; η_p is the pipeline efficiency; $\eta_{i,h}$ is the efficiency of the heating part of the CHP unit on a heating basis; $\eta_{i,e}$ is the absolute internal efficiency of the condensate generation portion of the CHP unit; q_{net} is the low-level heat content of the coal, kJ/kg; $B^s{}_{tp,e}$ is the standard coal consumption for CHP heating, kg of standard coal/h; η_{hs} is the heating efficiency; c_c is the the selling price of coal, in this paper, it takes the value of 650 yuan/t.

The energy consumption cost in the operation process is consists of two parts, which are the discounted cost of energy consumption of heating network pumps and the discounted cost of heat loss along the heating network (Li *et al.*, 2023). And the energy consumption cost in the operation process is calculated using the following formula:

$$C_{oper} = C_{pump} + C_{loss} \tag{7}$$

where C_{pump} is the discounted cost of energy consumption of heating network pumps, yuan; C_{loss} is the discounted cost of heat loss along the heating network, yuan.

The discounted cost of energy consumption of heating network pumps is calculated using the following formula:

$$N = \frac{\rho G H}{1000 \eta_{pump}} \tag{8}$$

$$C_{pump} = \frac{N \cdot c_e}{3600} \tag{9}$$

where N is the power of the pump, kW; ρ is the density of water, kg/m^3; G is the flow rate of water in the pipe, kg/s; H is the pump head, mH_2O; η_{pump} is the efficiency of the pump; C_e is the price of electricity, which generally takes the value of 0.68 yuan/(kW·h).

The discounted cost of heat loss along the heating network is calculated using the following formula:

$$q_{loss} = KL \cdot (T_{water} - T_o) \tag{10}$$

$$C_{loss} = \frac{q_{loss} c_C}{q_C \eta} \tag{11}$$

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where K is the thermal conductivity of the pipe, W/(m·℃); L is the length of pipe, m; T_{water} is the average temperature of the pipe, ℃; T_0 is the outdoor temperature, ℃; q_c is the calorific value of coal, kJ/kg; η is the efficiency of heat generation.

2.3 Model validation

In this paper, the system model is established in Matlab-Simulink. The calculation results of the CHP unit model established in this paper correspond to the heat balance diagram of the unit, and the error of the calculation results is shown in Table 1, it can be seen the errors are all within the allowable range, which proves that the model is effective (Liu *et al.*, 2019). And the dynamic model of the heating system established in this paper is proved in Ref (Wang *et al.*, 2024).

Table 1: CHP unit model verification

	Parameters	Unit	Heat balance diagram	Results of calculation	Error (%)
100% turbine heat acceptance (THA)	Mass flow rate of main steam	$t\cdot h^{-1}$	986.96	982.81	0.4
	Steam consumption rate	$kg\cdot kW^{-1}\cdot h^{-1}$	2.991	2.974	0.58
	Heat consumption rate	$kJ\cdot kW^{-1}\cdot h^{-1}$	7859.1	7872.4	0.17
50%THA	Output power	kW	164999	166387	0.84
	Steam consumption rate	$kg\cdot kW^{-1}\cdot h^{-1}$	2.909	2.884	0.84
	Heat consumption rate	$kJ\cdot kW^{-1}\cdot h^{-1}$	8286.4	8270.1	0.20
Rated heating	Output power	kW	257097	266998	3.85
	Steam consumption rate	$kg\cdot kW^{-1}\cdot h^{-1}$	4.069	3.918	3.72
	Mass flow rate of main steam	$t\cdot h^{-1}$	1046	1037.9	0.77

3 RESULTS AND DISCUSSION

3.1 Reference case

The main design parameters of the heating system are shown in Table 2. And the pipe network parameters are derived from urban heating design standards, and pipe diameters are computed based on pipeline flow requirements.

Table 2: Design data of the heating network

Parameters	Unit	Value	Parameters	Unit	Value
Mass flow rate of heating steam	$kg\cdot s^{-1}$	116.7	Enthalpy of heating steam	$kJ\cdot kg^{-1}$	2963.9
Enthalpy of heating steam backwater	$kJ\cdot kg^{-1}$	583.19	Outside temperature	℃	-5.7
Length of the primary network pipe	m	10000	Length of the secondary network pipe	m	5000
Primary network supply water temperature	℃	130	Primary network return water temperature	℃	60
Secondary network supply water temperature	℃	70	Secondary network return the water temperature	℃	45
Mass flow of primary network water	$kg\cdot s^{-1}$	1102.495	Mass flow of secondary network water	$kg\cdot s^{-1}$	4408.73
Diameter of the primary network pipe	m	0.7	Diameter of the secondary network pipe	m	1.2

In Table 3, numerical values corresponding to the indoor temperature, wall temperature of the heating user, and temperature of the supply and return water within the heating network under the design conditions are provided. These values are obtained through simulation calculations.

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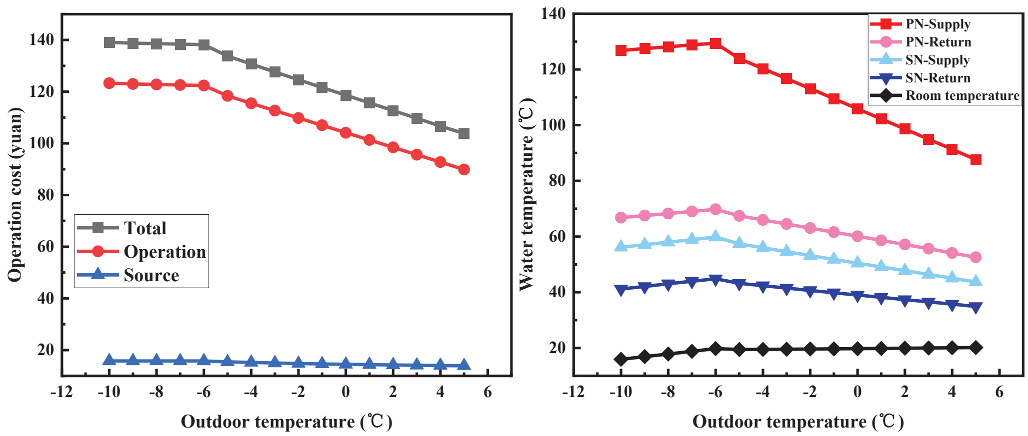
Table 3: Calculation data of benchmark conditions of heating system

Parameters	Unit	Value	Parameters	Unit	Value
Primary network supply water temperature	°C	129.5	Secondary network supply water temperature	°C	60.01
Primary network return water temperature	°C	69.96	Secondary network return the water temperature	°C	45.11
Wall temperature	°C	2.66	User's indoor temperature	°C	20.05

3.2 Impact of different heat loads on system operating costs

As shown in Fig. 2(a), the total system operating cost decreases with increasing outdoor temperature for a given constant electrical load. In this process the heat source cost remains basically unchanged, the heat network operating cost decreases, and the total cost decreases. The effect of outdoor temperature change on the water temperature of the heat network is shown in Fig. 2(b). Since the design condition is that the outdoor temperature is -5.7°C, the heat network water temperature increases when the outdoor temperature is less than the design outdoor temperature and decreases when the outdoor temperature is greater than the design outdoor temperature.



(a) Impacts on operating cost (b) Impacts on water temperature

Figure 2: Influence of different outdoor temperature on system costs

3.3 Impact of different electric loads on system operating costs

Fig. 3(a) shows the variation of total operating cost of the system with change in electrical load for constant outdoor temperature. It can be seen that the total operating cost of the system tends to increase and then decrease as the electric load increases, and the cost of the heat source increases as the electric load increases. The effect of power load change on water temperature of heat network is shown in Fig. 3(b). With the increase of electric load, the temperature of heat network water increases and then decreases, resulting in the system operating cost increasing and then decreasing.

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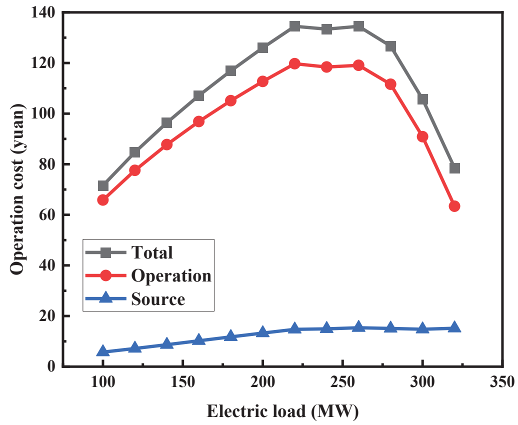

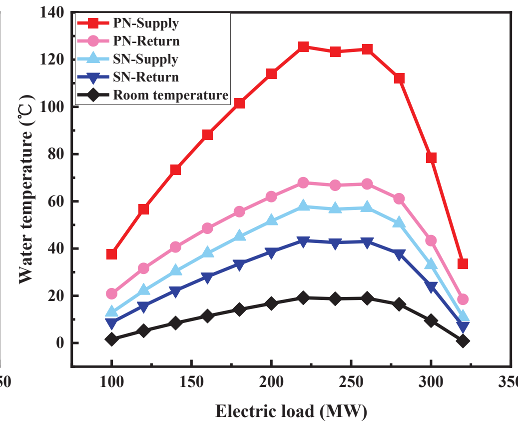

(a) Impacts on operating cost (b) Impacts on water temperature

Figure 3: Influence of different electric power on system costs

4 CONCLUSIONS

In this paper, the dynamic model of the system considering the heat storage of the DHS heat network is established, and the coal consumption of CHP unit is added to the system operating cost, and the change of the total operating cost of the system under different electric-heat loads is calculated. And the main conclusions are as follows:

- The total system operating cost decreases with increasing outdoor temperature for a given constant electrical load
- The total operating cost of the system tends to increase and then decrease as the electric load increases
- The total cost of the system is mainly affected by the temperature of the heat network water, and its trend is basically the same as that of the heat network water temperature.

NOMENCLATURE

Abbreviation

CHP	combined heat and power
DHS	district heating system
DR	demand response
THA	turbine heat acceptance

Symbol

B	standard coal consumption	(kg of standard coal/h)
C	system cost	(yuan¥)
c	unit cost	(kg of standard coal/h)
D	mass flow rate of steam	(t/h)
G	mass flow rate of water	(kg/s)
H	head	(mH_2O)
h	enthalpy	(kJ/kg)
K	thermal conductivity	(W/(m·℃))
L	length	(m)
N	power	(kW)
Q	thermal load	(kJ/h)
T	temperature	(℃)
W	electric power	(kW)
σ	enthalpy rise	(kJ/kg)
ρ	density	(kg/m^3)
η	efficiency	

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Subscript

A	All
b	boiler
C	carbon
c	condensate
e	electric
g	generator
gr	heating supply
grh	backwater of heating supply
h	heating
hs	heating system
i	stage i
i,e	absolute internal efficiency of the condensate generation portion
i,h	absolute internal efficiency of the heating part
loss	loss
m	machine
net	low standard
o	outdoor
oper	operation
p	pipe
pump	pump
source	source
tp,e	power generation of cogeneration
tp,h	heat of cogeneration
water	water
0	initial condition

REFERENCES

Chen, H. , Wang, Y. , An, L. , Xu, G. , Zhu, X. , & Liu, W. , et al. 2022. Performance evaluation of a novel design for the waste heat recovery of a cement plant incorporating a coal-fired power plant. *Energy, 246*.

Wang, H. , Hua, P. , Wu, X. , Zhang, R. , Granlund, K. , & Li, J. , et al. 2022. Heat-power decoupling and energy saving of the chp unit with heat pump based waste heat recovery system. *Energy*, 250.

Liu, M. , Wang, S. , Zhao, Y. , Tang, H. , & Yan, J. . 2019. Heat-power decoupling technologies for coal-fired chp plants: operation flexibility and thermodynamic performance. *Energy*, 188(Dec.1), 116074.1-116074.14.

Katulić S, Čehil M, Bogdan Ž. 2014. A novel method for finding the optimal heat storage tank capacity for a cogeneration power plant. *Applied Thermal Engineering*. 65(1-2):530-8.

Romanchenko, D. , Kensby, J. , Odenberger, M. , & Johnsson, F. . 2018. Thermal energy storage in district heating: centralised storage vs. storage in thermal inertia of buildings. *Energy Conversion & Management*, 162, 26-38.

Li, Y. , Wang, C. , Li, G. , Wang, J. , Zhao, D. , & Chen, C. . 2020. Improving operational flexibility of integrated energy system with uncertain renewable generations considering thermal inertia of buildings. *Energy Conversion & Management*, 207(Mar.), 112526.1-112526.15.

Korpela, T. , Kaivosoja, J. , & Majanne, Y. . 2017. Utilization of District Heating Networks to Provide Flexibility in CHP Production. *Energy Procedia*. 116:310-9.

Zheng, J. , Zhou, Z. , Zhao, J. , & Wang, J. . 2018. Effects of the operation regulation modes of district heating system on an integrated heat and power dispatch system for wind power integration. *Applied Energy*, 230, 1126-1139.

https://doi.org/10.52202/077185-0204

Sun P, Teng Y, Chen Z. 2021. Robust coordinated optimization for multi-energy systems based on multiple thermal inertia numerical simulation and uncertainty analysis. *Applied Energy*. 296.

Li, W., Li, T., Wang, H., Dong, J., Li, Y., Cui, D., Yang, J., Okoye, M. O., & Ge, W. 2019. Optimal dispatch model considering environmental cost based on combined heat and power with thermal energy storage and demand response. *Energies*, 12(5).

Shi, G., Yang, L., Zhang, H., Yang, X. 2020. Scheduling optimization model for multi-source district heating system. *Thermal Power Generation*, 49(3), 68-75. (in Chinese)

Li, H., Zhang, H., Wang, Y., Mi, L., Shi, K., You, S. 2023. Optimal Dispatching of District Heating Network Based on Dynamic Hydraulic-Thermal Coupling Model. *Journal of Tianjin University：Science and Technology*. 56(1), 27-36. (in Chinese)

Wang, J. , Huo, S. , Yan, R. , & Cui, Z. . 2022. Leveraging heat accumulation of district heating network to improve performances of integrated energy system under source-load uncertainties. *Energy*, 252.

Jiang, T. , Li, Z. , Jin, X. , Chen, H. , Li, X. , & Mu, Y. . 2018. Flexible operation of active distribution network using integrated smart buildings with heating, ventilation and air-conditioning systems. *Applied Energy*, 226(SEP.15), 181-196.

Zheng, J., Zhou, Z., Zhao, J., & Wang, J. 2018. Integrated heat and power dispatch truly utilizing thermal inertia of district heating network for wind power integration. *Applied Energy*, 211, 865–874.

Wang, L., Zhang, S., Fu, Y., Liu, M., Liu, J., Yan, J. 2024. Usable thermal energy stored in the district heating system for peak shaving: A dynamic simulation study. *Applied Thermal Engineering*, 239.

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