

Zhong, Wei et al.

Article

Investigation of optimized network splitting of large-scale urban centralized heating system operation

Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Zhong, Wei et al. (2020) : Investigation of optimized network splitting of large-scale urban centralized heating system operation, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, pp. 467-477, <https://doi.org/10.1016/j.egy.2020.02.012>

This Version is available at:

<https://hdl.handle.net/10419/244049>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by-nc-nd/4.0/>



Research paper

Investigation of optimized network splitting of large-scale urban centralized heating system operation

Wei Zhong^a, Jiaying Chen^a, Yi Zhou^a, Zhongbo Li^{a,b}, Zitao Yu^a, Xiaojie Lin^{a,*}^a College of Energy Engineering, Zhejiang University, Hangzhou, China^b Beijing District Heating Group, Beijing, China

ARTICLE INFO

Article history:

Received 26 November 2019

Received in revised form 17 February 2020

Accepted 19 February 2020

Available online xxxx

Keywords:

Urban centralized heating system

Operation scheme

Splitting optimization

ABSTRACT

Operation optimization is a critical issue in the management of the multi-source large-scale urban centralized heating system (UCHS). A major challenge is to deal with the complex topological structure of its heating network. We investigate the operation enhancement of UCHS from the view of network splitting. We carry out the network splitting analysis of UCHS by establishing its heating network model and corresponding simulation platform based on graph theory. We validate the model against experimental data in a city located in northern China, and further use the model to show the effectiveness of network splitting by calculating its energy consumption indices under different splitting schemes. Simulation results show that the optimal network splitting scheme could improve the load distribution among the heating sources and reduce the operation cost. We apply the scheme during the 2018–2019 heating season and compare the results with the previous season operated by its existing scheme. The optimized scheme reduces heat supply requirements for heating sources and improves the load distribution among heating sources. With the weather condition change considered, seasonal accumulated area specific daily heat supply is reduced by 3.9%. Overall, seasonal natural gas consumption is reduced by 16.8%.

© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

1.1. Background

So far, most of China's northern cities have built urban centralized heating systems (UCHS) (Zhang et al., 2015; Wang et al., 2008). According to Liu's research, the demand of urban residents on heating water keeps growing and more buildings adopt the centralized heating system to supply 24 h hot water in north China (Liu, 2011). These systems use water as the working medium to deliver heat from the heating sources to the heating substations (which further provides hot water to end-users such as residential communities) (Feng et al., 2014), as shown in Fig. 1. The heating system could be divided into a primary loop and a secondary loop. The primary loop connects the distributed heating sources and heating substations. The loops are connected through plate heat exchangers located in the heating substations, where the secondary loop water is heat up by the primary loop. In the secondary loop, heating substations deliver heat to the end-users through plate heat exchangers and the corresponding secondary loops, as shown in Fig. 1. The working medium in

both primary and secondary loop is water. During the operation, UCHS controls the water supply temperature in the secondary loop by adjusting the regulating valve in the primary water loop (Lu et al., 2001). Due to the difficulties of maintaining the thermal and hydraulic balance in the secondary loop, a fixed water supply temperature in the secondary loop is desirable. However, during the heating season, the weather conditions could vary. Usually in the beginning and end of the period outside temperature can be almost the same, while it can be much lower in the middle of the period, during coldest months.

The conventional operation control approach is to break up the operation problems into a series of preset scenarios. The heating system is managed in such a manner that the heating sources have a fixed set of supply temperatures and water flow rates based on these scenarios. The heating system is adjusted merely based on "temperature control" approach to avoid hydraulic imbalance (Jiang, 2006; Lei and Zou, 2008). The heating substations are distributed in the covered heating area and are controlled by local feedback actuators such as pumps and valves. This method is robust and straightforward per its nature. However, such an approach does not take the coupling effect between the thermal and hydraulic balance into consideration. It does not consider the coordination of all components of the heating system, such as the heating sources and end-user demands. During the heating season, UCHS tends to cause overheating. For example, as found in

* Corresponding author.

E-mail address: xiaojie.lin@zju.edu.cn (X. Lin).

Nomenclature

Symbols

D	relationship matrix between the nodes and the section of the heating system
C	relationship matrix between the loops and the section of the heating system.
Q_s	flow rate of the network node
Q_{es}	flow rate of the network section
P_s	pressure of the network node
ΔP_{es}	pressure drop of the network section
ΔP_{esj}	pressure drop of the water supply jth section
λ_{sj}	resistance coefficient of the water supply jth section
ξ_{sj}	local resistance factor of the water supply jth section
d_{sj}	inner diameter of the water supply jth section
q_{esj}	mass flow of the water supply jth section
ρ	density of the working medium
m	amount of water supply node in the heating system
n	amount of water supply section in the heating system
Δp^{sub}	pressure drop of the heating substation
P_s	water supply pressure
Δp_{esj}	pressure drop of the water supply jth section
P_{ri}	pressure of water return pipeline

Acronyms

CHP	combined heating and power
DCS	distributed control system
DSM	demand side management
SCADA	supervisory control and data acquisition
UCHS	urban centralized heating system

Subscript

i	serial number of node connection
j	serial number of section connection

that this heating source is in a low-load operating condition for most of the heating season (part-load operation ratio less than 50% or even lower), leading to a low heating efficiency (Liu, 2016).

However, UCHS keeps expanding in China during the last decade in terms of heating area. According to published statistics (Department of Planning, Financing and Foreign Affairs Ministry of Housing and Urban-Rural Development, 2018), China's UCHS heating area has grown rapidly in the past decade, with an average annual growth rate of 13%. By 2016, the total heating area of UCHS in northern China had reached about 13 billion square meters (NDRC, 2017). Currently, the trend is to have a coal-fired boiler. Meanwhile, more diverse heating sources such as industrial waste heat recovery, natural gas boilers, biomass boilers, and solar energy are connected to UCHS. The increase of heating area and heating source diversity together constitute a new operation challenge that could not be addressed by the conventional approach. Therefore, the analysis and optimization of the operation scheme of UCHS nowadays become a critical issue.

In the existing studies, some researchers focus on different aspects such as heating demand-side management (DSM), source side load dispatching optimization, and energy system transport analysis to improve the ability of operation. As Zia et al. pointed out, the goal of these efforts is to find out an optimal operation technology to ensure economical, sustainable, and reliable operation of the heating system subject to operational constraints (Zia et al., 2018). In heating DSM research, researchers focus on heating efficiency and users' demand. For example, Cai et al. proposed a realistic DSM mechanism to improve system efficiency and manage congestion issues from the view of building modeling (Cai et al., 2018). An example of the application of heating DSM technologies could also be found in the "4th Generation District Heating" systems developed in Nordic countries, where operators carry out dispatch schemes in a "smart" way (Pakere et al., 2018; Gao et al., 2017). As for load dispatching optimization in the heating sources and storage, Liu et al. proposed to change the current operation mode where power plants manage CHP and heating companies manage UCHS to a new one (Liu, 2015). The new mode allows power plants to carry out peak-shaving and manage primary networks, while heating companies deal with secondary networks and provide heating to end-users. Köfingler et al. proposed to combine the utilization of storage device and heating source in a sequential approach that effectively uses thermal storage as a short-term buffer used in both summer and winter (Köfingler et al., 2018). In the meanwhile, UCHS is closely related to building energy consumption. Therefore, researchers from the field of building energy systems also inspected UCHS operation from the view of transport capability, where it is investigated from a general perspective of energy systems. For instance, Postnikov et al. from the perspective of fault recovery rate, proposed a method to determine the optimal reliability-related parameters of heating system components to improve heating reliability (Postnikov et al., 2017). Wang et al. proposed optimization strategies for the planning of a multi-energy system and formulated it as a mixed-integer linear programming problem based on graph theory (Wang et al., 2018). A good summary of these studies could be found in IEA's "Energy in Buildings and Communities Programme Annex 67" (Jensen, 2016).

However, the discussion of UCHS operation from the view of network management is less found when compared to DSM, source side load dispatching optimization, and energy system transport analysis studies. From the view of network management, the operation of UCHS is to find an "ideal path" for the heating sources to deliver hot water to the substations and further the end-users with the constraints of pressure, mass flow rate distribution and pump/valve operation limits. In this area,

the report from Tsinghua University, the average overheating rate in China northern cities ranges from 10% to 20% (Tsinghua University, 2019). Once the system is affected by extreme weather conditions (such as snowstorms) and the operation condition falls out of the preset scenarios, this approach could fail to set up the new thermal and hydraulic balance of the heating system.

Another drawback of such an approach is the lack of operational flexibility or optimization capability since the scenarios are usually set up long before the heating season. Such an operation approach has been put into place since the 1970s, even though UCHS has become increasingly complex. The conventional operation dispatch approach has come up with a series of challenges since the 1990s. For example, Hu et al. found that such an approach is not designed to cooperate with cogeneration units such as combined heat and power (CHP) units, resulting in excessively high primary energy consumption (Hu et al., 2010). Liu found out

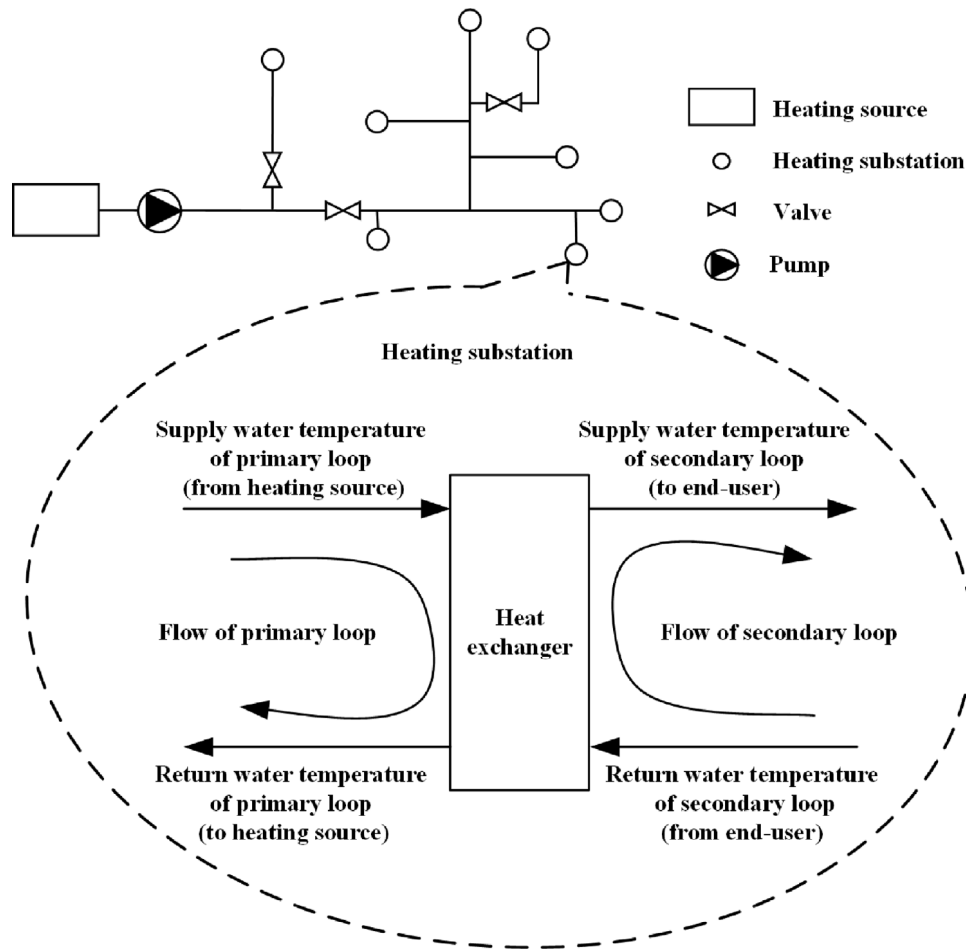


Fig. 1. Sketch map of the primary loop and the secondary loop.

similar to the grid study, some researchers have derived and investigated the ideas of flexibility and reliability. Zhong et al. quantified UCHS's capability of delivering heat to substations under different operating scenarios from the perspective of flexibility (Zhong et al., 2019). Shan et al. identified the laws of the reliability and availability for the district heating network, focusing on the failure-safe operation (Shan et al., 2017).

A typical UCHS network management operation is network splitting, where the heating network is split and divided into regions through disassembling/disengagement valves and pumps. The following effects can be achieved through network splitting:

- It can change the water pressure distribution of the whole network and helps to reach the hydraulic rebalance;
- The operation scheme can be changed and the appropriate scheme can save energy consumption of the entire heating system;
- The faulty components in the heat network can be blocked by network splitting to improve the reliability of the whole network;

For example, Jiang et al. divided the heating network into several regions through valve operation to adjust the hydraulic balance of each region (Jiang et al., 2018). Fan et al. and Fang et al. split heating sources in the network according to different operating conditions, thereby reducing energy consumption and heating costs (Fan et al., 2015; Fang et al., 2016). Qin and Jiang proposed to install regulating valves at proper positions on the main support line or the looped line and adjust the outputs of the heat sources to enhance the operation scheme (Qin and Jiang, 1999,

2001). Wang split the network and isolated the fault components to minimize the impact of component failure on the operation to improve the reliability of the heat network (Wang, 2010). It should be noted that network splitting of large-scale UCHS has been implied but rarely investigated by researchers from the area of district heating systems, where the operation studies start from modeling of such systems. Since modeling is also part of basis of this study, it is worthwhile including modeling studies of district heating systems. Allegrini et al. reviewed the modeling approaches and tools addressing district-level energy systems and assessed their competences (Allegrini et al., 2015). Gabrielaitiene et al. developed a complete model for a district heating system in Denmark covering a total heating pipe length of five kilometers via node method and compared the results against commercial tool TERMIS (Gabrielaitiene et al., 2007). Tol and Svendsen developed an optimization method for the design of a low-energy district heating system in Denmark to reduce heat loss, which is highly useful in pipe dimensioning (Tol and Svendsen, 2012). Vigrants and Blumberga developed a district heating system model to search for optimal thermal-hydraulic designs (Vigrants and Blumberga, 2011). Nikula et al. proposed a dynamic process simulator and the corresponding event-based controllers in order to demonstrate the effectiveness of the model-based dispatch solutions in a district heating system (Nikula et al., 2014). Similarly, Guelpa and Sciacovelli presented a thermal fluid dynamic model and applied a model-based approach to analyze transient operations in terms of temperature distribution during dispatch operation (Guelpa et al., 2019).

Overall, from the perspective of long-term development trend, UCHS will keep its diversity (either in terms of its heating sources

composition or end-user types) and its scale will grow along with urbanization. However, in existing large-scale UCHS, splitting operation is mainly decided by human experience, and less effort is paid to its optimization or its coordination with source load distribution. Moreover, as UCHS grows in scale and has a variety of heating sources (including renewable energy-based heating sources), such a manual approach is no longer sufficient. In large-scale UCHS with diverse heating sources, source load distribution and network splitting the heating system need to be carried out together via the concept of optimization while considering operation economy of heating sources and the change of heating load in the network. However, such studies are still limited in the open literature, and little effort has been paid to the verification of the effectiveness of this approach in a real city-scale UCHS.

1.2. Motivation

Based on the literature review, this paper focuses on the network splitting optimization of large-scale UCHS with multiple heating sources and the verification of the effectiveness of such an approach. We establish a UCHS model, validate the model, and investigate splitting scheme optimization. Further, this study uses a UCHS in Beijing as an exemplary site to carry out the verification of splitting schemes optimization in the field through the comparison of two heating season data. The paper is concluded with our findings and future work.

2. Modeling and network splitting scheme optimization

2.1. UCHS modeling

We use graph theory to divide the pipe network into multiple loops and use Kirchhoff's law to establish the relationship between the mass flow rate and pressure of each loop through the conservation equations in the nodes and the corresponding sections. The goal is to create the conservation equation sets of supply and return water pipes.

In the heating network, pumps, valves, and substations can be regarded as nodes; pipe segments can be regarded as sections.

The pipe network with m nodes and n sections can be expressed by a $(m - 1) \times n$ order incidence matrix $D = (d_{ij})_{m \times n}$.

$$d_{ij} = \begin{cases} 1 & \text{When } n_j \text{ is connected to } m_i \text{ and the direction is away from } m_i \\ -1 & \text{When } n_j \text{ is connected to } m_i \text{ and the direction is toward } m_i \\ 0 & \text{When } n_j \text{ and } m_i \text{ are not connected} \end{cases} \quad (1)$$

where D is the relationship matrix between the nodes and the section of the heating system.

The relationship between each section and the basic loop l is expressed by the $(n - m + 1) \times n$ order loop matrix $C = (c_{jk})_{l \times n}$.

$$c_{jk} = \begin{cases} 1 & n_j \in l_k \text{ and in the same direction} \\ -1 & n_j \notin l_k \text{ but in different directions} \\ 0 & n_j \notin l_k \end{cases} \quad (2)$$

where C is the relationship matrix between the loops and the section of the heating system.

After that, we simultaneously solve the conservation equation sets by feeding real-time working conditions such as overall flow rate and temperature leaving the sources. Since UCHS has both supply and return water loop, we consider establishing the equations for water supply and return pipelines respectively. The governing equations of supply water loop are shown in the following equations.

In a node the following mass conservation law can be written: the sum of input flow rates is equal to the sum of output flow rates.

$$D \cdot Q_{es} + Q_s = 0 \quad (3)$$

$$Q_s = [q_{s0}, q_{s1}, \dots, q_{si}, \dots, q_{sm}]^T, i \in [1, m] \quad (4)$$

$$Q_{es} = [q_{es0}, q_{es1}, \dots, q_{esj}, \dots, q_{esn}]^T, j \in [1, n] \quad (5)$$

where Q_s is the flow rate of the network nodes, kg/s; Q_{es} is the flow rate of the network sections, kg/s.

For each loop, the algebraic sum of the pressure losses is zero.

$$C \cdot P_s = 0 \quad (6)$$

$$P_s = [P_{s0}, P_{s1}, \dots, P_{si}, \dots, P_{sm}], i \in [1, m] \quad (7)$$

where P_s is the pressure of the network nodes, Pa.

The pressure drop of the pipe segment can be expressed as

$$\Delta P_{es} = [\Delta p_{es0}, \Delta p_{es1}, \dots, \Delta p_{esj}, \dots, \Delta p_{esn}], j \in [1, n] \quad (8)$$

$$\Delta P_{esj} = \frac{1}{2} (\lambda_{sj} + \xi_{sj}) \frac{q_{esj}^2}{\rho \pi^2 d_{sj}^4} \quad (9)$$

where ΔP_{es} is the pressure drop the network sections, Pa; ΔP_{esj} is the pressure drop of the water during the j th section, Pa; λ_{sj} is the resistance coefficient of the j th section; ξ_{sj} is of the local resistance factor of the j th section; d_{sj} is the inner diameter of the j th section, m; q_{esj} is the mass flow of the j th section, kg/s; ρ is the density of the working medium (water), kg/m³.

The model of the water return line is the same as the supply loop equations shown above. With equation sets in both loops formulated, we could use the heating source supply and return water pressure, measured heating substation flow rates and the pipe network structure as input conditions to calculate the water supply and return water pressure in each heating substation. The inlet and outlet pressure of each substation, together with the measurement flow rates, make up the hydraulic balance state of the system. Once the pressure distribution and flow distribution are achieved, we could carry out the thermal analysis of the topological heating system in a similar matrix manner. The detailed approach and its solving process could be found in our previous work, where we realized real-time modeling calculation and operation optimization for the steam network in a petroleum industry park (Zhong et al., 2019, 2015).

2.2. Model-based network splitting optimization

For multi-source UCHS, we carry out network splitting operation by adjusting the combination of valves and pumps based on the model developed in the previous section. The network splitting scheme coordinates the heat supply between multiple heating sources, ensures its operation economy, and provides emergent heat supply capability if necessary. As mentioned above, the challenge of network splitting is its complexity due to the ever-increasing system scale. Assume there are N valves participating in the network splitting; there are 2^N theoretical network splitting schemes should the valves only stay in either full-open or full-closed state. Although the amount of splitting schemes in the real UCHS is less due to the operating constraints, it still takes couple of months to manually generate all the possible schemes. Moreover, once the network splitting scheme is changed during the heating season, the hydraulic resistance characteristics of the entire UCHS changes. The change of its hydraulic resistance characteristics could cause a thermal and hydraulic delay as long as a couple of hours. Therefore, in modern large-scale UCHS, it is hardly possible to achieve a new operation scheme to catch up with the new heating demand simply by

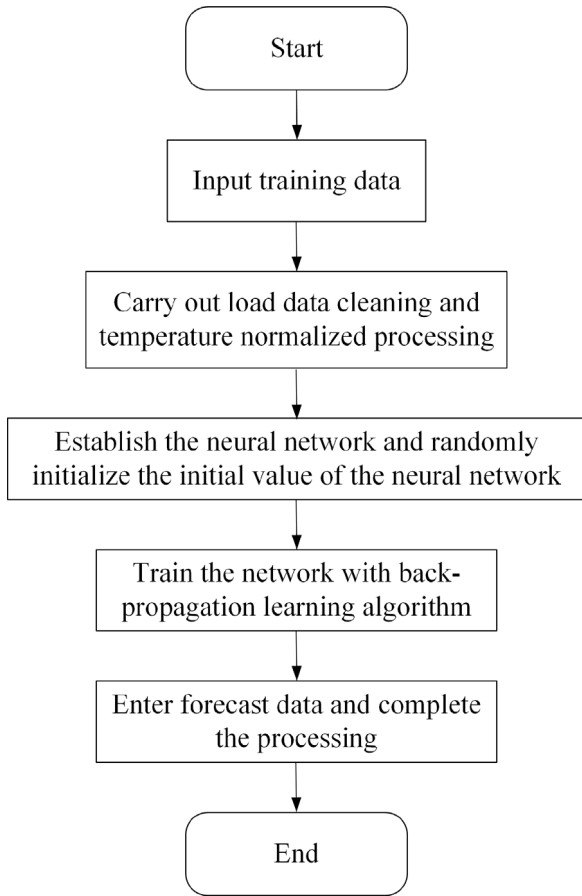


Fig. 2. Flow chart of load forecasting based on back-propagation neural network.

human experience. This is where the created UCHS model cuts in.

In this paper, we use the load prediction model to find out the desired mass flow rates in each substation. We built a historical database by collecting the data achieved from supervisory control and data acquisition (SCADA) systems installed in the heating network and the local ambient conditions in the heating substations. The parameters included in the database are water supply and return temperature in both primary and secondary loops, the water flow rate in the primary loop, frequency of secondary loop pump, and ambient temperature. We use a machine learning algorithm (back-propagation neural network) to forecast the upcoming flow rates of heating substations, which is shown in Fig. 2. By combing the data from the distributed control system (DCS) (mainly operation data of the heating sources), we could generate the boundary conditions (substation-wise mass flow rates) for the upcoming operation cycle.

By feeding the boundary condition into the UCHS model, we could get the corresponding system state (temperature, mass flow rate and pressure distribution across the entire network) through the modeling approach mentioned above and generate its corresponding operation schemes. For example, a critical part of the system state is the pressure drop across the substation, which directly affects the operational decisions. To calculate the pressure drop across the substation, we need to calculate the water pressure in both supply and return loops. For the supply loop, we calculate the pressure using the following equations.

With the predicted substation-wise flow rates, we could calculate the flow rate of each flow section in Eq. (10).

$$Q_{es} = -[D]^{-1} \cdot Q_s \quad (10)$$

Then, the water supply pressure P_s can be calculated from the flow of the section in Eqs. (11) and (12).

$$P_s = -[D]^{-1} \cdot \Delta P_{es} = -[D]^{-1} \cdot [\Delta p_{es0}, \Delta p_{es1}, \dots, \Delta p_{esj}, \dots, \Delta p_{esn}] \quad (11)$$

$$\Delta p_{esj} = \frac{1}{2} (\lambda_{sj} + \xi_{sj}) \frac{q_{es}^2}{\rho \pi^2 d_{sj}^4} \quad (12)$$

where λ_{sj} is the resistance coefficient of the water supply jth section; ξ_{sj} is of the local resistance factor of the water supply jth section.

The calculation process of the water return model is similar to the supply loop. With pressure in both loops calculated, the pressure drop to be provided in the substation is:

$$\Delta P_i = P_{si} - P_{ri} \quad (13)$$

where P_{ri} is the pressure of water return, Pa.

The pressure drop of all heating substations then is

$$\Delta P_{sub} = [\Delta P_1, \Delta P_2, \dots, \Delta P_i] \quad (14)$$

Once the pressure drop is obtained, we could find out the desired valve opening by referring to the valve discharge characteristic curve, which describes the relationship between its opening, mass flow rate and pressure drop. The opening of these valves could be summarized into a splitting scheme.

During the calculation, we could achieve more than one operation scheme. Therefore, it is necessary to compare the schemes by further referring to the UCHS model. In this paper, we will use “backward flow” (which means the supply pressure of substation is less than or close to the return water) as the criterion. We will choose the scheme with the best performance in terms of reducing “backward flow”. The aforementioned entire working flow of calculating the desired splitting scheme is shown in Fig. 3.

2.3. Operation platform based on optimal network splitting

Based on the modeling of UCHS and the selection of the network splitting scheme, we built a corresponding operation platform. As shown in Fig. 4, we use the DCS of the heating sources, the SCADA system of the heating system, and model prediction for substation-wise mass flow rates to obtain real-time input conditions. Then we input these parameters into the heating system model to obtain the temperature, pressure, flow rate distributions, and pump/valve operation data of the heating system. All the information will be sent to the network splitting scheme calculation part, and we could achieve the desired scheme (reducing operation cost, enhancing inter-source load distribution). The desired scheme is sent back to the field. With the operation platform, it is possible to achieve a fast simulation and makes it possible to integrate with the existing working flow in the real UCHS and carry out the field study.

3. Case demo

3.1. Target heating system

This paper carried out the application of network splitting optimization technology in a multi-source UCHS in Beijing. The location of heating sources and the topological structure of the heating system are shown in Fig. 5. At present, there are three centralized heating sources in the heating system. Among them,

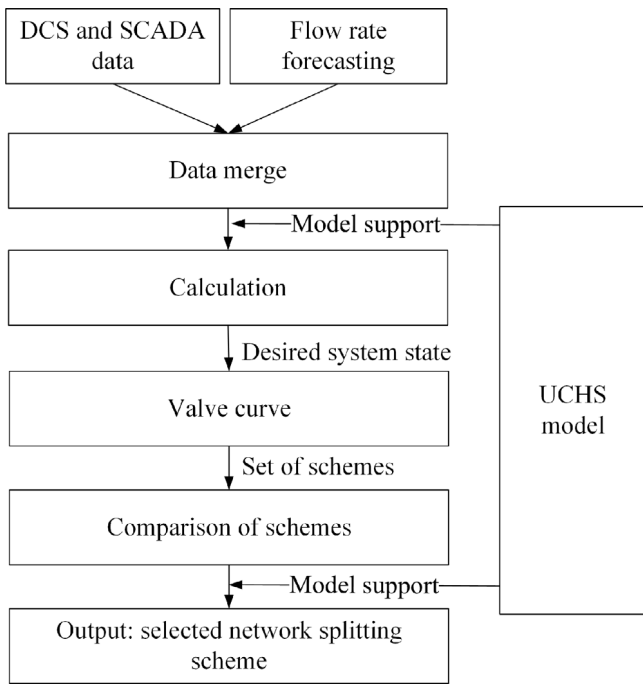


Fig. 3. Flowchart of network splitting optimization.

power plant #1 and #2 are the first-stage heating sources, which are designed to provide heat load of 500 MW with coal-fired CHP units; #3 and #4 power plants are the second-stage heating sources, which are designed to provide heat load of 620 MW with the same coal-fired CHP units. Another heating source is made up of four gas-fired hot water boilers with a capacity of 116 MW, which are connected to the main heating system in the heating season. There are 230 heating substations in the network. The overall heating area is divided into two main lines, line A (blue part of the picture) and line B (orange part of the picture). The heating area covered by line A is 8.5 million m², which is mainly supplied by power plant #1 and #2. The heating area covered by line B is seven million m², which is mainly supplied by power plant #3 and #4.

There is a surplus load of #1 and #2 power plant because the maximum output is 500 MW and the output of the initial and

Table 1
Inputs of simulation.

Input conditions	Value
Water supply pressure of line A (MPa)	0.75
Water return pressure of line A (MPa)	0.30
Water supply pressure of line B (MPa)	1.10
Water return pressure of line B (MPa)	0.30
Water supply temperature of line A (°C)	105
Water supply temperature of line B (°C)	95
Water supply temperature of boilers (°C)	95

final heating season is about 300 MW~400 MW. In heating season 2017–2018, three boilers were operated, and they consumed 70,695,036 m³ of natural gas (data as of March 20, 2018). During the heating season from 2018 to 2019, the goal of this paper is to use the developed model and selection of desired network splitting schemes to maximize the output of power plant #1 and #2, reduce the use of boilers, and reduce the overall costs.

3.2. Model validation

This paper first uses the heating season operation data to validate the accuracy of the developed model. The input conditions of the model shown in Table 1 are collected in the 2016–2017 heating season.

To verify the accuracy of the developed UCHS model, the measured and calculated water supply and return pressure data of 184 heating substations (equipped with corresponding sensors) were analyzed. The results of the data comparison are shown in Figs. 6 and 7.

Further, the histogram of the error distribution substations is shown in Fig. 8.

In Fig. 8, more than 95% of the substations have a relative error of water supply/return pressure less than 10%, and more than 87% of the substations have a relative error of water supply/return pressure less than 5%. The comparison shows that the simulation model of the UCHS system has enough accuracy to support further network splitting scheme calculation.

We used the operation platform to generate the best network splitting scheme for the target UCHS in terms of operation cost and the reduction of boiler operation period in real UCHS and applied the calculated scheme to the target UCHS in the field during the heating season 2018–2019. We compared the seasonal

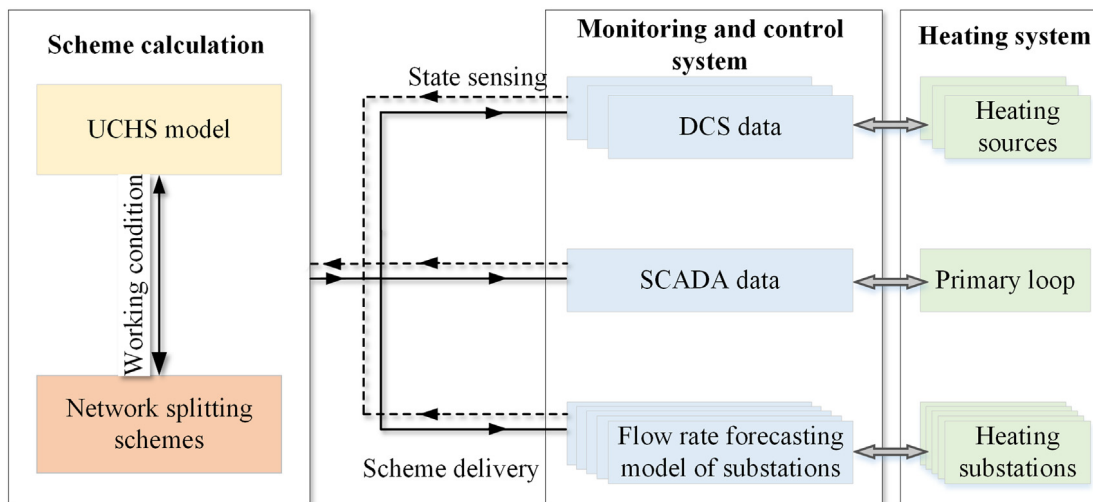


Fig. 4. Operation platform based on optimal network splitting.



Fig. 5. Topological structure of target network. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

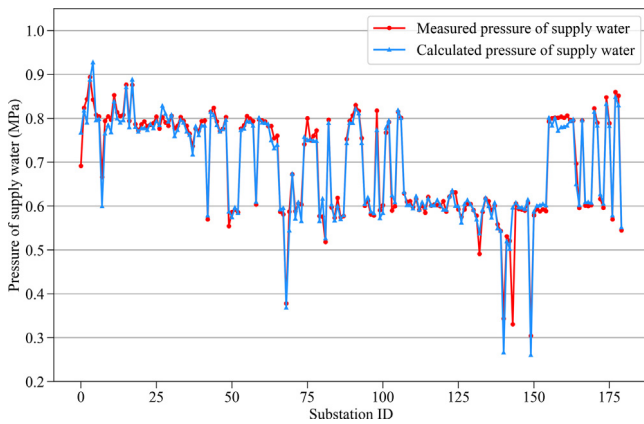


Fig. 6. Comparison of measured and calculated data of water supply pressure.

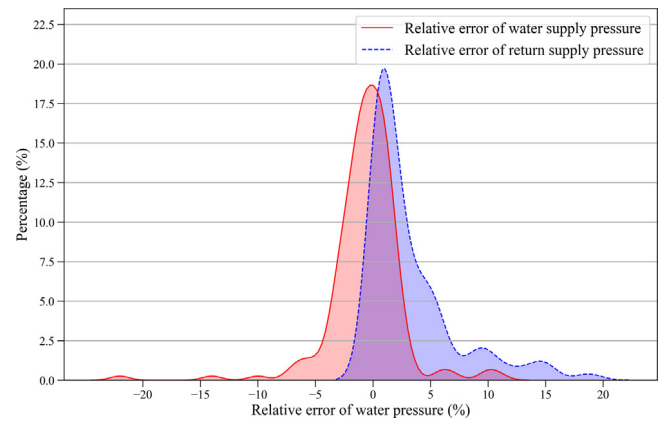


Fig. 8. Statistical results of the comparison between measured and calculated data of water supply and return pressure.

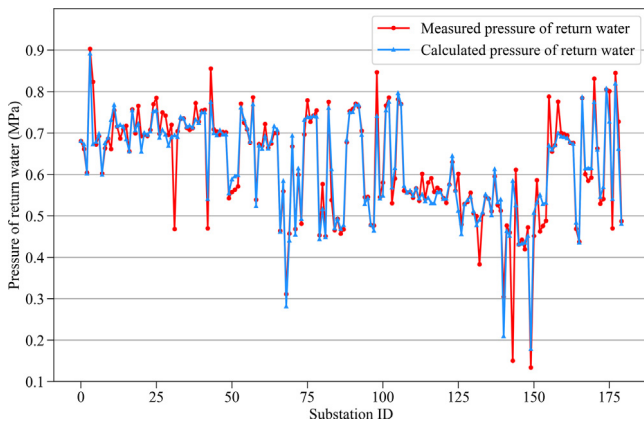


Fig. 7. Comparison of measured and calculated data of water return pressure.

performance with the previous heating season (2017–2018) focusing on two key energy/cost indices: natural gas consumption in the heating sources and area specific daily heat supply in the

heating substations. The first one reflects the reduction of energy consumption and operation cost, while the second reflects the enhancement of network wise heat transport.

4. Results and discussions

4.1. New network splitting scheme

To better reflect the actual operating conditions and generate practical schemes, we focus on the network splitting schemes in three key regions in the target UCHS, as shown in Fig. 9. These regions either belong to the remote area of each line or the joint area of lines where it is historically difficult to provide heating to end-users without proper splitting. In Fig. 9, nodes marked by arrows are the position of the valves/pumps participating in the network splitting. The final calculated network splitting schemes with a focus of seasonal lowest operation costs are shown in Table 2. In Table 2, the splitting area belonging to line A is denoted as “A” and the splitting area belonging to line B or hot water boiler is denoted as “B”.

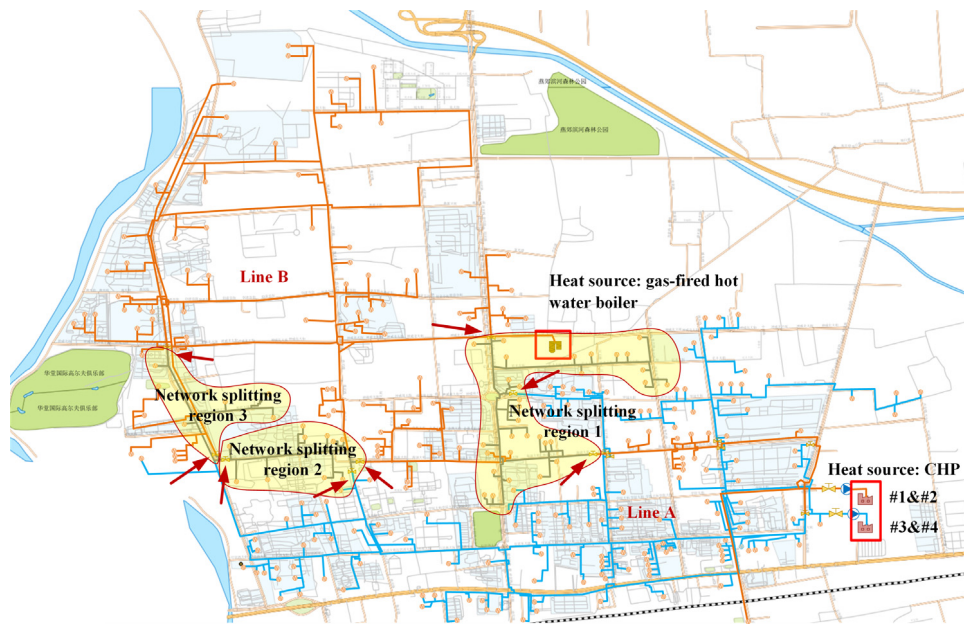


Fig. 9. Different network splitting regions.

Table 2
Heating system operation schemes.

Scheme	Splitting region 1	Splitting region 2	Splitting region 3
Scheme 1	A	A	A
Scheme 2	A	B	A
Scheme 3	A	B	B
Scheme 4	B	A	A
Scheme 5	B	B	A
Scheme 6	B	B	B
Scheme 7	A	A and B each half	A
Scheme 8	B	A and B each half	A

Table 3
Simulation results under different operation schemes.

Scheme	“Backward flow”	Number of “backward flow” substation	Minimal available water pressure drop (MPa)
#1	No	0	0.06
#2	No	0	0.21
#3	No	0	0.13
#4	Yes	20	–
#5	No	0	0.08
#6	Yes	21	–
#7	Yes	1	–
#8	Yes	1	–

Although all the schemes are generated by the platform based on the same traverse process, it is necessary to take a further look at the scheme by a dry-run simulation where a typical heating demand of 45 W/m^2 (selected based on historical data) is assumed in the end-user side. The comparison is shown in Table 3. During the operation of real UCHS, when there is a possibility of “backward flow”, the scheme is unlikely to meet the heating demand of all substations in the current working condition and should be discarded. There is no “backward flow” in scheme #2, #3, #5 and #6 while scheme #2 has the greatest available water pressure drop, we chose scheme #2 for the field test.

4.2. Heat supply analysis

After applying scheme #2 to the real UCHS in heating season 2018–2019, we collected the performance data and compared it with that of season 2017–2018. The comparison of the area specific heat supplied by UCHS is shown in Fig. 10. The average outdoor temperature of 2018–2019 is slightly higher, especially in the middle and end of the heating season. However, as can be seen from Fig. 11, when the outdoor temperature is close, the heat supply of 2018–2019 is lower, which indicates the improvement of heat transport and distribution in the entire network. The reason is that the conventional splitting scheme is designed to meet the overall seasonal heating load, not the beginning and end of the heating season. During that period, the conventional heating splitting scheme causes overheating. In other words, the new scheme could reduce the heat supply capability required by the entire UCHS when compared with the previous scheme. To eliminate the impact of outdoor temperature, we collate the area specific daily heat supply at the same ambient temperature in both seasons, as shown in Fig. 11.

As can be seen from Fig. 11, the area specific daily heat supply of UCHS is significantly reduced in the temperature range higher than $2 \text{ }^\circ\text{C}$, (that is, a relatively high-temperature period in the beginning and end of winter). If the splitting scheme is updated based on a scrolling basis as in this demo case, we find that the new scheme can reduce the seasonal accumulated area specific daily heat supply by 3.9% on average.

4.3. Load distribution in heating sources

As mentioned above, another goal of the new scheme is to improve the load distribution of heating sources by reducing the operation cost and reducing the operation time of natural gas boilers. With the new splitting scheme, the change of the number of boilers in operation is shown in Fig. 11.

In Fig. 12, it could be found that the average amount of boilers in operation drops to one when the ambient temperature is higher than $0 \text{ }^\circ\text{C}$. Moreover, the amount of boilers in operation during the beginning of the heating season drops to one and only reaches four when area specific daily average heat supply

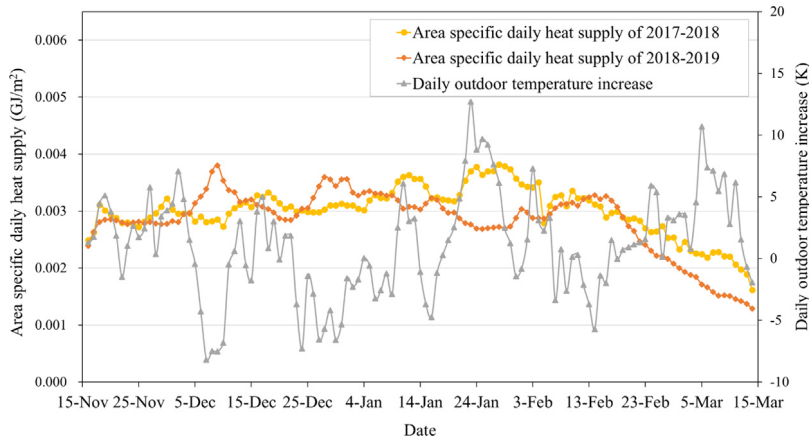


Fig. 10. Seasonal comparison of area specific daily heat supply.

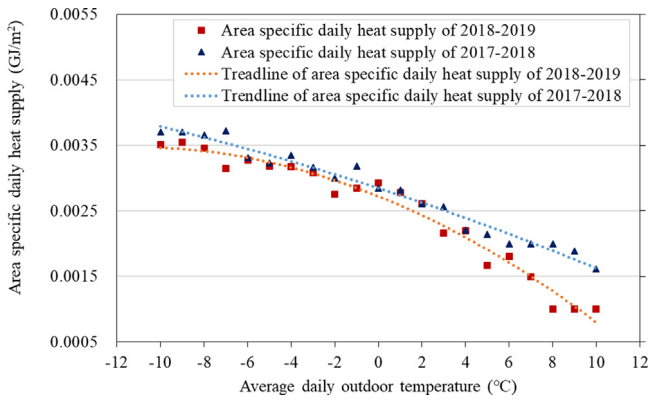


Fig. 11. Area specific daily heat supply with outdoor temperature.

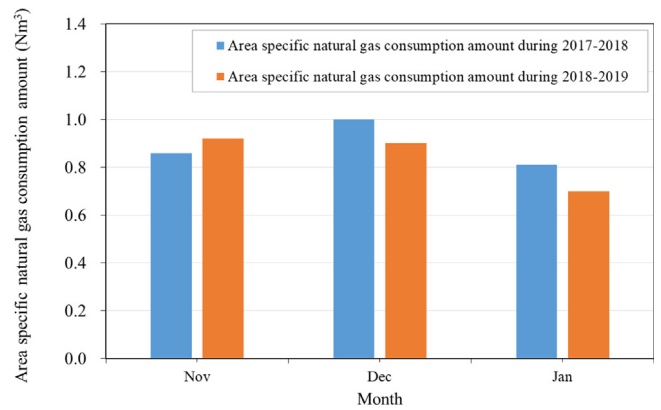


Fig. 13. Natural gas consumption comparison during two heating seasons.

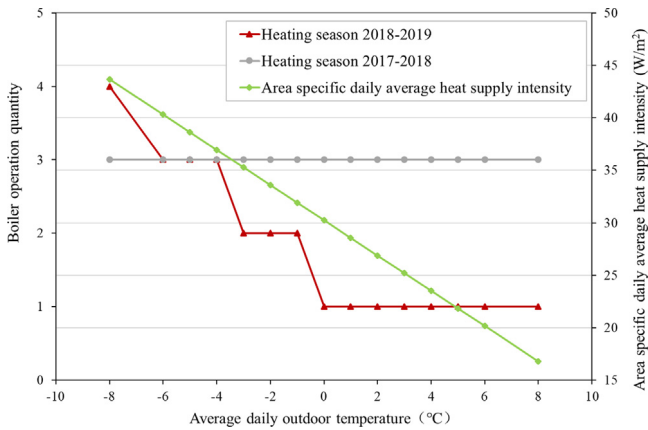


Fig. 12. Number of boilers in operation at different outdoor temperatures.

intensity is close to 45 W/m^2 , which is close to the typical heat supply required during most time of the heating season. In other words, these boilers now act as peak boilers, which is the initial design but not realized in the existing splitting schemes. Such operation helps to make full use of the CHP. Accordingly, the area specific natural gas consumption is reduced. As a result, comparing with the data collected from 2017 to 2018, seasonal natural gas consumption is reduced by 16.8% from 69.9 million m^3 to 58.1 million m^3 . The corresponding cost savings through the introduction of the new scheme is \$4.1 million with an average

natural gas price of $\$0.34/\text{m}^3$. With the weather condition change considered, the total heating cost drops by $\$0.2$ per heating area.

Since November and March are the beginning and end of the heating season, not all the data collected during these two months could be categorized as heating season data. To further show the natural gas consumption reduction, we take three consecutive months (December, January, and February) to make the comparison. The comparison of natural gas consumption during that period is shown in Fig. 13 and Table 4.

Fig. 13 shows the area specific natural gas consumption comparison between the two seasons. During the three consecutive months, the area specific natural gas consumption is reduced. The reason for the increase of natural gas consumption in December is that the December monthly temperature in season 2018–2019 is lower by 2 K when compared to that of the previous season. As can be seen from Fig. 12, in the new splitting scheme, the ambient temperature close to $-4 \text{ }^\circ\text{C}$ still requires up to three boilers in operation, which is same as the previous operation season. Therefore, the new network splitting scheme is not effective, and the heat supply is even higher due to a much lower ambient temperature. However, for January and February in season 2018–2019, the number of boilers in operation could be reduced by more than one once the ambient temperature stays in the range from $-2 \text{ }^\circ\text{C}$ to $0 \text{ }^\circ\text{C}$, leading to much lower natural gas consumption. For example, the monthly average February temperature in season 2018–2019 is slightly higher by 0.1 K while the natural gas consumption is reduced by 13.2%, as shown in Table 4. Overall, comparing with the data from 2017 to 2018, the area specific natural gas consumption is reduced by 4.9% on average, with a

Table 4
Area specific natural gas consumption reduction.

Month	Heating season 2017–2018		Heating season 2018–2019		Area specific natural gas consumption reduction (%)
	Average daily outdoor temperature (°C)	Area specific natural gas consumption amount (Nm ³)	Average daily outdoor temperature (°C)	Area specific natural gas consumption amount (Nm ³)	
Dec	−1.8	0.86	−3.6	0.92	−7.2
Jan	−3.0	1.00	−2.0	0.90	10.0
Feb	−1.6	0.81	−1.5	0.70	13.2
Average	−2.7	0.89	−1.6	0.84	4.9

maximal reduction of 13.2%. It shows that the new scheme could reduce gas consumption by improving the load distribution of heating sources.

5. Conclusions

As the scale of UCHS grows and its heating sources diversify, the operation of such a system has become challenging. One aspect of operation study of UCHS is to thermally and hydraulically split the system into a series of heating regions to achieve a better operation economy in the sense of operation. However, the network splitting of UCHS is relatively less discussed when compared with the modeling and design optimization studies of district heating systems. We established a UCHS system model and used a real UCHS in Beijing to validate the model. Based on the validated model, we investigated its optimized network splitting scheme aiming at reducing operation cost and improving network wise heat transport. After selecting the optimized scheme, we examined its effectiveness in the target UCHS through the seasonal test (2018–2019). We compared the performance data under the optimized scheme with that of the previous season (2017–2018), which was operated based on an existing scheme. From the seasonal comparison, we find that the new scheme can reduce the area specific daily heat supply by 3.9% on average under the same outdoor temperature, which indicates it reduces overheating and improves heat transport and distribution. In the three months with the highest heating intensity, compared with the data from 2017 to 2018, the area specific natural gas consumption is reduced by 4.9% on average, with a maximal reduction of 13.2%. Moreover, the optimized operation scheme helps to make full use of the CHP and returns the role of natural gas boilers to peak boilers. Under the new scheme, the number of boilers in operation can be selectively invested to adapt to the ambient temperatures. By reducing the amount and time of boilers in operation, it reduces the natural gas consumption by up to 16.8%, which is a cost-saving of \$4.1 million.

6. Future work

One limit of this study is that for this season, the goal is limited to reducing the area specific heat supply and operation costs while the emission factor is less considered. Though it is more straightforward to use the operation cost, it is necessary to consider the impact of emission, which will be the focus of our future work.

In addition to that, the proposed approach needs a more detailed techno-economic analysis. Another future will be investigating the impact of factors such as thermal-hydraulic operation conditions, indoor thermal setpoints, the scale of population, variety of heating sources. These factors directly affect the economic and environmental benefits of this approach and should quantify its economic sensitivity.

The ultimate goal of network splitting is to obtain an optimal thermo-hydraulic balance while reducing energy consumption and emission. Therefore, to further explore the optimization approach of network splitting in future UCHS, we suggest to apply network splitting analysis to multi-source (with renewable-energy-based heating sources) UCHS and solve dynamic and multi-objective non-linear programming in large-scale UCHS. This is critical to the design, operation, and optimization of large-scale UCHS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Wei Zhong: Investigation, Methodology. **Jiaying Chen:** Investigation, Validation, Writing - original draft. **Yi Zhou:** Methodology, Software, Formal analysis. **Zhongbo Li:** Resources, Data curation, Funding acquisition. **Zitao Yu:** Project administration, Supervision. **Xiaojie Lin:** Conceptualization, Methodology, Validation, Writing - review & editing.

Acknowledgments

This work is supported by National Key R & D Program of China (Grant No. 2017YFE0114700) and National Key R & D Program of China (Grant No. 2017YFA07003025). This work is supported by National Natural Science Foundation of China (Grant No. 51806190). This work is also supported by key project of Beijing Municipal Science and Technology Commission “Blue Sky Project” (Grant No. D171100001217001).

References

- Allegrini, J., Orehounig, K., Mavromatidis, G., Ruesch, F., Dorer, V., Evins, R., 2015. A review of modelling approaches and tools for the simulation of district-scale energy systems. *Renew. Sustain. Energy Rev.* <http://dx.doi.org/10.1016/j.rser.2015.07.123>.
- Cai, H., Ziras, C., You, S., Li, R., Honoré, K., Bindner, H.W., 2018. Demand side management in urban district heating networks. <http://dx.doi.org/10.1016/j.apenergy.2018.08.105>.
- Department of Planning, Financing and Foreign Affairs Ministry of Housing and Urban-Rural Development, P.R.C., 2018. *China Urban-Rural Construction Statistical Yearbook*. China Planning Press.
- Fan, X., Sun, L., Feng, J., 2015. Calculation of pressure at pressurization points of heating system with multi-heat sources. *Gas Heat*. 35, 1–4.
- Fang, Z., Zhang, X., Li, F., Wu, R., 2016. Case study on hydraulic condition of centralized heat network with multi-heat source. *Dist. Heat*. 2, 65–69.
- Feng, J., Xie, M., Bu, W., Jiang, C., 2014. Research on secondary network backwater temperature forecast for centralized heat-supply system based on neural network. *Comput. Simul.* 31, 351–354.
- Gabrielaitiene, I., Böhm, B., Sunden, B., 2007. Modelling temperature dynamics of a district heating system in Naestved, Denmark-A case study. *Energy Convers. Manag.* 48, 78–86. <http://dx.doi.org/10.1016/j.enconman.2006.05.011>.

- Gao, L., Cui, X., Ni, J., Lei, W., Huang, T., Bai, C., Yang, J., 2017. Technologies in smart district heating system. *Energy Procedia* 142, 1829–1834. <http://dx.doi.org/10.1016/j.egypro.2017.12.571>.
- Guelpa, E., Sciacovelli, A., Verda, V., 2019. Thermo-fluid dynamic model of large district heating networks for the analysis of primary energy savings. *Energy* 184, 34–44. <http://dx.doi.org/10.1016/j.energy.2017.07.177>.
- Hu, J., Meng, H., Li, Z., 2010. Analysis on features and energy consumption of various heating source. *Appl. Energy Technol.* 4, 46–49.
- Jensen, S.Ø., 2016. IEA EBC Annex 67 energy flexible buildings.
- Jiang, Y., 2006. Problems in improvement of central heating systems in China and possible solutions. *Heat. Vent. Air Cond.* 36, 42–46.
- Jiang, Z., Meng, J., Zhao, X., Li, J., Li, L., Lin, X., 2018. Research and application of optimized dispatch of smart steam heating system based on simulation model. *Dist. Heat.* 195, 83–88.
- Köfinger, M., Schmidt, R.R., Basciotti, D., Terreros, O., Baldvinsson, I., Mayrhofer, J., Moser, S., Tichler, R., Pauli, H., 2018. Simulation based evaluation of large scale waste heat utilization in urban district heating networks: Optimized integration and operation of a seasonal storage. *Energy* 159, 1161–1174. <http://dx.doi.org/10.1016/j.energy.2018.06.192>.
- Lei, C., Zou, P., 2008. Constant-variable flow control and energy consumption analysis of indirect connection heating systems. *Heat. Vent. Air Cond.* 38, 125–129.
- Liu, A., 2011. Application Analysis and Evaluation Method Study on Residential Solar Water Heating System. Tsinghua University.
- Liu, L., 2015. Major issues and solutions in the management system of space heating system in North China. *Renew. Sustain. Energy Rev.* 49, 221–231. <http://dx.doi.org/10.1016/j.rser.2015.04.116>.
- Liu, Q., 2016. The Analysis of Multi Heat Source Network Operation in the Eastern Part of Jinan City. Harbin Institute of Technology.
- Lu, G., Wang, H., Shao, R., Dai, D., Zhao, H., 2001. Compensation method selection of heating net. *Gas Heat.* 21, 58–60.
- NDRC, National Development and Reform Commission (NDRC) People's Republic of China, 2017. Clean Heating Planning for Winter in North China (2017–2021).
- Nikula, H., Vesaoja, E., Sierla, S., Karhela, T., Flikkema, P.G., Aikala, A., Miettinen, T., Yang, C., 2014. Co-simulation of a dynamic process simulator and an event-based control system: Case district heating system. In: 19th IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA 2014, <http://dx.doi.org/10.1109/ETFA.2014.7005184>.
- Pakere, I., Romagnoli, F., Blumberga, D., 2018. Introduction of small-scale 4th generation district heating system. Methodology approach. *Energy Procedia* 149, 549–554. <http://dx.doi.org/10.1016/j.egypro.2018.08.219>.
- Postnikov, I., Stennikov, V., Mednikova, E., Penkovskii, A., 2017. Methodology for optimization of component reliability of heat supply systems. *Appl. Energy* <http://dx.doi.org/10.1016/j.apenergy.2017.11.073>.
- Qin, X., Jiang, Y., 1999. Accessibility analysis of district heating networks. *Heat. Vent. Air Cond.* 29, 2–7.
- Qin, X., Jiang, Y., 2001. Hydraulic optimization of multi heat source heating networks. *Heat. Vent. Air Cond.* 31, 11–16.
- Shan, X., Wang, P., Lu, W., 2017. The reliability and availability evaluation of repairable district heating networks under changeable external conditions. *Appl. Energy* 203, 686–695. <http://dx.doi.org/10.1016/j.apenergy.2017.06.081>.
- Tol, H.L., Svendsen, S., 2012. Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: A case study in Roskilde, Denmark. *Energy* 38, 276–290. <http://dx.doi.org/10.1016/j.energy.2011.12.002>.
- Tsinghua University, B.E.C.R.C., 2019. 2019 annual report on China building energy efficiency.
- Vigant, G., Blumberga, D., 2011. Modelling of the district heating system's operation. *Environ. Clim. Technol.* 6, 132–137. <http://dx.doi.org/10.2478/v10145-011-0019-x>.
- Wang, P., 2010. Reliability of District Heating System Based on Graph Theory. Harbin Institute of Technology.
- Wang, Yongfeng, Ma, F., Liu, X., 2008. Hot water supply for residential building energy-saving. *Constr. Conserv. Energy* 3, 57–60.
- Wang, Y., Zhang, N., Zhuo, Z., Kang, C., Kirschen, D., 2018. Mixed-integer linear programming-based optimal configuration planning for energy hub: Starting from scratch. *Appl. Energy* 210, 1141–1150. <http://dx.doi.org/10.1016/j.apenergy.2017.08.114>.
- Zhang, Y., Liu, X., Qin, B., 2015. Energy saving operation optimization in urban district heating system: A case study. *Heat. Vent. Air Cond.* 45, 97–100.
- Zhong, W., Chen, J., Zhou, Y., Li, Z., Lin, X., 2019. Network flexibility study of urban centralized heating system: Concept, modeling and evaluation. *Energy* 177, 334–346. <http://dx.doi.org/10.1016/j.energy.2019.04.081>.
- Zhong, W., Feng, H., Wang, X., Wu, D., Xue, M., Wang, J., 2015. Online hydraulic calculation and operation optimization of industrial steam heating networks considering heat dissipation in pipes. *Energy* 87, 566–577. <http://dx.doi.org/10.1016/j.energy.2015.05.024>.
- Zia, M.F., Elbouchikhi, E., Benbouzid, M., 2018. Microgrids energy management systems: A critical review on methods, solutions, and prospects. *Appl. Energy* 222, 1033–1055. <http://dx.doi.org/10.1016/j.apenergy.2018.04.103>.