Coordinated economic dispatch of the primary and secondary heating systems considering the boiler's supplemental heating

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District heating systems have been widely used in large and medium-sized cities. Typical district heating systems consist of the primary heating system (PHS) and the secondary heating system (SHS) operating in isolation. However, the isolated dispatch of the PHS and the SHS has poor adjustability and large losses, resulting in unnecessary operation costs. To address these issues, a coordinated economic dispatching model (CEDM) for the primary and secondary heating systems considering the boiler's supplemental heating is proposed in this study, which characterized the physical properties of the PHS and the SHS in detail. Considering that the PHS and the SHS are controlled separately without central operators in practice, it is difficult to dispatch them in a centralized method. Thus, the master-slave splitting algorithm is innovatively introduced to solve the CEDM in a decentralized way. Finally, a P6S12 system is utilized to analyze and verify the effectiveness and optimality of the proposed algorithm.

Introduction

District heating is widely utilized at the urban scale because of its energy-saving and environmental protection. According to statistics, district heating has been under development in Russia for over 100 years. It contributes 86% of the total national heat demand, more than half of which comes from combined heat and power (CHP). In Denmark, district heating is now responsible for heating almost 98%. In China, the district heating supply rate in large and medium-sized northern cities has reached over 60%.

Many scholars have conducted research on the optimal design of district heating systems (DHS) in recent years. Lund and Mohammadi (2016) proposed ways to improve DH piping by increasing insulation standards, thereby reducing heat and temperature losses from the network. Noussan et al. (2017) proposed the types and determination of heating load to guarantee the safety and stability of the heating supply. Gu et al. (2018) used the BP algorithm methods for dynamic prediction of the heating load. Kaliatka et al.

(2014) increased the design stage of the valve layout based on the traditional design process. Dalla Rosa et al. (2011) introduced suggestions for the optimal design of district heating systems for low-energy applications. It also puts forward some methods for reducing heat loss. On the basis of these research studies, a three-dimensional numerical model of heat loss is proposed to explore the difficulties of modeling energy losses in heating systems (Danielewicz, et al., 2016).

In addition, the prerequisite for ensuring the quality and safety of heat supply is the stability of the operation, so the operation optimization and control strategy of the heating systems need to be studied. Wu et al. (2021) proposed a method which uses quality regulation for heating systems. A method that varies the flow rate by means of a pump with a frequency converter according to the outdoor temperature is proposed (Kuosa, et al., 2013). Sun et al. (2021) established a strategy based on online prediction and indoor temperature feedback, which is beneficial to improve the regulation level of heating. Wang et al. (2016) used a novel matrix model of district heating networks to improve the accuracy of calibration temperature predictions. Lu et al. (2021) developed an integrated model in TRNSYS to obtain operation optimization by considering the energy consumption and time-of-use price. Sun et al. (2022) researched the control strategy integrated to improve prediction accuracy and realized energy-saving operation.

However, the aforementioned studies considered that the PHS and SHS of the DHS operate in isolation, which would likely bring some problems: 1) the CHP has a flat output and a small adjustment range because the contract signed between the PHS and SHS specifies a stable temperature of the PHS. 2) The higher temperatures required to ensure the quality of heating will result in more heat loss. 3) Extensive use of the boiler output rather than cooperating with CHP will cause high costs. Thus, a novel dispatch mode in which the PHS and SHS are coordinated to fully utilize the heating sources should be studied in depth.

Considering that the PHS and SHS are controlled separately by different companies in practice, the centralized solution for the coordinated economic dispatch model (CEDM) of the primary and secondary heating systems may encounter some troubles. 1) Detailed topologies or operation states could not be exchanged between the PHS and SHS. 2) It is difficult to control both of them in the centralized method. To cope with these issues, the master-slave splitting algorithm is applied to realize privacy protection and information interaction between the PHS and SHS. The optimality and effectiveness of master-slave splitting are demonstrated. The main contributions of our work are as follows:

1) We develop the CEDM of the primary and secondary heating systems considering the boiler's supplemental heating in this study. The differences between the PHS and SHS are analyzed, which are also modeled. By coordinating the PHS and SHS, the problems including poor adjustability,

high losses in the heating systems, and high operating costs due to the isolated operation can be solved.

2) The master-slave splitting algorithm is innovatively introduced in the CEDM of the primary and secondary heating systems. The original problem will be broken down into PHS sub-problems and SHS sub-problems, which will be solved by iteration of the two sub-problems Thus, it will solve the problems of difficult information interaction and privacy protection.

The remainder of this study is organized as follows: in Section 2, the formulation of the problem is presented. In Section 3, a decentralized solution based on a master-slave splitting algorithm is developed. In Section 4, the cases are studied to verify the effectiveness and optimality of the algorithm. In Section 5, the conclusions are summarized.

2 Problem formulation

This section focuses on modeling the primary and secondary heating systems. First, it introduces the structure of the heating systems and analyzes the differences between the operation of the PHS and SHS. Based on this, the primary and secondary heating systems are modeled and the operation formulation is established finally.

2.1 The differences between the primary and secondary heating systems

Figure 1 shows a typical urban DHS consisting of a PHS and SHS. In the PHS, heat is generated by CHP units and delivered to the heat exchange station. Then, heat is distributed to consumers through the SHS. In the SHS, the boiler also generates heat for supplementary heat through the heat exchange station. These two parts of the heat are transported to the heat load through the secondary pipe network (Lin et al., 2019).

As shown in Table 1, the heating systems are regulated differently and the accommodation mode of the PHS is quality regulation. It is suitable for situations where the mass flow rate is considered to be constant in the model. So the hydraulic constraints for the PHS are satisfied. Both of the constraints of the SHS need to be considered. The mode of the SHS is quantity regulation because of the varied mass flow rate (Deng et al., 2021).

2.2 Modeling the primary and secondary heating systems

The pipe network is the most important of heating systems. A typical structure of the pipe is shown in Figure 2 (Li et al., 2015).
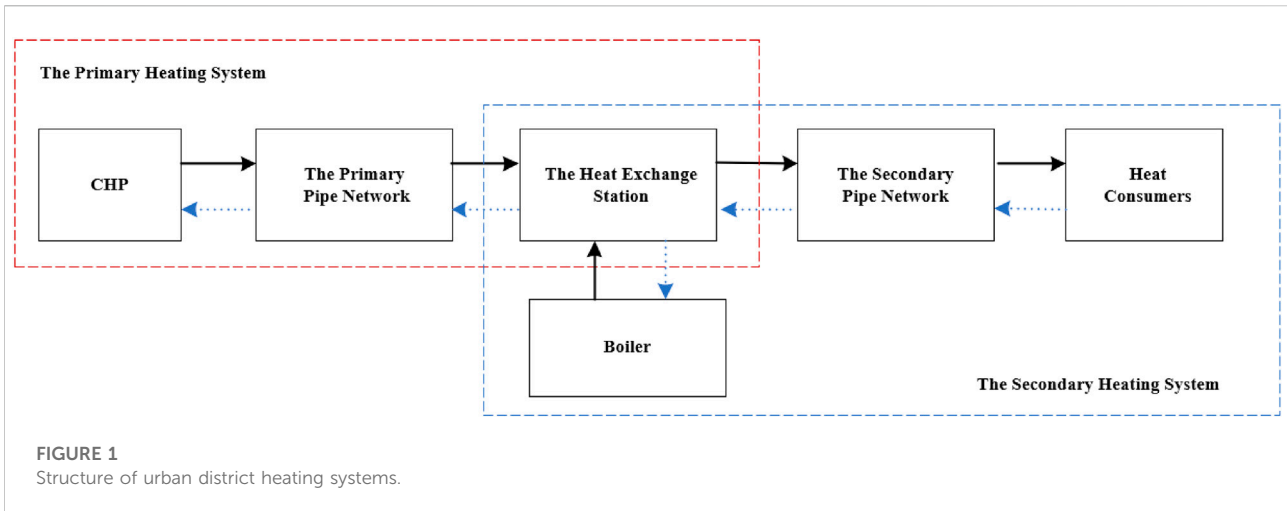
FIGURE 1
Structure of urban district heating systems.

TABLE 1 Difference between the primary and secondary heating systems.

Model	Source	Regulation methods	Hydraulic model	Thermal model
PHS	CHP	Quality regulation	–	Temperature mixing, Temperature dynamics, Heat loss
SHS	Heat exchange station, Boiler	Quantity regulation	Continuity of flow, Pressure loss	Temperature mixing, Heat loss

In Figure 2, the pipes are divided into supply pipes and return pipes. S_i^{pipe+} is expressed as the set of the starting of pipelines. S_i^{pipe-} is expressed as the set of the ending of pipelines. Mass flow from different pipes mixes and flows out at the node. The temperature of mixing is determined by the following equations.

$$\sum_{b \in S_i^{pipe-}} \left(\tau_{b,t}^{PS,\,out} \cdot ms_b^{pipe} \right) = \tau_{i,t}^{NS} \cdot \sum_{b \in S_i^{pipe+}} ms_b^{pipe}, \forall i \in S^{nd}, t \in T$$

$$\sum_{b \in S_i^{pipe-}} \left(\tau_{b,t}^{PR,\,out} \cdot mr_b^{pipe} \right) = \tau_{i,t}^{NR} \cdot \sum_{b \in S_i^{pipe+}} mr_b^{pipe}, \forall i \in S^{nd}, t \in T, \quad (1)$$

where ms_b^{pipe} and mr_b^{pipe} denote the mass flow rate at node i of the supply and return pipelines, respectively. $\tau_{b,t}^{PS,\,out}$ and $\tau_{b,t}^{PR,\,out}$ are expressed as the temperature at the outlet of the pipeline, respectively. $\tau_{i,t}^{NS}$ and $\tau_{i,t}^{NR}$ are expressed as the temperature at the node n, respectively. The temperature at the head of the pipe is equal to the temperature of the node.

$$\tau_{b,t}^{PS,in} = \tau_{i,t}^{NS}, \forall i \in S^{nd}, b \in S_i^{pipe+}, t \in T$$
$$\tau_{b,t}^{PR,in} = \tau_{i,t}^{NR}, \forall i \in S^{nd}, b \in S_i^{pipe+}, t \in T. \quad (2)$$

The aforementioned constraints are applicable to the PHS and SHS. The nodal method is utilized to formulate the thermal model in the PHS.

2.2.1 The primary heating network

However, these constraints are inapplicable in the CEDM because of numerous non-linear terms. It is difficult to solve non-linear problems in optimization problems. Thus, we simplify the model by temperature dynamics and heat loss. Temperature dynamics can be expressed as the pipe outlet temperature estimated using the pipe inlet temperature from past periods (Xue et al., 2020), as shown in Figure 3.

$\lfloor \ \rfloor$ denotes rounding down to the nearest whole number. ϕ_b^S and ϕ_b^S are expressed as the transmission period of the pipeline. However, ϕ_b^S and ϕ_b^S are often not calculated as integers in practical engineering; the temperature variables considered are discrete in dispatch interval, so $\tau'_{b,t}^{PS,\,out}$ is needed to represent the approximate expression as a linear weighted sum of the temperature in $t - \lfloor \phi_b^S \rfloor$ and $t - \lfloor \phi_b^S \rfloor - 1$. The left node $t - \lfloor \phi_b^S \rfloor$ can flow through a time period of $\Delta t = \phi_b^S - \lfloor \phi_b^S \rfloor$ to node j. Similarly, the right node $t - \lfloor \phi_b^S \rfloor - 1$ flows through node j, having already passed through a time period of $\Delta t = \lfloor \phi_b^S \rfloor + 1 - \phi_b^S$:

$$\tau'_{b,t}^{PS,\,out} = \left(\lfloor \phi_b^S \rfloor + 1 - \phi_b^S \right) \tau_{b,t-\lfloor \phi_b^S \rfloor}^{PS.in}$$
$$+ \left(\phi_b^S - \lfloor \phi_b^S \rfloor \right) \tau_{b,t-\lceil \phi_b^S \rceil -1}^{PS.in}, \forall b \in S^{pipe}, t \in T$$

$$\tau'_{b,t}^{PR,\,out} = \left(\lfloor \phi_b^R \rfloor + 1 - \phi_b^R \right) \tau_{b,t-\lfloor \phi_b^R \rfloor}^{PR.in} \left(\phi_b^R - \lfloor \phi_b^R \rfloor \right) \tau_{b,t-\lceil \phi_b^R \rceil -1}^{PR.in},$$

$$\forall b \in S^{pipe}, t \in T \phi_b^S = \frac{\rho A_b L_b}{ms_b^{pipe}}, \phi_b^S = \frac{\rho A_b L_b}{mr_b^{pipe}}, \forall b \in S^{pipe}, \quad (3)$$

where ρ, A_b, L_b indicate the density of water, cross-sectional area, and length of the pipeline, respectively. In addition, heat loss can refer to the heat dissipation from pipes to the environment. T c indicates the density of water and λ_b indicates the heat transfer coefficient.
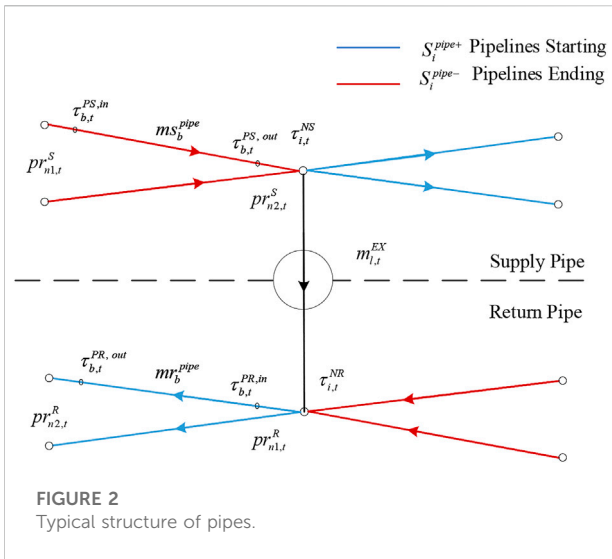
FIGURE 2
Typical structure of pipes.

FIGURE 3
Estimation of our temperature.

$$\tau_{b,t}^{PS,\,out} = \tau_t^{am} + \left({}'\tau_{b,t}^{PS,\,out} - \tau_t^{am} \right) \exp\left[-\frac{\lambda_b}{c} \frac{\rho A_b L_b}{mr_b^{pipe}} \right] \quad (4)$$

2.2.2 The secondary heating network

Unlike the PHS, the mass flow rate of the SHS is not constant. Thus, it is necessary to take the hydraulic constraints into account. The continuity of flow pressure loss is expressed as the sum of the inflow and outflow flows at the node 0.

$$\sum_{b\in S_i^{pipe2-}} ms_{b,t}^{pipe2} - \sum_{b\in S_i^{pipe2+}} ms_{b,t}^{pipe2} = \sum_{j\in S_i^{LOAD}} m_{j,t}^{LOAD} - \sum_{l\in S_i^{EX}} m_{l,t}^{EX}, \forall i \in S^{nd}, t \in T$$
$$\sum_{b\in S_i^{pipe2+}} mr_{b,t}^{pipe2} - \sum_{b\in S_i^{pipe2-}} mr_{b,t}^{pipe} = \sum_{l\in S_i^{EX}} m_{l,t}^{EX} - \sum_{j\in S_i^{HES}} m_{j,t}^{LOAD}, \forall i \in S^{nd}, t \in T$$

(5)

Considering the friction between the fluid and the pipes, there are fluid pressure drops in the SHS where $pr_{n1,t}^S, pr_{n2,t}^S, pr_{n1,t}^R$ indicate the pressure head of the supply and return systems, respectively. The pressure head the pressure loss along the pipe is the friction between the water flow. It is proportional to the square of the mass flow rate according to the Darcy–Weisbach equation (Li et al., 2015).

$$pr_{n1,t}^S - pr_{n2,t}^S = \mu_b \cdot \left(ms_{b,t}^{pipe2} \right)^2$$
$$pr_{n2,t}^R - pr_{n1,t}^R = \mu_b \cdot \left(mr_{b,t}^{pipe2} \right)^2 \quad . \quad (6)$$
$$\forall b \in S^{pipe2}, n1 = Nd_b^{PF}, n2 = Nd_b^{PT}, t \in T$$

The frequency of the pipeline decreases if the flow rate increases. It causes pipeline instability. So the pipeline flow rate must be limited.

$$0 \leq ms_{b,t}^{pipe2} \leq \bar{m}_b^{pipe2}, \forall b \in S^{pipe2}, t \in T$$
$$0 \leq mr_{b,t}^{pipe2} \leq \bar{m}_b^{pipe2}, \forall b \in S^{pipe2}, t \in T. \quad (7)$$

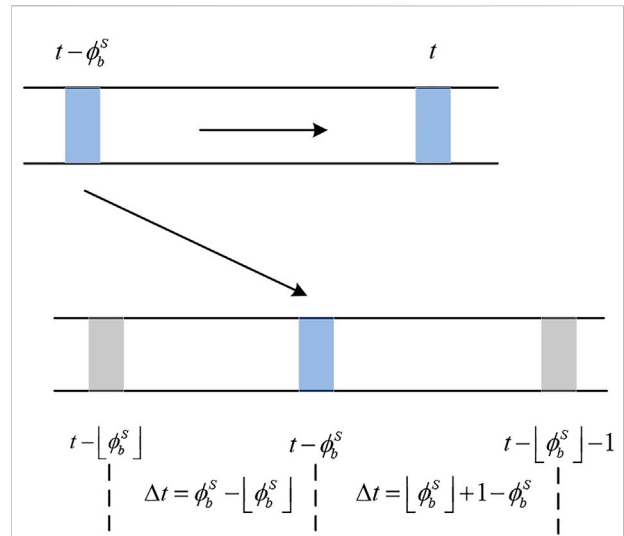Because of short piping distances in secondary heating systems, the delay is not taken into account. As the

temperature of the pipes differs from that of the outside world, there is a loss of temperature.

$$\tau_{b,t}^{PS,\,out2} = \tau_t^{am} + \left(\tau_{b,t}^{PS,\,in2} - \tau_t^{am} \right) \exp\left[-\frac{\lambda_b}{c} \frac{\rho A_b L_b}{mr_b^{pipe2}} \right]. \quad (8)$$

2.3 Operation model

The objective function of the CEDM is formulated as

$$\min \sum_{t\in T} \left[\sum_{i\in S^{CHP}} C_i^{CHP}\left(p_{i,t}^{CHP}, h_{i,t}^{CHP} \right) + \sum_{j\in S^{BOILER}} C_j^{BOILER}\left(f_{j,t}^{BOILER} \right) + \sum_{k\in S^{PUMP}} C_k^{PUMP}\left(d_{k,t}^{PUMP} \right) \right],$$

(9)

where $C_i^{CHP}(\cdot), C_j^{BOILER}(\cdot), C_k^{PUMP}(\cdot)$ indicate the cost function of the CHP, boiler, and pump, respectively. $p_{i,t}^{CHP}$ and $h_{i,t}^{CHP}$ represent the output of power and heat of the CHP, respectively. $f_{j,t}^{BOILER}$ and $d_{k,t}^{PUMP}$ indicate the fuel input of boiler and power consumption of the water pump, respectively.

The constraints are as follows: the power and heat output of the CHP (10), the output limit of the CHP (11), the heat generated by the CHP (12), the operating costs of the CHP (13), the heat transmission (14)-(15), the heat output of the boiler (16), the output limit of the boiler (17), the operating costs of the boiler (18), power consumption of the pump (19), the limit of power consumption (20), the operating costs of power consumption (21), the energy of the load (22), and the limit of temperature (23).

$$p_{i,t}^{CHP} = \sum_{z=1}^{NK_i} \alpha_{i,t}^z P_i^z, \forall i \in S^{CHP}, t \in T, h_{i,t}^{CHP} = \sum_{k=1}^{NK_i} \alpha_{i,t}^z H_i^z, \forall i \in S^{CHP}, t \in T,$$

$$\sum_{k=1}^{NK_i} \alpha_{i,t}^z = 1, 0 \le \alpha_{i,t}^z \le 1, \forall i \in S^{CHP}, z \in \{1,2,\ldots,NK_i\}, t \in T \quad (10)$$

$$\underline{p}_i^{CHP} \le p_{i,t}^{CHP} \le \bar{p}_i^{CHP} \ \underline{h}_i^{CHP} \le h_{i,t}^{CHP} \le \bar{h}_i^{CHP}, \forall i \in S^{CHP}, t \in T. \quad (11)$$

$$h_{i,t}^{CHP} = c \cdot m_n^{CHP} \cdot \left(\tau_{n,t}^{NS} - \tau_{n,t}^{NR}\right) \forall i \in S^{CHP}, n = Nd_i^{CHP}, t \in T, \quad (12)$$

$$C_i^{CHP}\left(p_{i,t}^{CHP}, h_{i,t}^{CHP}\right) = a_{0,i} + a_{1,i} p_{i,t}^{CHP} + a_{2,i} h_{i,t}^{CHP}$$
$$+ a_{3,i}\left(p_{i,t}^{CHP}\right)^2, \forall i \in S^{CHP}, t \in T, \quad (13)$$

$$h_{i,t}^{EX} = c \cdot m_n^{EX} \cdot \left(\tau_{n,t}^{EXI1} - \tau_{n,t}^{EXO1}\right), \forall i = S^{EX}, n = Nd_i^{HS}.$$
$$h_{i,t}^{EX} = c \cdot m_m^{EX} \cdot \left(\tau_{m,t}^{EXI2} - \tau_{m,t}^{EXO2}\right), \forall i = S^{EX}, m = Nd_i^{HS}, t \in T. \quad (14)$$

$$h_{i,t}^{EX} = K_i^{EX} A_i^{EX} \frac{\left(\tau_{n,t}^{EXI1} - \tau_{m,t}^{EXO2}\right) + \left(\tau_{n,t}^{EXO1} - \tau_{m,t}^{EXI2}\right)}{2}, \quad (15)$$

$$\forall i \in S^{EX}, n = Nd_i^{HS1}, m = Nd_i^{HS2}, t \in T$$

$$h_{i,t}^{BOILER} = \eta_i^{BOILER} f_{i,t}^{BOILER}, \forall i \in S^{BOILER}, t \in T, \quad (16)$$

$$0 \le h_{i,t}^{BOILER} \le \bar{h}_i^{BOILER}, \forall i \in S^{BOILER}, t \in T, \quad (17)$$

$$C_j^{BOILER}\left(f_{j,t}^{BOILER}\right) = k_j^{BOILER} f_{j,t}^{BOILER}, \forall j \in S^{BOILER}, t \in T, \quad (18)$$

$$d_{i,t}^{PUMP} = \frac{m_{i,t}^{HS} \cdot \left(pr_{n,t}^S - pr_{n,t}^R\right)}{\eta_i^{PUMP} \cdot \rho}, \forall i \in S^{PUMP}, n = Nd_i^{HS}, t \in T, \quad (19)$$

$$\underline{d}_i^{PUMP} \le d_{i,t}^{PUMP} \le \bar{d}_i^{PUMP}, \forall i \in S^{PUMP}, t \in T, \quad (20)$$

$$C_k^{PUMP}\left(d_{k,t}^{PUMP}\right) = r_k^{PUMP} d_{k,t}^{PUMP}, \forall k \in S^{PUMP}, t \in T, \quad (21)$$

$$h_{i,t}^{LOAD} = c \cdot m_n^{LOAD} \cdot \left(\tau_{n,t}^{NS2} - \tau_{n,t}^{NR2}\right), \forall i \in S^{LOAD}, n$$
$$= Nd_i^{LOAD}, t \in T, \quad (22)$$

$$\underline{\tau}_n^{NS2} \le \tau_{n,t}^{NS2} \le \bar{\tau}_n^{NS2}, \ \underline{\tau}_n^{NR2} \le \tau_{n,t}^{NR2} \le \bar{\tau}_n^{NR2}, \forall n = Nd_i^{LOAD}, t \in T, \quad (23)$$

where $\alpha_{i,t}^z, P_i^z, H_i^z$ indicate variables representing the coefficient, electricity, and heat production, respectively. $K_i^{EX}, \eta_i^{BOILER}, k_j^{BOILER}, r_k^{PUMP}$ indicate the heat transfer coefficient, conversion efficiency of the boiler, and cost coefficient of the boiler and pump, respectively. All of S indicate the set of corresponding elements. Nd indicates the set of nodes connected to corresponding elements.

3 Solving strategy

The PHS and SHS are controlled separately without central operators in practice which will face many problems. To solve the problems posed, the decentralized solving strategy of the CEDM is given in this section as shown in Figure 4.
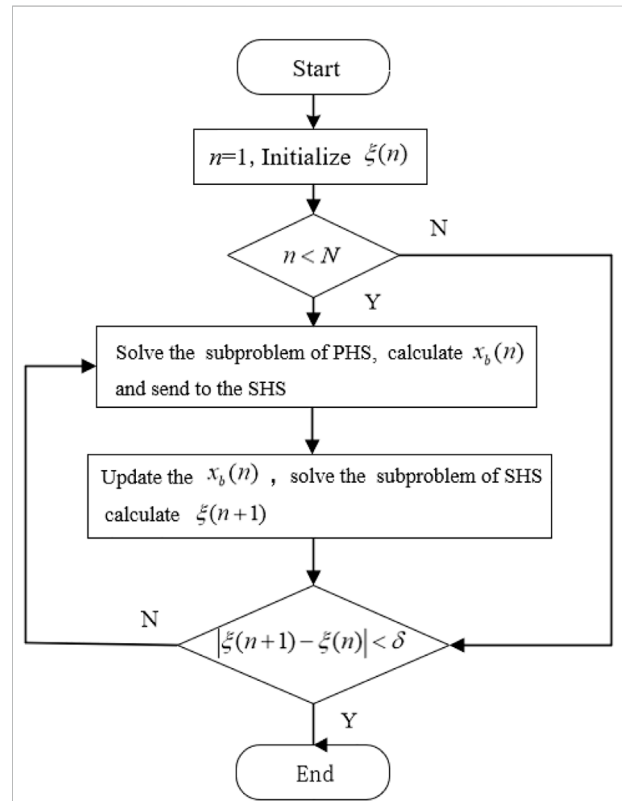

FIGURE 4
Diagram of the iteration procedure.

3.1 Model analysis

To facilitate the subsequent discussion, the CEDM is rewritten in a vector form (Xue et al., 2021).

$$\min_{x_F, x_B, x_S} f = C_F(x_F) + C_S(x_S),$$
$$\text{s.t.} \ A_F x_F + A_{BF} x_B = a_F$$
$$f_S(x_S, x_B) = 0 \quad , \quad (24)$$
$$B_F x_F + B_{BF} x_B \ge b_F$$
$$g_S(x_S, x_B) \ge 0$$

where the variable for the PHS is denoted as x_F, including $h_{i,t}^{CHP}, \alpha_{i,t}^k, \tau_{n,t}^{NS}, \tau_{n,t}^{NR}, \tau_{b,t}^{PS,\text{out}} \tau_{b,t}^{PR,\text{out}}, \tau_{b,t}^{PS,\text{in}}, \tau_{b,t}^{PR,\text{in}}, \tau_{m,t}^{EXI1}, \tau_{m,t}^{EXO1}$. The variable for the SHS is denoted as x_S, including $h_{i,t}^{BOILER}, f_{i,t}^{BOILER}, h_{l,t}^{LD}, \tau_{b,t}^{PS,\text{out2}}, \tau_{b,t}^{PR,\text{out}\,2}, \tau_{n,t}^{NS2}, \tau_{n,t}^{NR2} \tau_{b,t}^{PR,\text{in}\,2}$ and the boundary variable is denoted as x_B, including $h_{i,t}^{EX}, \tau_{m,t}^{EXI2}, \tau_{m,t}^{EXO2}$. $A_F x_F + A_{BF} x_B = a_F$ refers to the constraints (1)-(4), (10), and (12)-(13). $f_S(x_S, x_B) = 0$ refers to the constraints (5)-(6), (8), (14)-(16), (18)-(19), and (21)-(22). $B_F x_F + B_{BF} x_B \ge b_F$ refers to constraints (7) and (11). $g_S(x_S, x_B) \ge 0$ refers to constraints (17), (20), and (23).

FIGURE 5
Diagram of the F6S12 system.
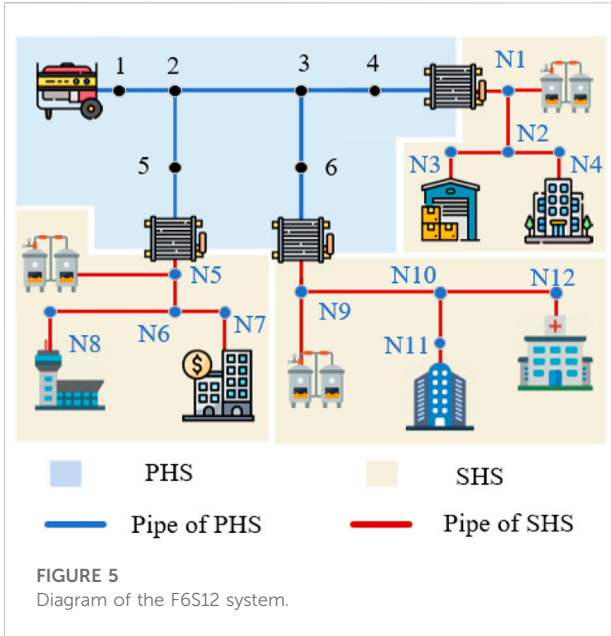
3.2 Formulation of the decentralized sub-problem

Based on the master-slave split method, the original problem can be decomposed into the PHS economic dispatch sub-problem and the SHS economic dispatch sub-problem. For the PHS economic dispatch sub-problem, it can be expressed as the following equation:

$$\min_{x_F, x_B} f = C_F(x_F),$$
$$\text{s.t. } A_F x_F + A_{BF} x_B^{sp} = a_F .$$
$$B_F x_F + B_{BF} x_B^{sp} \geq b_F \tag{25}$$

By solving the SHS economic dispatch sub-problem, the boundary information (BI) $\xi = A_{BF}^T \lambda_F + B_{BF}^T \mu_F$ is sent to the SHS. With the given BI, the SHS economic dispatch subproblem is formulated as

$$\min_{x_S, x_B} f = C_S(x_S) + \xi^T x_B,$$
$$\text{s.t. } f_S(x_S, x_B) = 0 \tag{26}$$
$$g_S(x_S, x_B) \geq 0$$

3.3 Iteration procedure

The two sub-problems decomposed from the original problem can be solved by iteration. First, the PHS solves its own scheduling problem. It passes the boundary information to the SHS after completing the solution. The SHS schedules internally based on this information then provide the boundary information injection to the PHS.

Figure 4 shows the specific iteration procedure. The iterations will begin with the PHS sub-problem after initialization including set $n = 1$, the maximum number of

iterations to N, the accuracy of convergence to δ, and initialize the boundary information $\xi(n)$. Then calculate $x_b(n)$ and send to the SHS. The SHS sub-problem will be solved by considering $x_b(n)$ as a constant. Then it will obtain $\xi(n+1)$ and provide the $\xi(n+1)$ injection to the PHS. Iteration keeps cycling until the condition $|\xi(n+1) - \xi(n)| < \delta$ is satisfied.

4 Case studies

4.1 Case setting

Figure 5 shows an F6S12 system which is composed of the primary and secondary heating systems with the 6-node PHS and the 12-node SHS. The time resolution is 1 h.

To verify the superiority of the CEDM, an isolated economic dispatch model (IEDM) is used for comparison. In the IEDM, the PHS and SHS can only exchange BI via the heat exchange station. In the CEDM, all decision variables can be changed.

The case was tested using MATLAB 2018b on a 2.80 GHz i7-1165G7 CPU with 16 G and solved using the MatlabYalmip toolbox and the open source packages Ipopt solver and Gurobi solver.

4.2 Comparison of coordinated and isolated modes

CHP units have poor regulation in the IEDM. The PHS and SHS have signed contracts that determine the temperature of the PHS. This temperature is largely stable, so the heating output of the CHP is flatter. A small adjustment range will lose the advantage of CHP. As shown in Figure 6, it is up to the boiler to respond to changes in load.
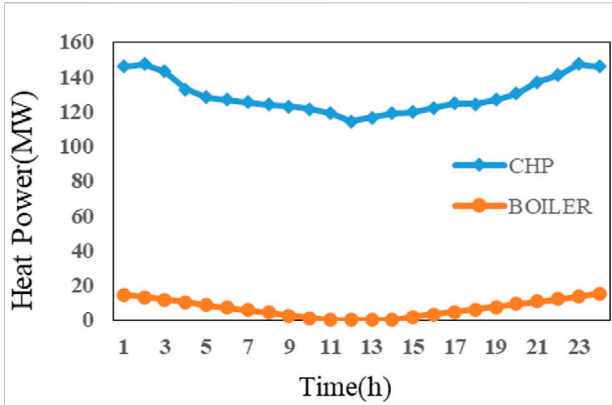

FIGURE 6
Heat source output in IEDM.
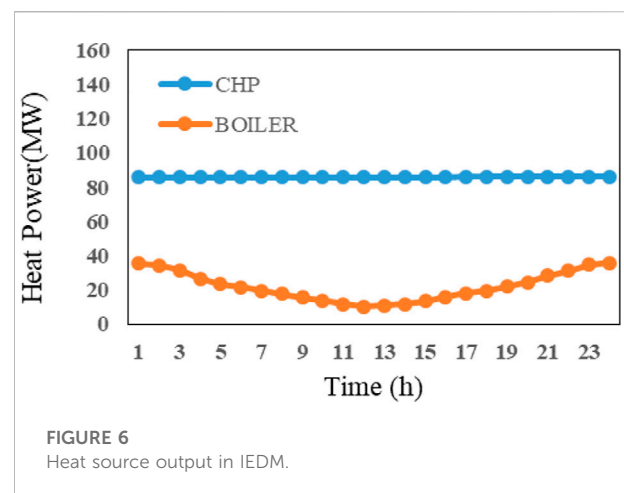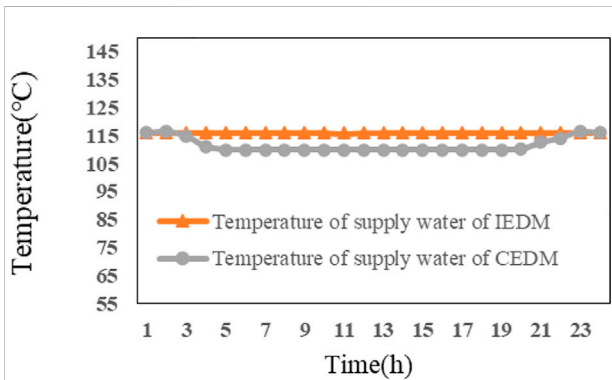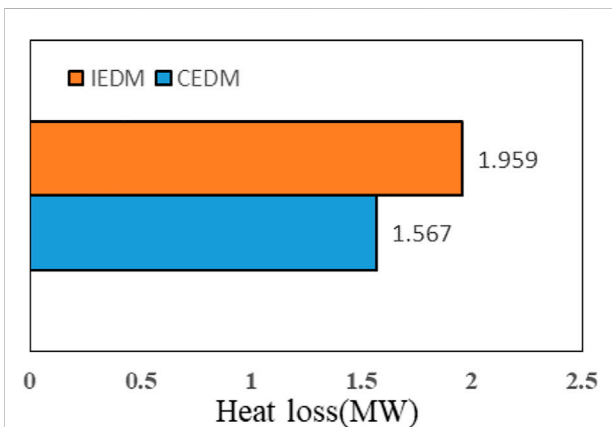
FIGURE 7
Heat source output in CEDM.

FIGURE 8
Supply water in two modes.

FIGURE 9
Heat loss in two modes.

TABLE 2 Cost of two modes and algorithms.

	CEDM		IEDM
	Decentralized	**Centralized**	
$\sum_{t \in T} \sum_{i \in S^{CHP}} C_i^{CHP}$ ($)	45404	45404	26706
$\sum_{t \in T} \sum_{i \in S^{BOIL}} C_i^{BOIL}$ ($)	9097	9097	29842
$\sum_{t \in T} \sum_{i \in S^{PUMP}} C_i^{PUMP}$ ($)	64	64	58
Total cost ($)	54565	54565	56606

On the contrary, the PHS and SHS work collaboratively with each other in the CEDM as shown in Figure 7. The CHP units have an increased range of regulation. The CHP units can provide peak loads, which can be balanced daytime heat load when less heat is required. The boiler's supplemental heating plays a role in the early hours of the morning or at night when the heat load is high.

In addition, the temperature of the PHS is generally set higher to ensure the quality of the supply in the IEDM, while the quality could be adjusted to the demand of the load in the CEDM. Therefore, the temperature could be brought down as shown in Figure 8. The temperature of the return water network has also been reduced, so it is not shown in Figure 8.

Moreover, the PHS has long lines during transmission as shown in Figure 9, which can cause significant heat loss in IEDM The CEDM, on the other hand, can reduce the heat loss to the environment during transmission by reducing the temperature.

As shown in Table 2, the coordinated economic dispatch in the CEDM is more economical than in the IEDM. The CEDM could take the advantages of CHP units to be fully exploited, using CHP units to meet the vast majority of the heat demand. It can also take advantage of the boiler's supplemental heating to reduce the output of the boiler and costs.

Moreover, centralized and decentralized algorithms have the same results, verifying the validity of the proposed algorithm which refers to the master-slave split method. Moreover, the decentralized algorithm converges with the same Karush–Kuhn–Tucker conditions compared to the centralized algorithm. So the solution obtained satisfies optimality.

5 Conclusion

In this study, the coordinated economic dispatch model (CEDM) of the primary and secondary heating systems considering the boiler's supplemental heating is established to solve the problems in DHS operations, such as the small regulation range of CHP units, high losses in the heating systems, and high costs. The reliability of the model has been verified using examples. Also, based on the actual physical

characteristics, the distributed coordinate economic dispatch based on the master-slave split method is applied in the primary and secondary heating systems, which solves the problems of difficult information interaction and privacy protection. It proved the optimality of the master-slave splitting method in non-convex scenarios.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

Author contributions

We develop the CEDM of the primary and secondary heating systems considering the boiler's supplemental heating in this study. The differences between the PHS and SHS are analyzed, which are also modeled. By coordinating the PHS and SHS, problems including poor adjustability, high losses in the heating systems, and high operating costs due to the isolated operation can be solved. The master-slave splitting algorithm is innovatively introduced in the CEDM of the primary and secondary heating systems. The original problem will be broken down into PHS sub-problems and SHS

sub-problems, which will be solved by iteration of the two sub-problems. Thus, it will solve the problems of difficult information interaction and privacy protection.

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Conflict of interest

YS was employed by China Power Integrated Smart Energy Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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