

Article

Optimal Dispatching of Integrated Electricity and Heating System with Multiple Functional Areas Considering Heat Network Flow Regulation

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Abstract: The integrated electricity and heating system (IEHS) can satisfy the diversified energy demand and improve energy efficiency through electro-thermal synergy and complementarity, which is beneficial for energy transformation and global climate governance. To reduce the operation cost, renewable energy source (RES) abandonment, and purchased electricity of IEHS, an optimal dispatching method of IEHS with multiple functional areas considering the flow regulation of the heat network is proposed. Firstly, the functional area of IEHS is classified and the functional area's load characteristics are analyzed. Secondly, a heat network model considering refined resistance and dynamic characteristics is constructed and the operation regulation modes of the heat network are analyzed. Thirdly, an optimal dispatching model of IEHS with multiple functional areas considering heat network flow regulation is established to minimize the operation cost of IEHS with multiple functional areas while considering the penalty cost of RES abandonment and time-of-use electricity price. Finally, a certain region in China is taken as a case study to verify the effectiveness of the proposed optimal dispatching model. The case study shows that the quality regulation mode of the heat network considering flow change in multiple stages can effectively reduce RES abandonment by 2.4%, purchased electricity by 5.4%, and the system operation cost by 1.7%. In addition, compared with the independent dispatching of each functional area, the joint dispatching of IEHS with multiple functional areas can reduce the amount of RES abandonment by 95.2% and purchased electricity by 66.5%, and lower the operation cost of IEHS by 23.6%.

Keywords: integrated electricity and heating system; heat network operation; flow regulation; multiple functional areas



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1. Introduction

In 2020, China proposed the strategic goals of carbon peak by 2030 and carbon neutralization by 2060, which will be conducive to promoting the process of global climate governance. Currently, carbon dioxide emissions of the power industry account for about 40% of China's carbon dioxide emissions. Accelerating the decarbonization of the power industry and the electrification of terminal energy has become the main approach to promote the low-carbon transformation of the energy system and a long-term reduction in greenhouse gas emissions [1–3]. Owing to its renewable energy sources, the integrated electricity and heating system (IEHS) has become one of the main ways to promote the decarbonization of the power industry. With the application and development of combined heat and power (CHP) technology, the coupling effect of electrical energy and thermal energy has been gradually enhanced [4,5]. The interaction between the power system and the

thermal system in IEHS plays an important role in facilitating the cost-effective transition to a low-carbon energy system with high penetration of renewable generation [6–8]. At present, it is urgent to establish a more perfect electro-thermal co-ordination dispatching mechanism, which can satisfy the requirements of heating load, reduce the operation cost of the system, and reduce the waste of wind and photovoltaic energy at the same time.

The urban electric heating network is a network of mutual coupling and interaction between the power system and regional heating system, which reflects the geographical and functional characteristics of the integrated energy system [9] and is conducive to improving the flexibility of the system [10]. According to the different divisions of economic and social functions, the interior of the urban electric heating network can be divided into multiple functional areas, thus forming an IEHS with multiple functional areas. IEHS with multiple functional areas can make use of the load difference characteristics between different functional areas to reduce the operation cost of the system. In [11], the heat network interaction among different load characteristic regions is introduced to optimize the configuration and operation of a multi-area integrated energy system. It is confirmed that compared with a single area co-generation mode, the integrated energy system with multi-area heat network interaction can improve the clean energy utilization rate of the system and provide better overall system benefits. On the basis of the existing integrated energy system model, the planning model of an integrated energy micro-grid is established in [12]. Compared with the isolated integrated energy system, the integrated energy micro-grid formed by connecting multiple regional integrated energy systems through the distribution network and heating network can further improve the reliability, flexibility, cleanliness, and economy of regional energy supply. In [13], an integrated energy system dispatching model considering the differences of multiple functional areas and the balance of cooling, heating, and electrical loads is proposed, which verifies that the consideration of multiple functional areas can produce obvious economic benefits. However, most of the existing research studies on IEHS with multiple functional areas mainly focus on the energy interaction among multiple regions, and research on dynamic characteristics modeling and the operation mode of thermodynamic systems is not intensive and comprehensive enough.

Thermodynamic systems have some intrinsic attributes such as multi-variability, non-linearity, and time-delay, and the heat transfer process is complex and related to many factors [14,15]. The operation and regulation of the heat network are independent of the power system dispatching. As a result, when describing and evaluating the regulation capability of the heat network, it is difficult to integrate the dynamic modeling of the electric-heating system and to coordinate the operation mechanism of the heterogeneous energy system. By bringing the heat pipe network into IEHS scheduling and implementing refined management, the consumption of renewable energy can be improved and the increasing demand of users for thermal comfort can be satisfied [16,17]. Heat transfer and the turbulent flow of water in different heat exchangers are investigated in [18], and the use of counter flow heat exchangers is recommended in higher Reynolds numbers. Through the modeling of heat loss and transmission delay from an electrical analog perspective, an equivalent representation of distributed heating networks is proposed in [19] to accommodate more wind power. In [20], a two-stage robust IEHS dispatching model considering uncertainties of the heat load, environmental temperature, and heat dissipation coefficient of heating pipelines is proposed for the inherent uncertainties of pipeline parameters and environmental temperature in the regional heating network. The empirical model of the heat transfer process of the pipeline heat carrier is established in [21,22] to study the thermal inertia and transmission delay of thermal systems, which shows that the consideration of the natural heat storage capacity of heating supply networks in the optimal dispatching of the integrated energy system can effectively improve the dispatching flexibility of the system and reduce the operation cost. However, the existing research on IEHS rarely considers the operation and regulation mode of the heat network, which cannot give full play to the regulating capability of the heat network.

Based on the shortcomings of the existing research, the feature and load characteristics of IEHS with multiple functional areas are analyzed first, and then the refined dynamic model of the heat network is constructed and the operation and regulation mode of that is analyzed. Next, a dispatching model of IEHS with multiple functional areas considering heat network flow regulation is constructed. Finally, a certain region in China is taken as a case study to verify the effectiveness of the proposed optimal dispatching model.

2. Integrated Electricity and Heating System with Multiple Functional Areas and Its Load Characteristics

When the same kind of economic and social activities are highly concentrated in a city space, different functional areas can be formed. A functional area is the carrier to realize various functions of the city, which has an obvious agglomeration effect and significant economic benefits. Therefore, multiple functional areas can improve the operation efficiency of the city. In this paper, the functional areas are divided into residential, commercial, office, and industrial areas. Different functional areas have different social functions, architectural features, land use types, and geographical distribution [13]. The typical electric load and thermal load data curves in winter of a certain region in China are shown in Figure 1.

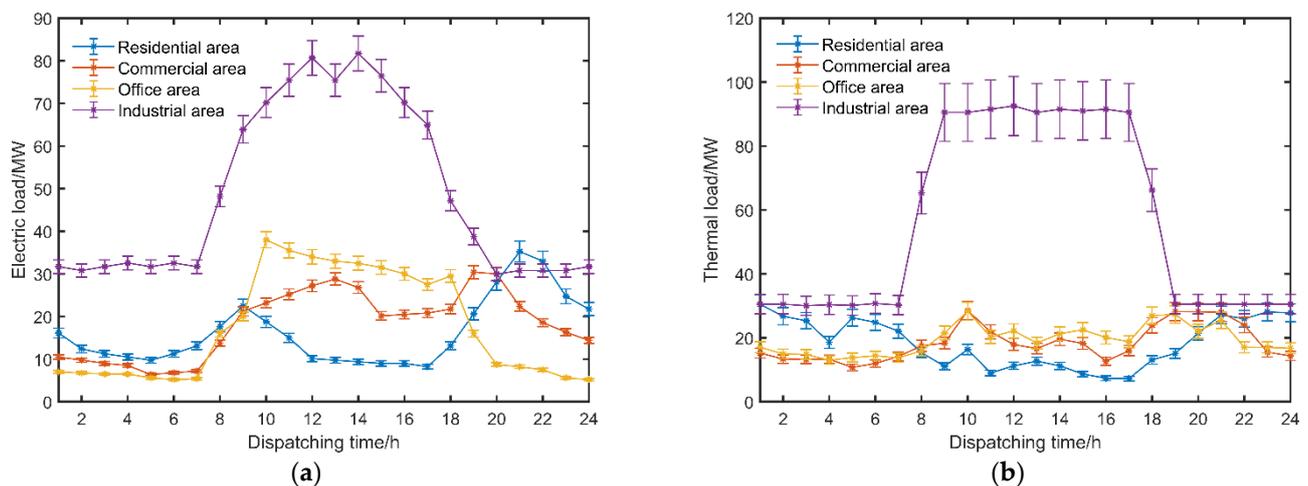


Figure 1. Typical characteristics of each functional area: (a) Electric load; (b) Thermal load.

The main function of the residential area is for people to live, so its buildings are mainly ordinary residential buildings, with some green land and a small amount of shopping land. The proportion of residential land in the residential area should be more than 50%, which is usually distributed in the city center and suburbs. It can be observed from Figure 1 that the electric load of the residential area presents a double peak in the morning and at night, which is consistent with people's travel habits. The peak of thermal load in the residential area occurs at night but it is lower in the daytime, which is consistent with the living habits of residents who leave for work early and return late.

The main functions of the commercial area are shopping, catering, and entertainment, so its buildings are mainly shopping malls. The proportion of commercial land in the commercial area should be more than 60%, which is usually distributed in the city center. It can be seen from Figure 1 that the peak period of electricity consumption of the commercial area is during business hours, while the electric load remains at a low level in other periods except for business hours. The thermal load of the commercial area is also higher during business periods but lower during non-business periods.

The main functions of the office area are administrative offices, conference receptions, financial services, and property rights transactions, so its buildings are mainly office buildings and financial buildings, which are usually distributed in the city center. It can be observed from Figure 1 that the electric load rises rapidly to the peak after the start of

work and decreases significantly after work. The thermal load of the office area is higher during working hours but lower at night.

The main function of the industrial area is industrial production, so its buildings are mainly industrial factories. The proportion of industrial land in the industrial area should be more than 40%, which is usually distributed in remote suburbs. It can be seen from Figure 1 that the electric load of the industrial area is high during the whole day and the daytime load is higher than the night load, which is consistent with the regime of the factory. Because most of the thermal load in the industrial area is the production demand, the thermal load is very high during the operation of the machines in factories, and relatively low at night because the machines in factories stop working.

The load valley of the residential area corresponds to the load peak of other functional areas, and the abundant wind and photovoltaic power output at this stage can be transported to other functional areas through joint dispatching of multiple functional areas, which can not only support the peak power consumption of other areas but also increase the wind and solar energy consumption of the residential area.

Through studying the load complementary difference characteristics among different functional areas, the operation efficiency can be effectively improved, the operation cost can be reduced, and the consumption of renewable energy can be promoted.

3. Model and Operation Regulation Mode of Heat Network Considering Flow Adjustment

It is hard to completely achieve the coordinated optimization of IEHS separately considering the performance of the power system or thermal system. Therefore, the coordinated operation strategy of IEHS considering the power system and thermal system is necessary. At present, research on the operation regulation mode of the heat network has been relatively mature, but the operation regulation mode for the heat network to participate in the optimal coordinated operation of IEHS is not comprehensive enough. Therefore, a comprehensive analysis for the operation regulation mode of the heat network will be conducive to construct a better dispatching strategy when performing electricity–heat coordinated optimization.

The typical structure of a heat network includes a water supply network and return network, which is shown in Figure 2. The heat network can be divided into a transmission system (primary heat supply network) and a distribution system (secondary heat supply network) [23]. The first and the last two ends of the primary heat supply network are the heat station and the heat exchange station. There is not a direct connection between the physical network of the primary and secondary heat network, and heat exchange should depend on the heat exchange station. Due to the short heat transfer distance of the secondary heat network, the heat loss during transmission can be ignored, and the heat consumed by the heat exchange station is usually equivalent to users' heat load.

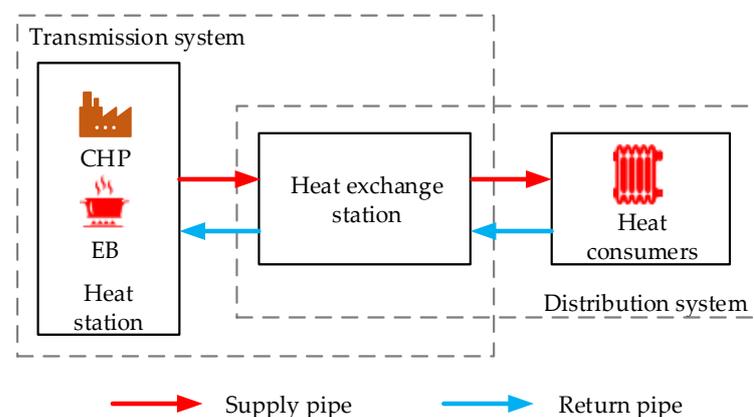


Figure 2. Structure of heat network.

3.1. Heat Network Model Considering Refined Resistance and Dynamic Characteristics

In order to study the influence of the heat network's operation mode on the whole system, refined model construction for the heat network should be firstly considered. The model of the heat network is mainly divided into two main parts: the hydraulic model and the thermodynamic model. The hydraulic model is used to describe the flow state of hot water in heating pipes and the thermodynamic model is used to describe the energy transfer process in heating pipes.

3.1.1. Hydraulic Model Considering Refined Resistance

1. Flow continuity equation

According to the law of conservation of mass, the difference between the pipe mass flow rate of the inflow node and that of the outflow node is equal to the mass flow rate of the outflow node, as shown in Equation (1).

$$Am = m_q \quad (1)$$

where A is the node–branch incidence matrix of the heat network; m is the matrix of the pipeline mass flow rate; and m_q is the mass flow rate matrix of the outflow node.

2. Loop pressure equation considering refined resistance

According to the law of conservation of energy, in any closed loop, the sum of the pressure loss of hot water flowing in the pipeline is equal to zero, as shown in Equation (2).

$$Bh = 0 \quad (2)$$

where B is the loop–branch incidence matrix of the heat network and h is the pressure loss matrix of the pipeline.

With respect to pipeline pressure loss, a model of resistance elements' impact on pipeline water flow is constructed, which takes the equivalent length method to convert the local loss of the pipeline into the loss along the way. The pipeline pressure loss considering refined resistance can be calculated by Equations (3)–(6) [24].

$$h = R_a(L + L_d) \quad (3)$$

$$R_a = 6.88 \times 10^{-3} \varepsilon^{0.25} \frac{m|m|}{\rho D^{5.25}} \quad (4)$$

$$L_d = \sum \xi \frac{D}{\lambda} \quad (5)$$

$$\lambda = 0.11 \left(\frac{\varepsilon}{D} \right)^{0.25} \quad (6)$$

where h is the pipeline pressure loss; R_a is the friction resistance; L is the length of the pipeline; L_d is the equivalent length of local resistance; ε is the absolute roughness value of the pipeline; m is the mass flow rate of the pipeline; D is the pipe diameter; ρ is the density of water; ξ is the local resistance coefficient; and λ is the pipe resistance coefficient.

3.1.2. Thermodynamic Model Considering Dynamic Characteristics of Heat Network

When the heat network is disturbed, the hot water flow state can reach the steady state in a few seconds to a few minutes, but the heat transfer, which relies on the hot water flow, will have a lag of tens of minutes to a few hours. Therefore, it is necessary to consider the interaction of the transmission delay effect from dynamic characteristics of the heat network and the micro-elements in the pipeline when constructing the thermodynamic model.

A. Node thermal power model

The thermal power of the heat source and heat load is related to the node water supply temperature, return water temperature, and hot water parameters in the pipeline, which

can be expressed by Equation (7). In addition, the temperature of supply and return water should satisfy the design upper and lower limits of pipeline temperature, as shown in Equations (8) and (9).

$$H_{i,t} = c_w m_{i,t} (T_{sup,i,t} - T_{ret,i,t}) \tag{7}$$

$$T_{sup,min} \leq T_{sup,i,t} \leq T_{sup,max} \tag{8}$$

$$T_{ret,min} \leq T_{ret,i,t} \leq T_{ret,max} \tag{9}$$

where i is the node number, $i = 1, 2, \dots, N$; N is the number of nodes; t is the period number, $t = 1, 2, \dots, T$; T is the number of dispatching periods; $H_{i,t}$ is the thermal power of node i in period t ; c_w is specific heat capacity; $m_{i,t}$ is the mass flow rate of node i in period t ; $T_{sup,i,t}$ is the water supply temperature of node i in period t , namely, the temperature of hot water flowing into the load node or out of the source node; $T_{ret,i,t}$ is the water return temperature of node i in period t , namely, the temperature of hot water flowing out of the load node or into the source node; and $T_{sup,max}$, $T_{sup,min}$, $T_{ret,max}$, and $T_{ret,min}$ are upper and lower limits of pipe supply/return water temperature, respectively.

B. Dynamic heat transfer model of pipe

The temperature of hot water flowing out of the node is the same when hot water is mixed at the node, which is defined as the node temperature. According to the law of conservation of energy, the total thermal power of the inflowing node is equal to the total thermal power of the outflowing node, which can be expressed by Equation (10).

$$\sum_{j \in S_n^{pipe-}} T_{out,j,t} m_{j,t} = T_{in,k,t} \sum_{k \in S_n^{pipe+}} m_{k,t} \tag{10}$$

where S_n^{pipe-} and S_n^{pipe+} are the set of pipes connected to node n and ending and starting from node n , respectively; $T_{out,j,t}$ is the outlet water temperature of pipe j in period t ; $T_{in,j,t}$ is the inlet water temperature of pipe j in period t ; and $m_{j,t}$ and $m_{k,t}$ are the hot water flow of pipe j and pipe k in period t , respectively.

C. Hybrid model of node temperature

The water temperature change at the entrance will slowly extend to the exit in the heat supply pipeline, and the transmission delay τ_j is basically consistent with the time of hot water through the pipe. In reference to the literature, an improved node method is used to describe the quasi-dynamic process of thermal energy transportation. The basic principle is as follows. By transmission delay τ_j and the time series of the historical data of the water temperature at the inlet of the pipeline, combined with the heat loss in the transmission process, the water temperature at the outlet of each period is calculated. A dispatching period is composed of T consecutive and equal length scheduling periods Δt , and the part that flows into the pipe from the inlet at each scheduling period Δt is called water mass (WM). In a period of scheduling time, IEHS is considered to be in a steady state, and the physical parameters of WM remain unchanged. A sectional drawing of a section of the heat supply pipeline is shown in Figure 3.

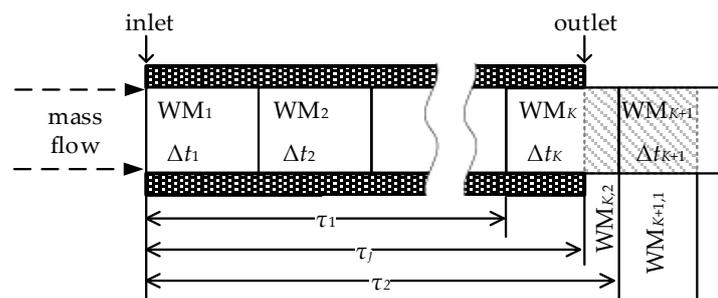


Figure 3. Vertical section of the thermal pipeline.

In Figure 3, time is recorded as t , and the first block of WM at the entrance enters the pipe at the time of $t - \Delta t$, which is recorded as WM_1 . Next, the mark is successive until the exit side, and the WM at the exit is recorded as WM_K . Considering the condition that τ_j is not an integral multiple of Δt , τ_j is assumed to vary between τ_1 and τ_2 , where $\tau_1 = (K - 1)\Delta t$ and $\tau_2 = K\Delta t$. Thus, the outflow part from the pipeline in this period should be composed of WM_K and WM_{K+1} , which is shown in the shadow of Figure 3. $WM_{K,2}$ is the outflow water from the pipeline of WM_K within $\tau_2 - \tau_j$, and $WM_{K+1,1}$ is the outflow water from the pipeline of WM_{K+1} within $\tau_j - \tau_1$. Therefore, hot water out of the pipe in the period of time Δt is the sum of $WM_{K,2}$ and $WM_{K+1,1}$, and the water temperature at the exit of the pipe can be expressed by the weighted average of mass of these two water masses, which is shown in Equation (11) [25].

$$\begin{aligned} T_{out,j,t} &= \frac{m_K(\tau_2 - \tau_j)T_{out,j,K} + m_{K+1}(\tau_j - \tau_1)T_{out,j,K+1}}{m_K(\tau_2 - \tau_j) + m_{K+1}(\tau_j - \tau_1)} \\ &= C_1 T_{out,j,K} + C_2 T_{out,j,K+1} \end{aligned} \quad (11)$$

where C_1 and C_2 are the weight coefficients; and m_K and m_{K+1} are the water flow of WM_K and WM_{K+1} , respectively.

During hot water transmission, the exchanged heat with the outside will result in heat loss and the temperature of WM_K flowing out of the pipe will decrease, as shown in Equations (12) and (13) [8].

$$T_{out,K} = T_{in,K} e^{-a_K l_j} + (1 - e^{-a_K l_j}) T_a \quad (12)$$

$$a_K = k_j / (m_K c_w) \quad (13)$$

where k_j is the heat loss coefficient of pipeline leakage; l_j is the length of the pipeline; and T_a is the environmental temperature around the pipeline.

The coupling relationship of hot water temperature at the inlet and outlet of the heating pipeline in time is the key to describe the dynamic characteristics of the heating network. As shown in Figure 3, the temperature of WM_K flowing into the pipeline should be the water temperature at the inlet of the pipeline at $t - \tau_1$, and after transmitting for $(K - 1)\Delta t$, part of WM_K begins to flow out of the pipeline at t . In the same way, WM_{K+1} will transmit in the pipeline for $K\Delta t$, and its temperature of flowing into the pipeline should be the water temperature at the inlet of the pipeline at $t - \tau_2$. Thus, Equation (12) can be rewritten as follows.

$$T_{out,K,t} = C_3 (T_{in,t-\tau_1} - T_a) + T_a \quad (14)$$

$$T_{out,K+1,t} = C_4 (T_{in,t-\tau_2} - T_a) + T_a \quad (15)$$

where $C_3 = e^{-a_K l_j}$ and $C_4 = e^{-a_{K+1} l_j}$.

Equation (16) is sorted out as follows by substituting $T_{out,K,t}$ and $T_{out,K+1,t}$ in Equation (11) with Equations (14) and (15), respectively.

$$T_{out,j,t} = C_1 C_3 T_{in,j,t-\tau_1} + C_2 C_4 T_{in,j,t-\tau_2} + (1 - C_1 C_3 - C_2 C_4) T_a \quad (16)$$

In Equation (16), the quasi-dynamic process is described, which is suitable for both the water supply and return pipes of the heat network. On condition that the pipe flow is given, all the coefficients C_1 , C_2 , C_3 , and C_4 are constant and the outlet temperature of the pipe can be expressed by the linear combination of the inlet temperature at different dispatching times. Because the dynamic transmission process of thermal energy has a large time scale, the inflow and outflow heat of hot water are not necessarily equal in the same period of time, which reflects the effect of the energy buffer and response delay of the heat network. Thereby, the external performance of the heat network is similar to the charging and discharging characteristics of a virtual energy storage system. The temperature of circulating water in the primary heat network will increase through the

initial heat exchange station and the increasing value is related to the heat output of the heat source, while the temperature of circulating water will decrease through the heat exchange station and the decreasing value is related to the heat load of the heat users. During a dispatching period, if the heat output of the heat source is greater than (less than) the user's heat demand, the virtual energy storage system of the heat network will play the role of energy storage (or release), which is reflected by the increase (or decrease) in return water temperature compared with the previous period. If the return water temperature is too high, the loss of the heat network will increase, while if the return water temperature is too low, the heat transfer effect between the primary and secondary heat network will be affected.

3.2. Operation Regulation Mode of Heat Network Based on Characteristics of Heat Network

The operation regulation means that the water supply temperature or the circulation flow of the heat network is in accordance with the change in outdoor meteorological conditions. According to the different locations of heating regulation, it can be divided into three regulating modes, that is, centralized regulation, local regulation, and individual regulation. Centralized regulation is regulated at the heat station; local regulation is regulated at the heat exchange station or the heat consumer; and individual regulation can directly make the regulation at heating equipment. Centralized regulation has become a major heating regulation method because it is easy for implementation and convenient for operation and management. According to the variation law of heat load with outdoor temperature, the heat network can regulate the whole system to satisfy the heat supply demand. There are two main regulating methods, i.e., temperature regulation and flow regulation of hot water in the primary pipe network. According to different regulation methods, the regulation mode of the heat network can be divided into quantity regulation, quality regulation, quality regulation considering flow change in multiple stages, and intermittent regulation.

3.2.1. Quality Regulation Mode of Heat Network

Quality regulation refers to the regulation mode that only the water supply temperature changes while the circulation flow keeps constant. In this mode, the condition of network hydraulic power can keep steady and it is convenient for operation and management. However, operation in a mode with a small temperature difference but large flow when the heat supply load is small will produce large transmission energy consumption of the circulation water pump, which is harmful to energy saving.

3.2.2. Quantity Regulation Mode of Heat Network

Quantity regulation refers to the regulation mode that only the circulation flow changes while the water supply temperature keeps constant. In practical application, the water flow in the pipeline decreases rapidly with the increase in outdoor temperature. Due to the mutual influence of the hydraulic conditions between the loops of the heating network, the flow change of the water supply pipeline at the heat station will lead to flow redistribution between the heat exchange stations, resulting in hydraulic imbalance [26]. Hydraulic imbalance means that the actual flow is inconsistent with the design flow, which is unfavorable to the operation of the heating network. Therefore, the application of quantity regulation is rare in past studies.

3.2.3. Quality Regulation Mode of Heat Network Considering Flow Change in Multiple Stages

Quality regulation considering flow change in multiple stages refers to the regulation mode that the change in circulation flow is divided into several stages, but the water supply temperature changes at every stage of constant flow. To be concrete, the flow will be kept at a higher level when the outdoor temperature is at a lower stage, and be kept at a lower level when the outdoor temperature is at a higher stage, which can improve the performance of energy saving on the promise of the steady operation of hydraulic power.

3.2.4. Intermittent Regulation Mode of Heat Network

Intermittent regulation refers to the regulation mode that only the hours of daily heat supply decrease while the quantity of network circulation water and water supply temperature keep constant when the outdoor temperature rises.

As a result of the less frequent application of quantity regulation and intermittent regulation in practice, quantity regulation (flow is constant) and quality regulation considering flow change in multiple stages (flow is variable) will be compared in this paper.

4. Dispatching Model of Integrated Electricity and Heating System with Multiple Functional Areas Considering Flow Regulation of Heat Network

4.1. Structure of Integrated Electricity and Heating System with Multiple Functional Areas

In this paper, the structure of IEHS with multiple functional areas is shown in Figure 4. The system is divided into residential, commercial, office, and industrial areas, and there are wind turbines (WT) and photovoltaic (PV) units with different capacities for each functional area. The heat can be supplied by CHP and the electric boiler (EB).

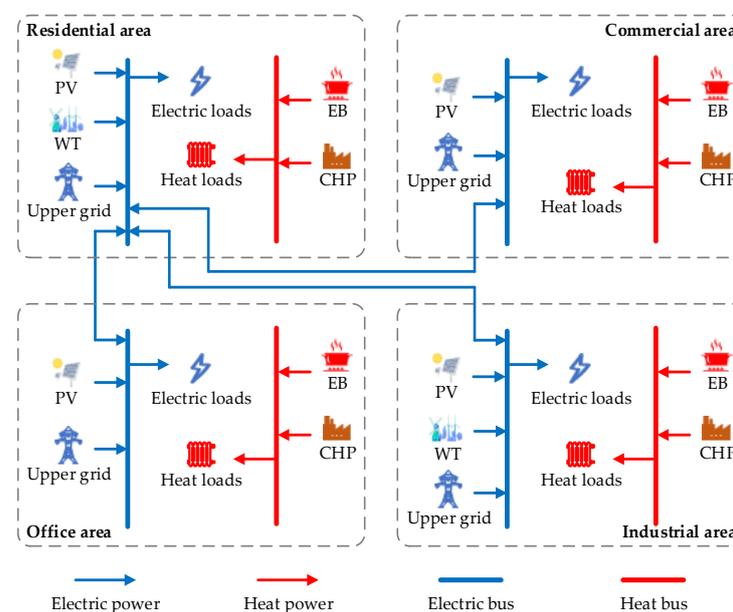


Figure 4. Structure of integrated electricity and heating system with multiple functional areas.

4.2. Objective Function of Optimal Dispatching of Integrated Electricity and Heating System with Multiple Functional Areas Considering Heat Network Flow Regulation

Due to the differences in the electric and thermal load characteristics of each functional area, there are load complementary characteristics among different functional areas. Moreover, the operational mode of quality regulation considering flow change in multiple stages can bring more energy saving effects. Therefore, the dispatching model of IEHS with multiple functional areas considering the regulation of heat network flow is constructed to achieve the optimal operation of IEHS with multiple functional areas.

The scenario analysis is used to deal with the uncertainty of renewable energies such as wind power and photovoltaic power. The total scenario amount of renewable power output is S , the probability of scenario s is p_s , and the total number of dispatching periods is T . The minimum total operational cost of the system is taken as the objective function of the proposed model, and for the purpose of promoting the consumption rate of renewable energies, the penalty cost of wind and photovoltaic energy is considered. The objective function is shown in Equation (17). In Equation (17), the total operation cost of the system is calculated, which includes the generation cost of CHP, the power purchasing cost, the penalty cost of wind and photovoltaic power abandonment, and the operation cost of the

heat network. The generation cost of CHP, the penalty cost of wind and photovoltaic power abandonment, and the cost of the heat pump are shown in Equations (18)–(20), respectively.

$$\min F = \sum_{s=1}^S p_s \sum_{t=1}^T \sum_{r=1}^R \left\{ c_{\text{CHP}}(P_{\text{CHP},r,t}^s, H_{\text{CHP},r,t}^s) + \varphi_t P_{\text{buy},r,t}^s + \rho P_{\text{cut},r,t}^s + c_{\text{HN}} P_{\text{HN},r,t}^s \right\} \quad (17)$$

$$c_{\text{CHP}}(P_{\text{CHP},r,t}^s, H_{\text{CHP},r,t}^s) = a_0 + a_1 P_{\text{CHP},r,t}^s + a_2 H_{\text{CHP},r,t}^s + a_3 (P_{\text{CHP},r,t}^s)^2 + a_4 (H_{\text{CHP},r,t}^s)^2 + a_5 P_{\text{CHP},r,t}^s H_{\text{CHP},r,t}^s \quad (18)$$

$$P_{\text{cut},r,t}^s = P_{\text{PW},r,t,\text{max}}^s + P_{\text{PV},r,t,\text{max}}^s - P_{\text{PW},r,t}^s - P_{\text{PV},r,t}^s - P_{\text{PWH},r,t}^s - P_{\text{PVH},r,t}^s \quad (19)$$

$$P_{\text{HN},r,t}^s = \chi m_{1,r,t} \quad (20)$$

where $P_{\text{CHP},r,t}^s$ and $H_{\text{CHP},r,t}^s$, respectively, represent the electric output and thermal output of CHP of area r at dispatching time t in scenario s ; $r = 1, 2, 3, 4$ correspond to residential, commercial, office, and industrial area, respectively; $P_{\text{buy},r,t}^s$ is the purchased power; $P_{\text{cut},r,t}^s$ is the wind and photovoltaic power abandonment; $P_{\text{HN},r,t}^s$ is the power supplied for the water pump in the heat network; $P_{\text{PW},r,t,\text{max}}^s$, $P_{\text{PV},r,t,\text{max}}^s$, $P_{\text{PW},r,t}^s$, $P_{\text{PV},r,t}^s$, $P_{\text{PWH},r,t}^s$, and $P_{\text{PVH},r,t}^s$ are the available power, grid-connected power, and heat supply power of wind and photovoltaic power, respectively; φ_t is the unit price of the power purchase; c_{HN} is the operating cost coefficient of the water pump in the heat network; and a and χ are the corresponding coefficients.

4.3. Constraints of Optimal Dispatching of Integrated Electricity and Heating System with Multiple Functional Areas Considering Heat Network Flow Regulation

4.3.1. Electricity Constraints of Integrated Electricity and Heating System with Multiple Functional Areas

Intermittent regulation refers to the regulation mode that only the hours of daily heat supply decrease while the quantity of network circulation of water and water supply temperature keep constant when the outdoor temperature rises.

A. Constraints of wind and photovoltaic power

$$P_{\text{PV},r,t}^s \geq 0 \quad (21)$$

$$P_{\text{PW},r,t}^s \geq 0 \quad (22)$$

$$P_{\text{PWH},r,t}^s \geq 0 \quad (23)$$

$$P_{\text{PVH},r,t}^s \geq 0 \quad (24)$$

$$0 \leq P_{\text{PV},r,t}^s + P_{\text{PVH},r,t}^s \leq P_{\text{PV},r,t,\text{max}}^s \quad (25)$$

$$0 \leq P_{\text{PW},r,t}^s + P_{\text{PWH},r,t}^s \leq P_{\text{PW},r,t,\text{max}}^s \quad (26)$$

B. Power purchase constraint

As shown in Equation (24), the power purchase constraint means that all functional areas are only allowed to purchase electricity, but not to sell electricity.

$$P_{\text{buy},r,t}^s \geq 0 \quad (27)$$

C. Tie line constraint

$$-P_{\text{tie},l,t}^{\text{max}} \leq P_{\text{tie},l,t}^s \leq P_{\text{tie},l,t}^{\text{max}} \quad (28)$$

where $P_{tie,l,t}^s$ is the transmission power of tie line l ; $P_{tie,l,t}^{max}$ is the transmission capacity of tie line l ; $P_{tie,l,t}^s > 0$ means that the tie line l inputs power to the area at time t ; and $P_{tie,l,t}^s < 0$ means that the tie line l outputs power to the area at time t .

D. Power balance constraint

$$P_{CHP,r,t}^s + P_{buy,r,t}^s + P_{PV,r,t}^s + P_{PW,r,t}^s + P_{PWH,r,t}^s + P_{PVH,r,t}^s + P_{tie,l,t}^s = P_{L,r,t}^s + P_{EB,r,t}^s + P_{HN,r,t}^s \quad (29)$$

where $P_{L,r,t}^s$, $P_{EB,r,t}^s$ and $P_{HN,r,t}^s$ are the electric load of users, EB, and water pumps in the heat network of area r at dispatching time t in scenario s , respectively.

4.3.2. Thermal Constraints of Integrated Electricity and Heating System with Multiple Functional Areas

A. Heat source constraint

$$H_{CHP,r,t}^s + H_{EB,r,t}^s = c_w m_{1,r,t} (T_{sup,1,r,t} - T_{ret,1,r,t}) \quad (30)$$

where $H_{CHP,r,t}^s$ and $H_{EB,r,t}^s$ are the heat supply power of CHP and EB of area r at dispatching time t in scenario s , respectively.

B. Heat load constraint

The user's perception of temperature comfort is fuzzy to some extent. For example, according to the "Design Code for Heating, Ventilation and Air Conditioning" of China, the predicted mean vote (PMV) index of thermal sensation should be in the optimal range of ± 1 , that is, slightly cold and slightly hot are allowed.

$$\lambda_{PMV} = (0.303e^{-0.036M} + 0.028) \{ M - W - 3.05 \times 10^{-3} \\ \times [5733 - 6.99(M - W) - P_a] - 0.42[(M - W) - 58.15] \\ - 1.7 \times 10^{-5} M(5867 - P_a) - 0.0014M(34 - t_a) \\ - 3.96 \times 10^{-8} f_{cl} [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} h_c (t_{cl} - t_a) \} \quad (31)$$

where M is the energy metabolic rate of the human body; W is the mechanical power of the human body; f_{cl} is the human body ratio of the area covered by clothing to the area exposed to the air; h_c is the heat transfer coefficient of the human body surface; P_a is the water vapor pressure of the environment around the human body; and t_a , t_r , and t_{cl} are the ambient temperature around the human body, the average radiation temperature, and the outer surface temperature of the clothing, respectively. The ambient temperature around the human body corresponds to the indoor temperature of heated buildings, namely, $t_a = T_n$. This paper mainly focuses on the heat supply, and the indoor temperature is the most important feeling of the human body to the heating comfort, so it is assumed that in this formula, except for the ambient temperature of the human body, other parameters are given values.

$$-\sigma_{r,t}^s \leq \lambda_{PMV,r,t}^s \leq +\sigma_{r,t}^s \quad (32)$$

where $\lambda_{PMV,r,t}^s$ and $\sigma_{r,t}^s$ are the index and the limit of PMV of area r at dispatching time t , respectively.

The indoor temperature of a heated building in a certain period of time is the result of the combined action of the heat supply of the heating network in the past several periods. Therefore, the indoor temperature of a heated building $T_{n,r,t}$ and the water return temperature $T_{ret,r,t}$ of area r at dispatching time t are expressed as Equations (33) and (34), respectively.

$$T_{n,r,t} = \theta_1 T_{n,r,t-1} + \phi_1 T_{sup,r,t-1} + \omega_1 T_{a,r,t-1} \quad (33)$$

$$T_{ret,r,t} = \sum_{j=1}^J \alpha_j T_{n,r,t-j} + \sum_{j=0}^J \beta_j T_{sup,r,t-j} + \sum_{j=0}^J \gamma_j T_{a,r,t-j} \quad (34)$$

where J represents the thermal inertia of the heat network and $J = 0$ means the system is thermal inertia free; the coefficients θ_1 , ϕ_1 , ω_1 , α_j , β_j , and γ_j are the physical parameters of the thermal inertia of the heating system, which can be obtained from the measured data; and $T_{a,r,t}$ is the outdoor temperature of the heated building of area r at dispatching time t .

The thermal load of the i th node $H_{i,r,t}^s$ and total thermal load $H_{L,r,t}^s$ of area r at dispatching time t in scenario s are shown as Equations (35) and (36), respectively.

$$H_{i,r,t}^s = c_w m_{i,r,t} (T_{\text{sup},i,r,t} - T_{\text{ret},i,r,t}) \quad (35)$$

$$H_{L,r,t}^s = \sum_{i=2}^N H_{i,r,t}^s \quad (36)$$

C. Heat network constraints

The constraints of the heat network are shown in Equations (1)–(16).

D. Power balance constraint of thermal power

$$H_{\text{CHP},r,t}^s + H_{\text{EB},r,t}^s = H_{L,r,t}^s + \Delta H_{L,r,t}^s \quad (37)$$

where $\Delta H_{L,r,t}^s$ represents the thermal loss of area r at dispatching time t in scenario s .

4.3.3. Thermoelectric Coupling Constraints of Integrated Electricity and Heating System with Multiple Functional Areas

A. Constraints of CHP

CHP can be in multiple working states, and in general, the constant heat to power ratio mode is common. Thus, CHP is assumed to operate in this mode and the corresponding model is as follows.

$$P_{\text{CHP},r,t}^s = H_{\text{CHP},r,t}^s / k_{\text{HP},r} \quad (38)$$

$$P_{\text{CHP},r,\min} \leq P_{\text{CHP},r,t}^s \leq P_{\text{CHP},r,\max} \quad (39)$$

$$-U_{r,\max} \cdot \Delta t \leq P_{\text{CHP},r,t+1}^s - P_{\text{CHP},r,t}^s \leq U_{r,\max} \cdot \Delta t \quad (40)$$

where $k_{\text{HP},r}$, $P_{\text{CHP},r,\max}$, $P_{\text{CHP},r,\min}$, and $U_{r,\max}$ are the thermoelectric ratio, the lower limit of electric output, the upper limit of electric output, and maximum unit regulated power of CHP of area r , respectively.

B. Constraints of EB

$$P_{\text{EB},r,t}^s = P_{\text{PWH},r,t}^s + P_{\text{PVH},r,t}^s \quad (41)$$

$$H_{\text{EB},r,t}^s = \eta_{\text{EB},r} P_{\text{EB},r,t}^s \quad (42)$$

$$0 \leq H_{\text{EB},r,t}^s \leq H_{\text{EB},r,\max} \quad (43)$$

where $P_{\text{EB},r,t}^s$ and $H_{\text{EB},r,t}^s$ are the electric power consumed and thermal power output of the EB of area r at dispatching time t in scenario s , respectively; and $\eta_{\text{EB},r}$ and $H_{\text{EB},r,\max}$ are the electrothermal conversion efficiency and the upper limit of thermal output of the EB of area r , respectively.

The proposed dispatching model of the integrated electricity and heating system with multiple functional areas considering the flow regulation of the heat network is established using the programming software YALMIP R20190425 in MATLAB 2019b, and is then solved by the commercial optimization solver Gurobi 9.1.0. The process of the optimization algorithm is shown in Figure 5.

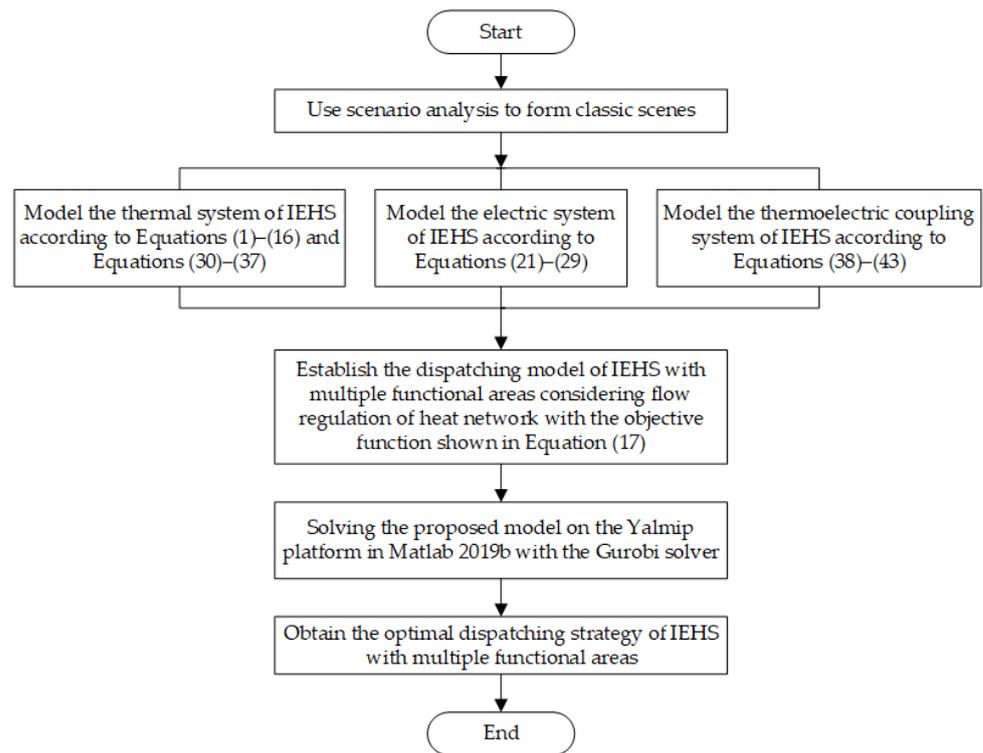


Figure 5. The process of the optimization algorithm.

5. Results and Discussion

A revised integrated electricity and heating energy system with multiple functional areas in a certain area of China is taken as an example and is used to verify the effectiveness of the proposed model. As shown in Figure 6, the residential area is connected with the commercial area, the office area, and the industrial area by tie lines. It is assumed that the power flowing into the residential area is positive, and each functional area is equipped with renewable energy sources (RES) (WT and PV), CHP, and EB. The parameters of power configuration of each functional area and the parameters of CHP in different functional areas are shown in Tables 1 and 2, respectively. The data of Tables 1 and 2 result from an actual IEHS in a certain area of China [13].

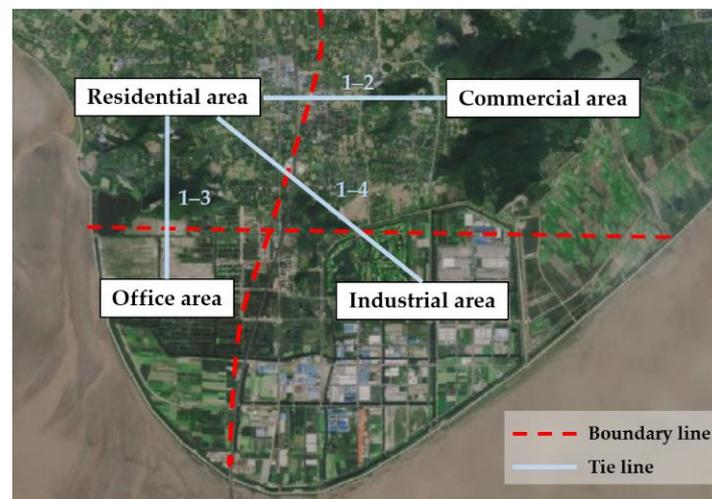


Figure 6. The integrated electricity and heating system in a certain region in China.

Table 1. Power configuration of each functional area.

| Power Source/(MW) | Residential Area | Commercial Area | Office Area | Industrial Area |
|-------------------|------------------|-----------------|-------------|-----------------|
| CHP | 15 | 14 | 14 | 35 |
| WT | 15 | 0 | 0 | 50 |
| PV | 45 | 30 | 30 | 100 |

Table 2. The parameters of CHP in different functional areas.

| Functional Area | Maximum Generating Power/(MW) | Minimum Generating Power/(MW) | Ramp Rate/(MW) |
|------------------|-------------------------------|-------------------------------|----------------|
| Residential Area | 15 | 3 | 4.5 |
| Commercial Area | 14 | 2.4 | 3.6 |
| Office Area | 14 | 2.4 | 3.6 |
| Industrial Area | 35 | 7 | 10.5 |

5.1. Dispatching of Integrated Electricity and Heating System with Multiple Functional Areas Considering Regulation of Heat Network Flow

On the basis of the supplement of dispatching strategy considering heat network flow regulation in each functional area, a more comprehensive understanding of the effect of joint scheduling in multiple functional areas can be formed through the comparison of the results of independent dispatching in each functional area and joint dispatching in multiple functional areas.

5.1.1. Independent Dispatching of Integrated Electricity and Heating System with Multiple Functional Areas Considering Regulation of Heat Network Flow

Firstly, the situation of independent dispatching when there is no tie line between the functional areas is analyzed. The operation states of the residential area, commercial area, office area, and industrial area are also analyzed, respectively.

The independent dispatching of the residential area is shown in Figure 7. In terms of electric power, the electricity purchase occurs from 19:00 to 24:00. The residents return from work/study areas to residential areas after sunset, which results in an increase in load in residential areas. Meanwhile, the renewable energy in residential areas is mainly photovoltaic, and there is no output after sunset. Thus, it is necessary to purchase electricity to satisfy the power demand of users during this period. Photovoltaic abandonment is mainly concentrated during 11:00–16:00, which results from the condition that the residents are mostly in work/study areas during this period, and the load of the residential area is low and the photovoltaic output is higher. In terms of thermal power, there is photovoltaic output from 6:00 to 17:00. In order to absorb more renewable energy and reduce the operation cost of the system, the EB supplied by wind and solar energy has more output at this stage, the total thermal output of the system is higher than the thermal load, and the excess heat energy is stored in the heat network. After 18:00, when the sun goes down, the renewable energy in the residential area remains as only a little wind power and the load in the residential area increases. Thus, the CHP has more output at this stage, and the heat energy stored in the heat network is gradually released.

The independent dispatching results of the commercial area are shown in Figure 8. When the commercial area is independently dispatched, wind or photovoltaic abandonment is eliminated. In terms of electric power, there is more power purchasing from 18:00 to 24:00. This is because there is no wind power in the commercial area, but there is photovoltaic power. The typical daylight hours in winter are from 6:00 to 17:00. Therefore, renewable energy supply is only available during this period, and for the other periods, power purchases are needed to meet the load demand. In terms of thermal power, from 18:00 to 5:00 of the next day, only CHP supplies heat, and in order to meet the higher load during the daytime, the output of CHP at this period exceeds the heat load demand. The excess energy can be further stored in the heating network to obtain the lowest system operating cost of the entire dispatching time.

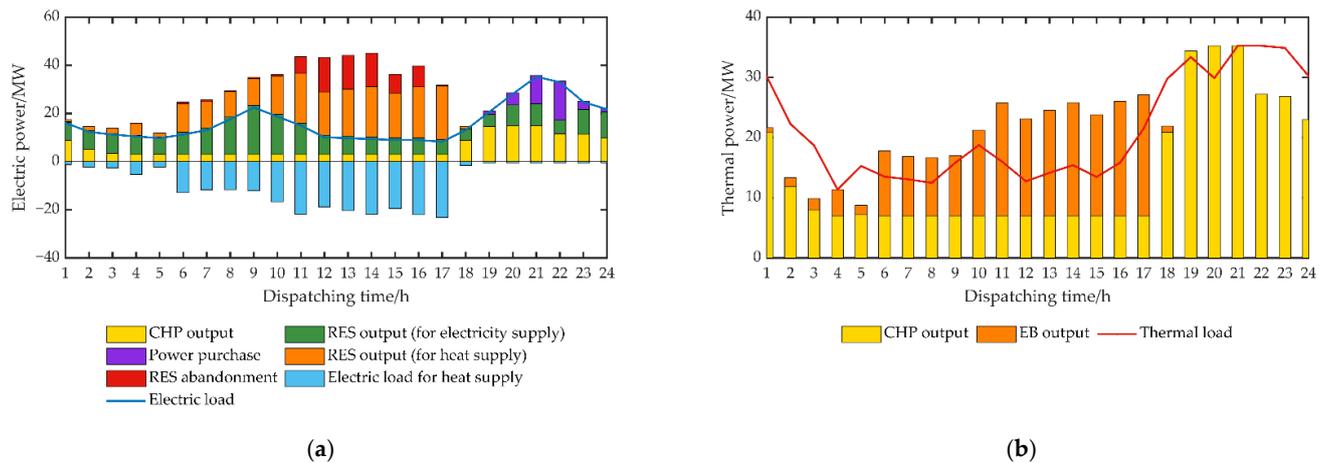


Figure 7. Independent dispatching in the residential area: (a) Electric power; (b) Thermal power.

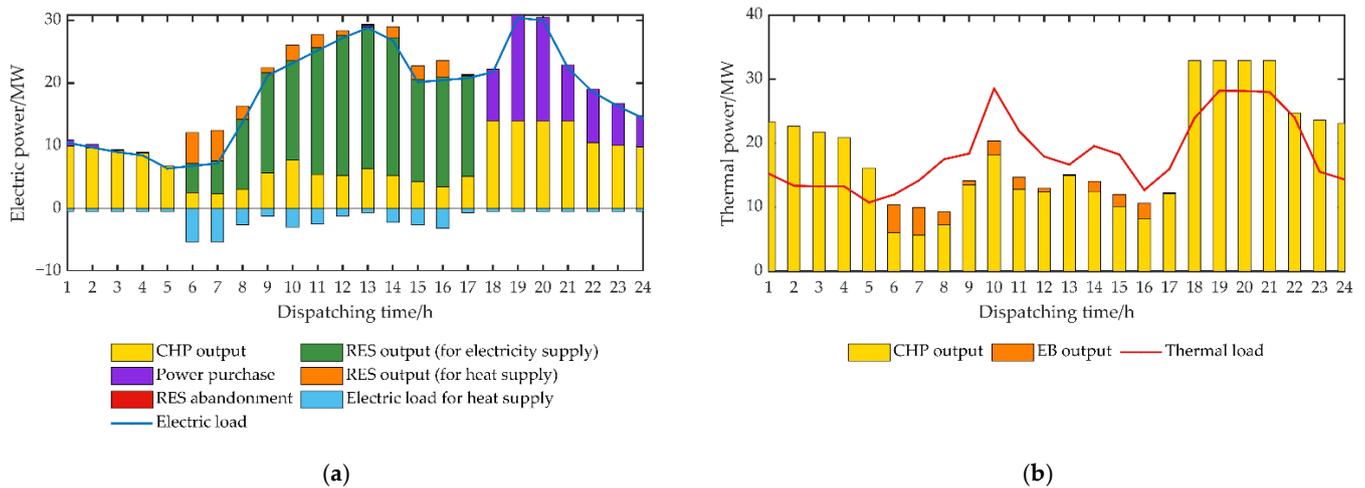


Figure 8. Independent dispatching in the commercial area: (a) Electric power; (b) Thermal power.

The independent dispatching of the office area is shown in Figure 9. Similar to the commercial area, there is only photovoltaic power but no wind power in the office area. Renewable power also cannot supply electricity at night, so there is also more purchased power at night. Different from the commercial area, the load of the office area is mainly concentrated in the 8:00–18:00 working hours, and there is only a certain basic load remaining after work. During 6:00–7:00, when the sun comes out, the photovoltaic power begins to work. At this time, only part of the staff goes to work and the load is small, so wind and photovoltaic power are abandoned. In terms of thermal power, due to the small capacity of renewable power in the office area, the output of renewable energy is preferentially used for power supply, so all the thermal load of the office area is supplied by CHP. Meanwhile, the energy storage effect of the heat network is also utilized to realize the heat transfer in the time scale.

The independent dispatching of the industrial area is shown in Figure 10. Because the industrial area has two kinds of renewable energy, wind power and photovoltaic power, and the power supply is sufficient, the independent dispatching of the industrial area can be self-sufficient in most cases, and only a very small amount of purchased power is needed from 18:00 to 19:00. Compared with the nighttime with only wind power output, the time from 6:00 to 7:00 when the photovoltaic output increases and the load does not increase before working hours will have a small amount of RES abandonment. In terms of thermal power, the output of EB and CHP in the industrial area is relatively uniform.

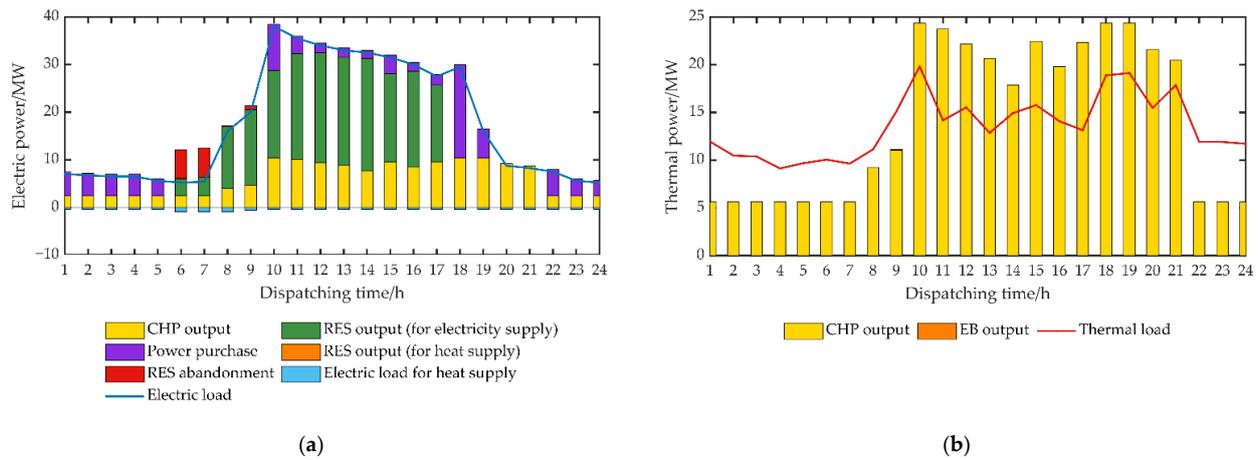


Figure 9. Independent dispatching in the office area: (a) Electric power; (b) Thermal power.

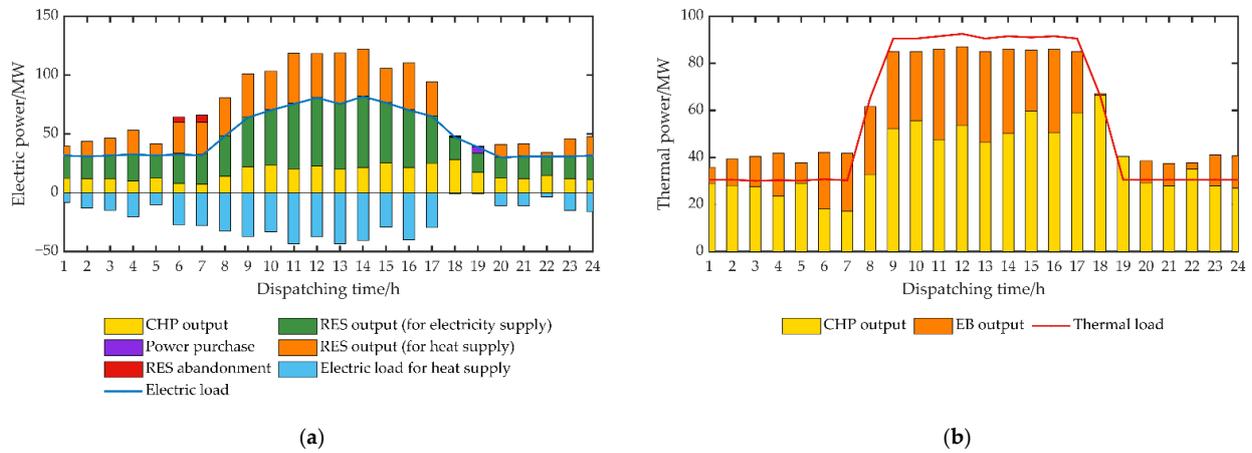


Figure 10. Independent dispatching in the industrial area: (a) Electric power; (b) Thermal power.

The operation cost, purchased electricity, and RES abandonment of each functional area under independent dispatching are shown in Table 3. Taking residential areas as an example, it can be seen that the operation cost, purchased electricity, and RES abandonment under the quality regulation mode considering flow change in multiple stages are CNY 696, 1.82 MWh, and 1.7 MWh lower than that under the quality regulation mode with constant flow, respectively. The same is true for other functional areas. Therefore, compared with the quality regulation mode with constant flow, the quality regulation mode considering flow change in multiple stages can significantly reduce the purchased electricity and RES abandonment of each functional area of IEHS, and the operation cost also decreased obviously.

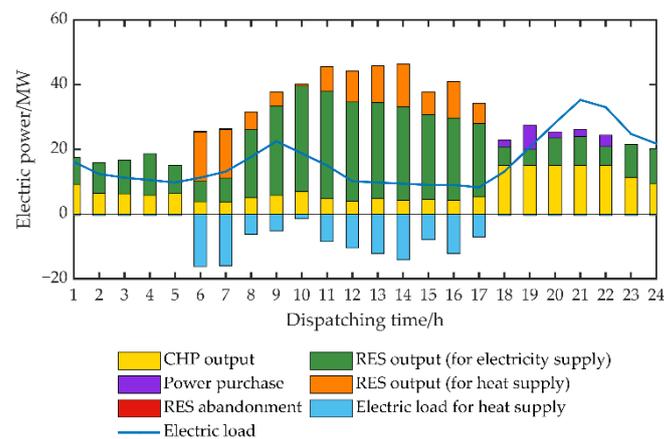
Table 3. System operation cost, purchased electricity, and RES abandonment of each functional area under independent dispatching.

| Functional Area | Flow | Operation Cost/(CNY) | Purchased Electricity/(MWh) | RES Abandonment/(MWh) |
|------------------|----------|----------------------|-----------------------------|-----------------------|
| Residential Area | Constant | 53,783 | 41.57 | 71.12 |
| | Variable | 53,087 | 39.75 | 69.42 |
| Commercial Area | Constant | 66,233 | 77.05 | 0.00 |
| | Variable | 65,251 | 72.82 | 0.00 |
| Office Area | Constant | 69,726 | 93.12 | 13.62 |
| | Variable | 67,618 | 87.63 | 13.26 |
| Industrial Area | Constant | 46,492 | 6.39 | 10.70 |
| | Variable | 46,238 | 6.11 | 10.50 |

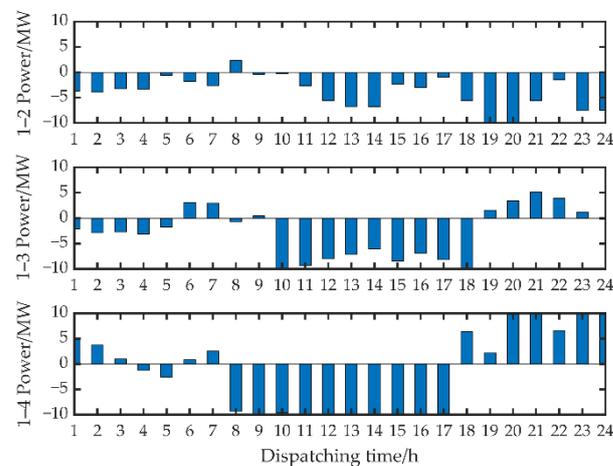
5.1.2. Joint Dispatching of Integrated Electricity and Heating System with Multiple Functional Areas Considering Regulation of Heat Network Flow

The multiple functional areas have the characteristics of load complementarity. The commercial area, office area, and industrial area are connected with the residential area, respectively, through the tie line. The thermal power of each functional area is balanced locally, and the electric power transmission is complementary.

The joint dispatching of residential areas is shown in Figure 11. The difference between the total output of the power supply and the electric load is equal to the sum of the power of tie lines. In the condition of joint dispatching, the daytime output of residential areas is far greater than the load, which can be transmitted to other functional areas through tie lines to realize the complete consumption of renewable energy. Office and industrial areas provide electricity to residential areas from 6:00 to 7:00, when the residential areas transmit the received electricity together with the surplus renewable energy to the business area through the tie line, so as to achieve the complete consumption of renewable energy. The residential area transmits power to the other three functional areas from 9:00 to 17:00. After 18:00, the load of the residential area increases, but the sun has set at this time, which leads to the loss of the photovoltaic output in the residential area. In order to meet the load demand, the difference between load and power output can only be supplied by other functional areas or the power purchased from the grid. Compared with independent dispatching, the power purchased from the outside grid of the residential area under joint dispatching is significantly reduced.



(a)



(b)

Figure 11. Dispatching strategy of the residential area under joint dispatching: (a) Electric power of the residential area; (b) Electric power of the tie lines.

The joint dispatching of the commercial area is shown in Figure 12. In the condition of joint dispatching, most of the electric loads in the commercial area are supplied by the electric energy transmitted from other functional areas during the period without photovoltaic power, the purchased electricity is only needed from 18:00 to 22:00, and the quantity of purchased electricity is significantly reduced compared with that of independent dispatching.

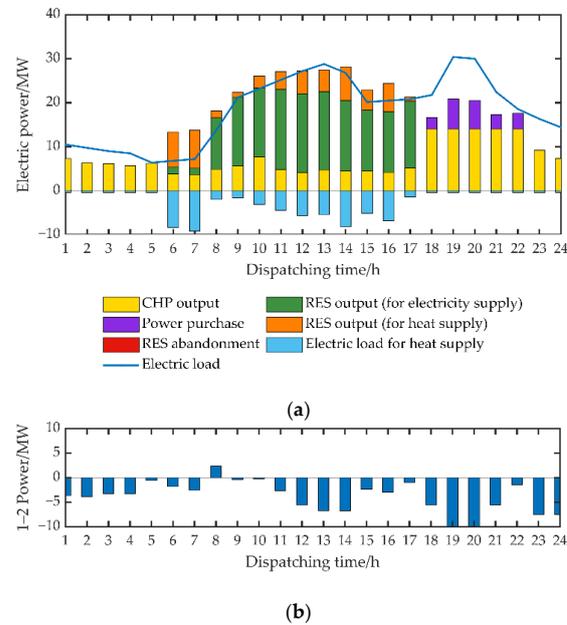


Figure 12. Dispatching strategy of the commercial area under joint dispatching: (a) Electric power of the commercial area; (b) Electric power of the tie line.

The joint dispatching of the office area is shown in Figure 13, which is similar to that of the commercial area. Under joint dispatching, the amount of purchased electricity in the office area is significantly reduced compared with that under independent dispatching, and there is only a small amount of purchased electricity from 18:00 to 22:00.

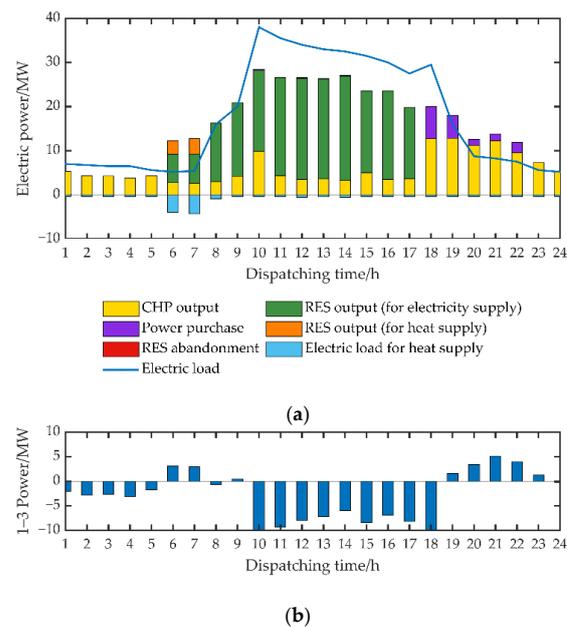


Figure 13. Dispatching strategy of the office area under joint dispatching: (a) Electric power of the office area; (b) Electric power of the tie line.

The joint dispatching of the industrial area is shown in Figure 14. In the condition of joint dispatching, the RES abandonment and the amount of purchased electricity are significantly reduced. The power output is smaller than the power load as a result of receiving the electricity transmitted from the residential area from 8:00–17:00.

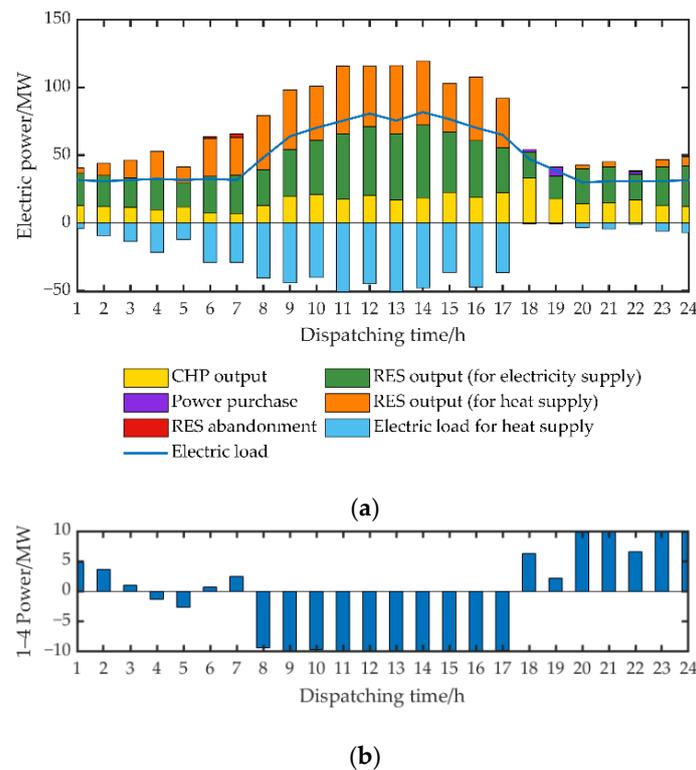


Figure 14. Dispatching strategy of the industrial area under joint dispatching: (a) Electric power of the industrial area; (b) Electric power of the tie line.

The operation cost, purchased electricity, and RES abandonment of each functional area under different dispatching modes are shown in Table 4. It can be seen that compared with the independent dispatching of each functional area, the joint dispatching of multiple functional areas can utilize the load supplementary characteristics of different functional areas, significantly reduce the purchased electricity and RES abandonment, and reduce the operation cost of the system. For example, when the flow of the heat network is constant, the operation cost, purchased electricity, and RES abandonment under joint dispatching are CNY 55,854, 145.11 MWh, and 90.9 MWh lower than that under independent dispatching, respectively. When the IEHS is under joint dispatching, the quality regulation mode considering flow change in multiple stages can reduce the operation cost, purchased electricity, and RES abandonment by CNY 2390, 4.78 MWh, and 0.09 MWh, respectively, compared with the quality regulation mode with constant flow.

Table 4. System operation cost, purchased electricity, and RES abandonment under different dispatching modes.

| Dispatching Mode | Flow | Operation Cost/(CNY) | Purchased Electricity/(MWh) | RES Abandonment/(MWh) |
|-------------------------|----------|----------------------|-----------------------------|-----------------------|
| Independent Dispatching | Constant | 236,234 | 218.13 | 95.44 |
| | Variable | 232,194 | 206.33 | 93.18 |
| Joint Dispatching | Constant | 180,380 | 73.02 | 4.54 |
| | Variable | 177,990 | 68.24 | 4.45 |

5.2. Influence of Heat Network Model Considering Refined Resistance and Dynamic Characteristics on Integrated Electricity and Heating System

Taking the industrial area as an example, through the comparison between the hydraulic model considering the refined resistance and the ordinary hydraulic model, and the comparison between the static heat network model and the dynamic heat network model, the influence of the heat network model considering refined resistance and dynamic characteristics on IEHS is analyzed.

5.2.1. Influence of Hydraulic Power Model Considering Refined Resistance on Pipeline Flow

As shown in Figure 15, the pipeline flow of the refined model is smaller than that of the ordinary model, and the changing trend is consistent. This is because the refined model considers more detailed pipeline friction loss than the ordinary model, and the pressure loss becomes larger, which leads to the total loop flow of the network in the refined hydraulic model scenario being smaller than that of the ordinary hydraulic model scenario.

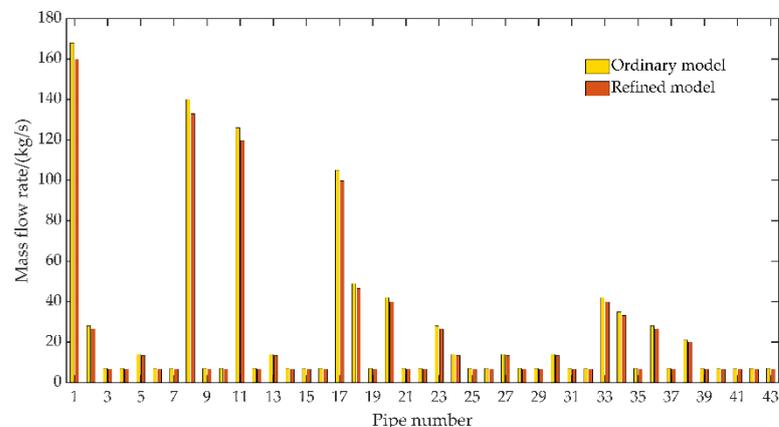


Figure 15. Mass flow rate of water under different models.

5.2.2. Influence of Thermodynamic Model Considering Dynamic Characteristics of Heat Network on Heat Supply

As shown in Figure 16, the heating power of the two modeling methods is larger than the thermal load, which is due to the transmission loss of the heating network. Compared with static modeling, there is no need to keep the heating power and heat load equal at all times in the dynamic modeling of the heat network. This is because the consideration of the dynamic characteristics of the heat network can give full play to the heat storage characteristics of the heat network, which has the peak shaving and valley filling effect. Correspondingly, the flexibility of the system is improved and the operation cost of the system is reduced.

5.3. Influence of Heat Network Operation Mode Considering Flow Regulation on the Dispatching of Integrated Electricity and Heating System

The key of quality regulation considering flow change in multiple stages is to determine the method of stage division and the amount of flow in each stage. The analysis of the influence of flow regulation on the system operation cost is helpful to formulate the optimal quality regulation operation strategy considering flow change in multiple stages. On this basis, through the impact analysis of flow regulation on purchased electricity and RES abandonment, a more comprehensive understanding of the flow regulation mechanism can be summarized.

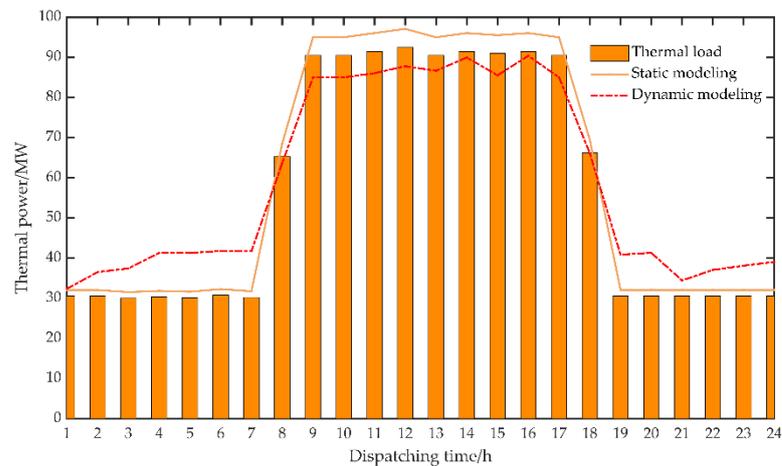


Figure 16. Thermal power under different models.

5.3.1. Influence of Heat Network Operation Mode Considering Flow Regulation on Operation Cost

Let the ratio of the system flow and the maximum design flow be γ , and for the guarantee of the safe operation of the system, the value range of γ is 0.5~1.0. Taking the residential area as an example, the flow in the heat network with quality regulation ($\gamma = 0.8$) is adopted as the benchmark to study the impact of flow changes on the system operation cost. As shown in Figure 17, the system operation cost is related to the dispatching time under different flow. In order to minimize the total operation cost of IEHS, the system should be dispatched by stages along the envelope line with the lowest operation cost. Because the traffic should not be adjusted frequently, the system flow can be dispatched in two stages: 6:00–17:00, $\gamma = 0.50$; 18: 00–5:00 of the next day, $\gamma = 1.00$.

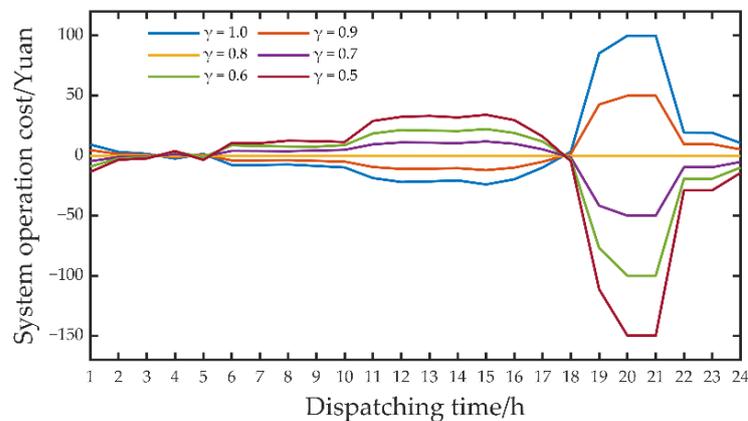


Figure 17. System operation cost under different mass flow rates.

5.3.2. Influence of Heat Network Operation Mode Considering Flow Regulation on Power Purchase

The flow in the heat network with quality regulation ($\gamma = 0.8$) is adopted as the benchmark to study the impact of flow changes on the power purchase. As shown in Figure 18, with the decrease in flow, the power purchased from the outside grid gradually decreases, which results from the phenomenon that the electric power required by the water pump in the heat network decreases with the decrease in the flow, and the overall electric load of the system decreases. Thus, the purchased electric power will decrease with the decrease in flow.

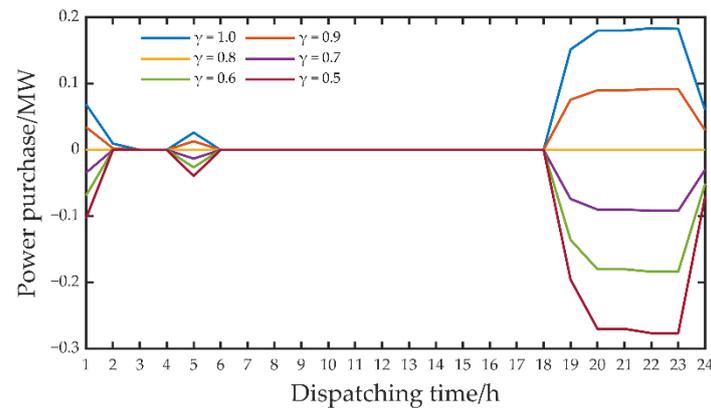


Figure 18. Power purchase under different mass flow rates.

5.3.3. Influence of Heat Network Operation Mode Considering Flow Regulation on Power of RES Abandonment

The flow in the heat network with quality regulation ($\gamma = 0.8$) is adopted as the benchmark to study the impact of flow changes on the power of RES abandonment. As shown in Figure 19, with the decrease in flow, the power of RES abandonment increases, which results from the fact that heat supply is the effective outlet of the wind and photovoltaic output of the system. With the decrease in the flow, the electric power required by the heat network water pump decreases. Thus, the power of RES abandonment will increase with the decrease in flow.

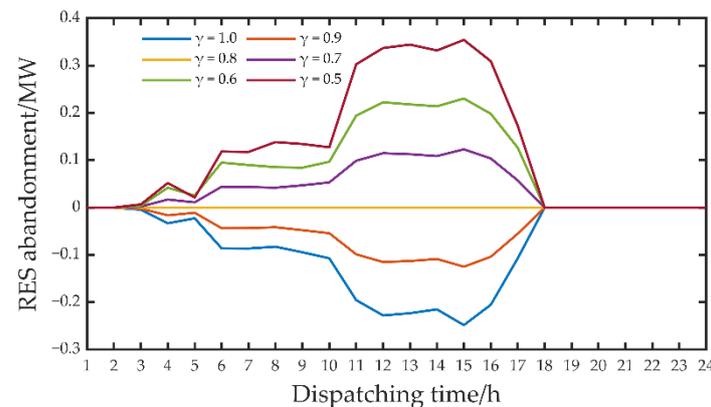


Figure 19. RES abandonment under different mass flow rates.

6. Conclusions

In this paper, the functional areas of IEHS are classified and the load characteristics are analyzed, and the heat network model considering the refined resistance and dynamic characteristics is constructed. On the basis of considering the operation and regulation mode of the heat network, the dispatching method of IEHS with multiple functional areas considering the flow regulation of the heat network is proposed. The main conclusions obtained by the case study are described below.

- (1) The dispatching of IEHS can be effectively optimized by making use of the load complementary difference characteristics between different functional areas. The lower the operation cost, the less electricity will be purchased and the more consumption of renewable energy can be achieved in the joint dispatching of IEHS when compared with the independent dispatching of each functional area.
- (2) The operation regulation mode of the heat network has a great influence on the dispatching of IEHS. Compared with quality regulation, quality regulation considering flow change in multiple stages divides the operation of the heat network into different

stages according to the characteristics of each functional area, which can effectively reduce purchased electricity, RES abandonment, and the operation cost of IEHS.

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