

Article

Cluster Optimization of an Integrated Energy System for a Park Based on Demand Response

Hongwei Yue ^{1,*}, Hongkai Yuan ², Kaikai Man ², Zhuo Zuo ¹ and Peng Sun ³

¹ School of Automotive Engineering, Shandong Jiaotong University, Jinan 250357, China

² Binzhou Power Supply Company, State Grid Shandong Electric Power Company, Binzhou 256603, China; bzj0543@163.com (H.Y.); yuanhkai@163.com (K.M.)

³ Key Laboratory of Modern Power System Simulation and Control & Renewable Energy Technology, Northeast Electric Power University, Jilin 132012, China

* Correspondence: 202067@sdjtu.edu.cn

Abstract

To address the issues of insufficient operational flexibility and low energy coordination efficiency of the integrated energy system in the park under the integration of large-scale distributed renewable energy, it is essential to carry out research on multi-energy complementary cluster division and optimal operation to improve regional energy utilization efficiency. Focusing on the multi-energy coupling system of electric heating and gas in the park, this paper proposes a method of electric heating and gas collaborative cluster division that considers the demand response potential. First, the multi-energy coupling topology model of the integrated energy system in the park is constructed, and the demand response potential index of each sub-region is quantitatively evaluated. A modularity evaluation function integrating multi-energy coupling characteristics is proposed. Based on the improved Louvain algorithm, the dynamic cluster division of the electric heating and gas system in the park is realized. On this basis, a cluster-level optimization operation model considering demand response resource integration is established, and optimal scheduling is carried out with the goal of minimizing operating costs. Finally, an industrial park in Northeast China is used as an actual case for verification. The results show that the proposed cluster division method can divide the park into four electricity, heating, and gas integrated energy clusters with clear characteristics and close coupling. After the integration of demand response resources, the overall operating cost of the system is reduced and the new energy consumption rate is increased. This verifies the effectiveness and superiority of the proposed method and provides technical support for the optimal operation of the integrated energy system in the park.

Keywords: integrated energy system for parks; demand response; cluster partition; Louvain algorithm; electric heating gas multi-energy coupling



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1. Introduction

As the core carrier of energy consumption and distributed energy access, park-level integrated energy systems have been promoted and constructed on a large scale in recent years. Through the coupling conversion and coordinated scheduling of electricity, heat, gas, and cold energy, such systems can effectively give full play to the advantages of multi-energy complementarity and improve the consumption capacity of renewable energy. However, with the continuous expansion of the park scale and the increasingly complex energy coupling relationship, the centralized optimal scheduling model faces problems

such as high computational pressure, difficulties in protecting information privacy, and insufficient adjustment flexibility, making it difficult to meet the efficient operation requirements of large-scale park integrated energy systems. On the one hand, the original large-scale optimization problem is broken down into multiple small-scale sub-problems through cluster division, which can significantly reduce the computational complexity and improve the efficiency of the optimization process. On the other hand, the integration of regions with similar load characteristics and complementary resource conditions in the same cluster can better integrate the demand response resources in the region, give full play to the multi-energy complementarity and supply–demand synergy within the cluster, and improve the new energy consumption capacity and operation economy. Therefore, it is of great theoretical value and practical significance to study the cluster division method of integrated energy systems in multi-energy-coupled parks considering demand response potential [1,2].

Research on park integrated energy systems has been widely undertaken by scholars at home and abroad. Early research mainly focused on the planning and operation optimization of integrated energy systems of individual parks. In Reference [3], the aim was to present a fast and modular framework implementation for the thermal analyses of foreign metal objects in the context of wireless power transfer (WPT), to evaluate whether they pose a hazard to the system. In Reference [4], the energy storage configuration of the integrated energy system in the park is studied, and a bi-level optimal configuration model considering uncertainty is constructed to reduce the investment cost under the premise of ensuring the reliable operation of the system. Some scholars have introduced the carbon trading mechanism to construct a low-carbon optimal operation model for the low-carbon operation of the park's integrated energy system, and verified the promotion effect of the carbon trading mechanism on the system's emission reduction. With the development of distributed new energy, more and more research has begun to focus on the optimization of integrated energy clusters with multi-park interconnections. Multiple adjacent parks achieve resource complementarity through energy sharing, which can effectively improve the overall economy and reliability of the system. In the existing research, Reference [5] constructed a distributed optimal scheduling model of a multi-park integrated energy system, using the alternating direction multiplier method to realize multi-agent distributed optimization, which addressed the problem of information privacy protection. However, most of the existing research assume that each subject is completely rational, and the adjustment potential of demand-side resources in cluster collaborative optimization is less fully explored. The collaborative game mechanism for multi-stakeholders still needs to be further improved.

To address the division of integrated energy system clusters, scholars worldwide have carried out a series of related research studies. The existing research focuses primarily on two directions: power grid partition and multi-energy partition. Reference [6] mainly focuses on the partitioning of transmission and distribution networks, dividing the power grid cluster based on electrical distance, modularity, and other indicators, for the purpose of voltage control, power flow analysis, and other scenarios. With the development of integrated energy systems, an increasing amount of research has begun to pay attention to the cluster division of multi-energy coupling systems. In Reference [7], a partition method of regional integrated energy systems based on a clustering algorithm is proposed, and the partition scheme is obtained by clustering the load side and energy side data, respectively. References [8–11] proposed a cluster division method based on a complex network community discovery algorithm, using the Louvain algorithm to realize the cluster division of electric–thermal integrated energy systems and thereby verifying the superiority of community discovery algorithms in cluster division. However, most of the existing

research focuses on the electric–thermal two-energy coupling system. For park integrated energy systems with electric–thermal–gas multi-energy coupling, existing research has paid insufficient attention to the coupling characteristics of the three energy sources. At the same time, demand response potential is rarely included in the consideration index of cluster division, which makes it difficult for the divided cluster to fully integrate the demand-side adjustment resources and to give full play to the supporting role of demand response in system optimization.

In the cluster division method of integrated energy systems, all energy nodes in the park are taken as the vertices of the graph, and the comprehensive coupling weight between nodes is calculated based on the cluster division index of power, heat, and gas subsystems constructed above. To address the multi-energy coupling characteristics, the traditional Louvain algorithm is improved, and constraints such as multi-energy coupling strength and operation economy are introduced. Cluster division of the integrated energy systems is performed by maximizing the improved modularity. At the same time, considering the time-varying characteristics of load and new energy output in the park, a dynamic cluster division adjustment mechanism is designed. By calculating the information on the energy supply and demand and equipment operation status of each node, when the cluster division no longer meets the operation demand, the local or global cluster division adjustment is triggered to ensure that the microgrid cluster remains in an efficient, stable, and economical operation state at all times. Finally, the proposed indicators and methods are verified and analyzed through actual parks or simulation scenarios.

References [12–14] proposed a two-stage configuration and operation collaborative optimization model of shared hydrogen energy storage suitable for wind farm clusters. The significant increase in the proportion of renewable energy access has led to an increase in the demand for flexible resource scheduling in the power system. The existing demand-side response research mainly focuses on peak load control, while the demand response optimization to adapt to renewable energy fluctuations remains insufficient. To address this problem, Reference [15] initially examined the flexibility mechanism of demand-side resource provision, proposing a calculation method for the adjustable capacity of demand-side flexible resources.

Section 1 provides an introduction, which introduces the research status of the project at home and abroad. Section 2 aims to model the electrical and thermal coupling system of the integrated energy system in the park. Section 3 presents the cluster division method for integrated energy systems based on the coupling of electricity, heat, and gas, and establishes the index models for the cluster division of each power subsystem. The index model for the thermal subsystem cluster division is established, along with the index model for the gas subsystem cluster division. Section 4 presents a multi-energy system cluster division method based on the Louvain algorithm, and the integrated energy system cluster optimization process is obtained. Section 5 presents a simulation verification of the effectiveness of the proposed method. Section 6 sets out the conclusion, which summarizes the findings set out in this paper.

2. Electrical–Thermal Coupling Model of Integrated Energy System in Park

The integrated energy system of the park integrates distributed new energy power generation, energy conversion equipment, energy storage equipment, and various loads to achieve multi-energy complementarity and coordinated supply. The structure of the typical integrated energy system of the park is shown in Figure 1. The energy production side includes distributed new energy, such as wind power generation and photovoltaic power generation. The energy conversion side includes cogeneration units, gas boilers,

heat pumps, and other equipment. The energy storage side includes electric energy storage, thermal energy storage, and other equipment. The load side comprises electric and heat loads, including electric vehicles for charging. In this paper, the mathematical models of the main equipment used are established as follows [16]:

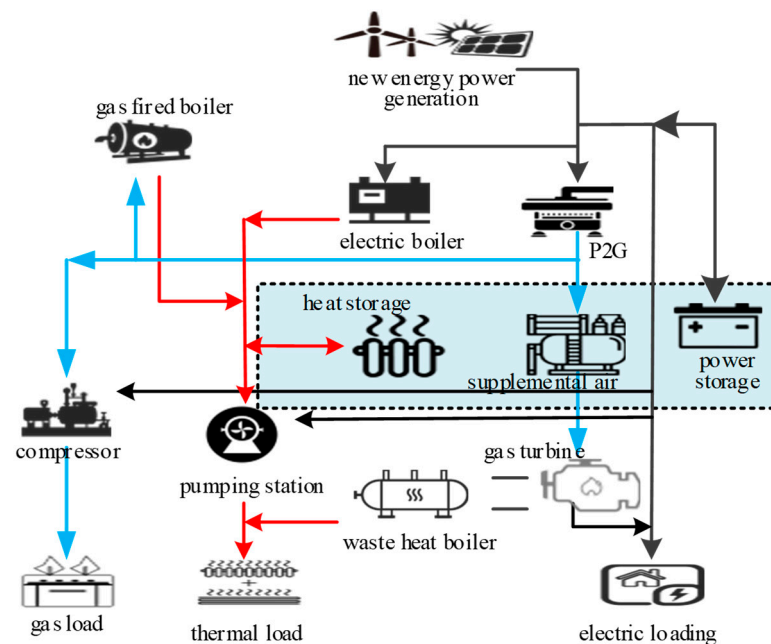


Figure 1. Typical park integrated energy system structure.

2.1. Steady-State Model of Integrated Energy System

In the multi-energy system, the control variable deviation equations for the nodes of the electricity, gas, and heat energy carriers constitute the steady-state model of the integrated energy system. The power flow calculation of the power system is consistent with the AC power flow calculation of the traditional system. The node power deviation equation can be written as:

$$\begin{aligned}\Delta P_i &= P_i^{GG} + P_i^{CHP} + P_i^{EG} - P_i^{ED} - P_i^{GC} - P_i^{HP} - P_i^{EB} - V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\ \Delta Q_i &= Q_i^{EG} + Q_i^{SH} - Q_i^{ED} - V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})\end{aligned}\quad (1)$$

In the formula, the meaning of each variable is shown in Table 1. G_{ij} and B_{ij} are the real and imaginary parts of the admittance matrix. P_i^{EG} and Q_i^{EG} are used to inject power into the generator. P_i^{ED} and Q_i^{ED} are the power consumption of the power load at the bus i . P_i^{GG} and P_i^{CHP} are the active power injected into bus i by the bgas generator and CHP unit, respectively. P_i^{GC} , P_i^{HP} and P_i^{EB} are the active power consumed by the electric compressor, heat network circulating pump, and electric boiler, respectively. Q_i^{SH} is the reactive power injected into the reactive power compensator.

Table 1. The results of the multi-energy cluster division index under different weights.

Parameter	Scheme 1	Scheme 2
Modularity index of power subsystem ρ^E	0.6124	0.4237
Modularity index of thermal subsystem ρ^H	0.623	0.384
Modularity index of gas subsystem ρ^G	0.5214	0.8123
Power subsystem modularity index weight coefficient v_ρ^E	0.5	0.5

Table 1. Cont.

Parameter	Scheme 1	Scheme 2
Power subsystem supply and demand balance index weight coefficient v_{φ}^E	0.3	0.3
Power subsystem adjustment ability index weight coefficient v_{γ}^E	0.2	0.2
Weight coefficient of thermal subsystem modularity index v_{ρ}^H	0.2	0.2
Weight coefficient of supply and demand balance index of thermal subsystem v_{φ}^H	0.1	0.1
The weight coefficient of the adjustment ability index of the thermal subsystem v_{γ}^H	0.2	0.2
Weight coefficient of gas subsystem modularity index v_{ρ}^G	0.3	0.3
Weight coefficient of supply and demand balance index of gas subsystem v_{φ}^G	0.2	0.2
Weight coefficient of electrothermal coupling index v_{ε}^{EH}	0	0.3
Electrothermal coupling index ε^{EH}	0.6244	0.7412
Weight coefficient of electrical coupling index v_{ε}^{EG}	0.2	0.2
Electrical coupling index ε^{EG}	0.5147	0.6914
Weight coefficient of gas–heat coupling index v_{ε}^{HG}	0.3	0.6
Gas–heat coupling index ε^{HG}	0.5241	0.6941
Number of clusters	5	4

2.2. Steady-State Model of Natural Gas System

Assuming that there is no height difference between the two ends of the natural gas pipeline and the gas flows isothermally, the node flow deviation equation is

$$\Delta f_i = f_i^{GS} - f_i^{GD} - f_i^{GG} - f_i^{CHP} - f_i^{GB} - f_i^{GC} - \sum_{j \in i} C_{ij}^{Gp} \text{sign}_{ij} \sqrt{\text{sign}_{ij} (\Pi_i^2 - \Pi_j^2)} \quad (2)$$

In the formula, f_i^{GS} and f_i^{GD} are the flow rate required for gas source injection and load at node i , respectively. f_i^{GG} , f_i^{CHP} and f_i^{GB} are the natural gas flow consumed by gas generators, CHP units and gas boilers. C_{ij}^{Gp} is a natural gas pipeline constant. The sign_{ij} represents the flow direction of natural gas in the pipeline. When the pressure of node i is greater than node j , the sign_{ij} is 1, and vice versa is -1 .

2.3. Steady-State Model of Thermal System

The energy transmission of the thermal system is mainly in the form of hot water or steam, from the heat source to the consumer. Therefore, while satisfying Kirchhoff's law, the thermal network also includes a temperature solution model:

$$T_{\text{exd}} = (T_{\text{start}} - T_a) e^{\frac{-\lambda L}{C_{j,m}}} + T_a \quad (3)$$

$$(\sum \dot{m}_{\text{out}}) T_{\text{out}} = \sum (\dot{m}_{\text{in}} T_{\text{in}}) \quad (4)$$

Formula (3) is the temperature drop equation of the pipeline, which is related to the length of the pipeline and the ambient temperature. In the formula, T_{exd} and T_{start} are the temperature at the end and head of the pipeline, respectively. T_a is the ambient temperature. λ is the thermal conductivity of the unit pipe. L represents the length of the pipe. Equation (4) is used to calculate the temperature of the mass flow leaving the node after mixing in multiple pipes. Usually, the heating temperature T at the heat source and the outlet temperature T_r of each load before mixing are known.

Since the main control objectives of the optimal operation process of the integrated energy system are electric power balance, thermal power balance, and capacitive voltage balance, in order to achieve stable control of the system power balance, it is necessary

to establish a unified multi-energy system coupling power balance equation, which is expressed as:

$$\left\{ \begin{array}{l} P_{Ei}^s - \sum_{j \in i} P_{Eij}(U_i, U_j, \theta_i, \theta_j) + \alpha P_{Ei} = 0 \\ Q_{Ei}^s - \sum_{j \in i} Q_{Eij}(U_i, U_j, \theta_i, \theta_j) - Q_{Ei} = 0 \\ P_{Gi}^s - \sum_{j \in i} P_{Gij}(\mu_i, \mu_j, \beta_i, \beta_j) - \lambda P_{Gi} = 0 \\ Q_{Gi}^s - \sum_{j \in i} Q_{Gij}(\mu_i, \mu_j, \beta_i, \beta_j) - Q_{Gi} = 0 \\ P_{Hi}^s - \sum_{j \in i} P_{Hij}(\varphi_i, \varphi_j, \tau_i, \tau_j) - \zeta P_{Hi} = 0 \\ Q_{Hi}^s - \sum_{j \in i} Q_{Hij}(\varphi_i, \varphi_j, \tau_i, \tau_j) - Q_{Hi} = 0 \end{array} \right. \quad (5)$$

Among them, P_{Ei}^s and Q_{Ei}^s are the active power and reactive power of each distributed power injection node in the integrated energy system, respectively. P_{Eij} and Q_{Eij} are the active power and reactive power from node e to node f in the integrated energy system. U_i and θ_i are the voltage amplitude and phase angle at node i in the integrated energy system. U_j and θ_j are the voltage amplitude and phase angle of j between adjacent nodes i in the integrated energy system. P_{Ei} and Q_{Ei} are the active power and reactive power loss at node i , respectively. α is the signal variable connected to the rectifier or inverter. When the node is connected to the rectifier, α takes -1 , and when the node is connected to the inverter, α takes 1 . P_{Gi}^s and Q_{Gi}^s are the active power and reactive power of the power flow corresponding to the volume flow of the gas pipeline injected into node i . μ_i is the compression ratio of gas at node i . β_i is the temperature of the gas at node i . μ_j is the compression ratio of gas at node j . β_j is the temperature of gas at node j . λ is the loss factor of the compressor. The active and reactive power flows corresponding to the thermal energy injected by the integrated energy system into the thermal pipeline node i are P_{Hi}^s and Q_{Hi}^s , respectively. φ is the flow rate of the transmission medium of the thermal system. τ is the temperature of the transmission medium of the thermal system. ζ is the loss factor of the pressurized pumping station. P_{Hi} and Q_{Hi} are the active power and reactive power loss of the electro-thermal coupling device at node i in the thermal system, respectively.

The constraint equation of the power transmission channel of the integrated energy system is:

$$\left\{ \begin{array}{l} P_G = g_{as} S \\ P_H = C \cdot G \cdot \Delta T \end{array} \right. \quad (6)$$

Among them, g_{as} is the calorific value of gas. S is the gas flow. P_G is the power flow corresponding to the volume flow of the gas pipeline. C is the specific heat capacity of the transmission medium. G is the medium flow rate, and ΔT is the medium temperature difference between the inlet and outlet.

From Equations (5) and (6), the mixed power flow correction equation of the integrated energy system is:

$$\begin{bmatrix} \Delta P_d \\ \Delta P \\ \Delta Q \\ \Delta P_G \\ \Delta Q_G \\ \Delta P_H \\ \Delta Q_H \end{bmatrix} = \begin{bmatrix} \frac{\partial P_d}{\partial I_d} & \frac{\partial P_d}{\partial U} U & 0 & 0 & 0 & 0 & 0 \\ \frac{\partial P}{\partial I_d} & \frac{\partial P}{\partial U} U + \frac{\partial P_d}{\partial U} U & \frac{\partial P}{\partial \theta} & 0 & 0 & 0 & 0 \\ \frac{\partial Q}{\partial I_d} & \frac{\partial Q}{\partial U} U + \frac{\partial Q_d}{\partial U} U & \frac{\partial P}{\partial \theta} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{\partial P}{\partial \mu} \mu + \frac{\partial P_G}{\partial \mu} \mu & \frac{\partial P_G}{\partial \beta} & 0 & 0 & 0 \\ 0 & 0 & \frac{\partial Q}{\partial \mu} \mu + \frac{\partial Q_G}{\partial \mu} \mu & \frac{\partial P_G}{\partial \beta} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{\partial P}{\partial \varphi} \varphi + \frac{\partial P_H}{\partial \varphi} \varphi & \frac{\partial P_H}{\partial \tau} & 0 \\ 0 & 0 & 0 & 0 & \frac{\partial Q}{\partial \varphi} \varphi + \frac{\partial Q_H}{\partial \varphi} \varphi & \frac{\partial P_H}{\partial \tau} & 0 \end{bmatrix} \begin{bmatrix} \Delta I_d \\ \frac{\Delta U}{U} \\ \Delta \theta \\ \Delta \mu \\ \Delta \beta \\ \Delta \varphi \\ \Delta \tau \end{bmatrix} \quad (7)$$

Among them, P and Q_{IN} are the column vectors of active power and reactive power at the node, respectively. ΔP and Q_{INV} are the column vectors of the node active power and

reactive power imbalance, respectively. ΔP_G and ΔQ_G are the active power and reactive power imbalance column vectors of the equivalent power flow of the gas pipeline network nodes. I_d and ΔI_d are the current column vector and the current correction column vector of the transmission unit in the integrated energy system, respectively. Q_d is the column vector of inverter reactive power in the transmission unit. $P_r(d = d_i) = p_i$ and $p_i \geq 0$ are the modified amplitude column vectors of the node voltage amplitude and phase angle, respectively. $\sum_{i=1}^m p_i = 1$ is the column vector of the node voltage amplitude. P_d and ΔP_d are the active power column vector and the active power imbalance column vector of the transmission unit. $\Delta\varphi$ and $\Delta\tau$ are the medium flow deviation and temperature deviation, respectively.

2.4. Load Demand Response of Integrated Energy System

Users can flexibly adjust their electrical loads during working hours in response to electricity and heat prices. This adjustable load is called the transferable load. The time-sharing energy price is used as a signal to guide users to transfer their peak load to the valley period. The price elasticity coefficient E is used to describe the sensitivity of load to price:

$$E = \frac{\rho_0}{P_{L0}} \cdot \frac{\Delta P_L}{\Delta \rho} \quad (8)$$

where ρ_0 is the initial price, P_{L0} is the initial load, ΔP_L is the change in load after demand response, and $\Delta \rho$ is the change in price after the demand response. Thus, the transferable load variation is:

$$\Delta P_{SL,t} = P_{SL,t}^0 \left[\sum_{j=1}^{24} E(t,j) \frac{\rho_j - \rho_j^0}{\rho_j^0} \right] \quad (9)$$

where $P_{SL,t}^0$ is the initial transferable load at time t , $E(t,j)$ is the price demand elasticity matrix, and ρ_j^0 is the energy price at time j .

For a specific load, it can be supplied by electric or heat energy. When the electricity price is low, the electric energy supply can be selected, and when the electricity price is high, the heat energy supply can be selected, so as to achieve the mutual substitution and complementary use of electrical and thermal energy. This mathematical model is:

$$\begin{aligned} \Delta R_t^e &= -\varphi_{e,h} \Delta R_t^h \\ \varphi_{e,h} &= \frac{v_e \varepsilon_e}{v_h \varepsilon_h} \end{aligned} \quad (10)$$

where ΔR_t^e is the amount of charge used for the substitution or conversion, $\varphi_{e,h}$ is the electrothermal conversion coefficient, ΔR_t^h is the amount of heat load replaced or converted, v_e is the unit calorific value of electrical energy, v_h is the calorific value per unit of heat, ε_e is the power utilization rate, and ε_h is the utilization rate of heat energy.

2.5. Load Demand Response Operation Cost Model

Cluster division determines the architecture of the system decomposition and coordination. The partition results define the boundary, internal resource composition, and external coupling relationship of each subproblem.

If the geographical distribution and adjustment characteristics of DR resources are not taken into account in the division, a cluster with uneven internal adjustment capabilities or excessive pressure to interact with external networks may be formed. This ‘congenitally deficient’ cluster structure will limit the overall performance upper limit that can be achieved by subsequent scheduling algorithms, no matter how advanced they are.

The division of embedded DR essentially uses DR as a structural resource to help shape the cluster structure at the beginning of system decomposition, with the aim of

forming a cluster with better ‘autonomy’ with strong self-balancing ability of internal supply and demand (including flexible load) and low demand for external interaction.

2.6. Integrated Demand Response Load Model

The comprehensive load demand response of the park established in this paper is mainly divided into electricity, heat, gas, and cold load demand, and the load type is divided into rigid and flexible loads. Rigid load has low adjustability in the system scheduling, mainly to meet park users’ basic needs. The flexible load in the system comprises reducible, transferable, and replaceable loads. Among them, the time-of-use electricity price is used for price-based load response to reduce and transfer load, and energy substitutability is used for alternative load response. Because the running time of the cooling load is relatively fixed, it is used in the form of a fixed load in the system energy scheduling.

Reducible load demand response cost model:

$$C_{cu} = \sum_{y=1}^3 \alpha_{cu}^y \sum_{t=1}^T \beta_{cu,t}^y [P_{cu}^y(t) - P_{cu}^{y'}(t)] \quad (11)$$

In the formula, C_{cu} is the compensation cost after the load is reduced and α_{cu}^y is the compensation price for each type of load of the system after reduction. The variable $\beta_{cu,t}^y$ is $[0, 1]$. When $\beta_{cu,t}^y = 1$, the load is reduced for the system. $P_{cu}^y(t)$ and $P_{cu}^{y'}(t)$ are the load power before and after the load reduction at the system time t .

Transferable load demand response cost model:

$$C_{sh} = \sum_{y=1}^3 \alpha_{sh}^y \sum_{t=1}^T \beta_{sh,t}^y |P_{sh}^y(t) - P_{sh}^{y'}(t)| \quad (12)$$

$$\sum_{t=1}^T P_{load,sh}^y = 0, y = 1, 2, 3 \quad (13)$$

In the formula, C_{sh} is the compensation cost after the load is transferred, α_{sh}^y is the compensation price after the transfer of each load of the system, and the variable $\beta_{sh,t}^y$ is $[0, 1]$. When $\beta_{sh,t}^y = 1$, load transfer is performed for the system. $P_{sh}^y(t)$ and $P_{sh}^{y'}(t)$ are the load power before and after the load transfer at the system time t . $P_{load,sh}^y$ is the transferable amount of energy, and the total transferable amount is 0 in one scheduling period.

Alternative load demand response cost model:

$$C_{rep} = \alpha_{rep} \sum_{t=1}^T P_{rep}(t) \quad (14)$$

In the formula, C_{rep} is the compensation cost after energy substitution, α_{rep} is the compensation price of the system after load substitution, and $P_{rep}(t)$ is the total power of energy substitution at time t .

According to the demand response type and cost model of each load, the total cost of the system based on demand response is:

$$C_{DR} = C_{cu} + C_{sh} + C_{rep} \quad (15)$$

The stepwise demand response cost model is optimized by using the variation before and after the demand response. The stepwise compensation model of demand response cost is as follows:

$$\begin{cases} P_{\text{dcu}}^y(t) = P_{\text{cu}}^y(t) - P_{\text{cu}}^{y'}(t) \\ P_{\text{dsh}}^y(t) = |P_{\text{sh}}^y(t) - P_{\text{sh}}^{y'}(t)| \end{cases} \quad (16)$$

In the formula, $P_{\text{dcu}}^y(t)$, $P_{\text{dsh}}^y(t)$ are the system load reduction and the transfer amount, respectively.

3. Integrated Energy System Cluster Based on Electro–Thermal–Gas Coupling

In the integrated energy system, the objective behind the cluster division between multiple energy sources is mainly to integrate energy coupling equipment with similar operating characteristics and close electrical distance, so as to achieve unified centralized control.

The multi-energy system cluster, as shown in Figure 2, is mainly composed of four layers: power grid layer, heat network layer, gas network layer, and electro–thermal–gas coupling layer. In the cluster division process, initial clustering of the electricity, heat, and gas is carried out. In the cluster division process, the input and output power of each power grid node is mainly considered, and the electrical distance between electrical nodes is determined according to the sensitivity of active and reactive power to voltage amplitude. The adjustment equipment in the power subsystem, such as cogeneration, distributed power supply, gas turbines, and reactive power compensation devices, is analyzed, and its adjustment ability is evaluated. In the thermal subsystem, the structural aspect mainly considers the loss along the path between the two nodes during the heat transfer process, as well as the loss of temperature. In terms of functionality, the operation characteristics of cogeneration and the storage characteristics of the heat pipe network are mainly considered, and the heat subsystem is divided into multiple initial clusters of the heat network. For the structural aspect of gas copper, pressure loss in the transmission process is mainly considered. In terms of function, the gas subsystem containing electrical gas equipment is divided into multiple initial gas clusters. For the electro–thermal–gas coupling layer, multi-energy coupling is performed by multi-energy coupling devices. According to the transmission power deviation between each energy subsystem, the coupling form of the multi-energy system is adjusted to further realize the energy clustering of the multi-energy system.

3.1. Power Subsystem Cluster Division Index

In order to represent the closeness of the connection between two nodes in the system, References [17–19] proposed the modularity index to quantify the structural strength of the complex structure system. The larger the value, the closer the connection between the nodes, which is expressed as:

$$\rho = \frac{1}{2\sigma} \sum_i \sum_j \left[B_{ij} - \frac{k_i k_j}{2\sigma} \right] \beta(i, j) \quad (17)$$

Among them, B_{ij} is the weight value of the edge between node i and node j in the system, which is defined as the edge weight, σ is the sum of all edges in the system, $b = 1/2 \sum_i \sum_j B_{ij}$. k_i is the weight sum of all edges connected to node i in the system, and $k_i = 1/2 \sum_j B_{ij}$. If nodes i, j are in the same cluster, then $\beta(i, j) = 1$, otherwise $\beta(i, j) = 0$.

(1) Modularity index of structural cluster partition

In the power subsystem cluster division process, the structural modularity index is calculated first, and the network edge weight is defined mainly according to the electrical distance between two nodes in the power subsystem. The electrical distance mainly reflects

the coupling relationship between nodes. The two nodes with a large electrical distance are divided into different clusters, and the nodes with a close electrical distance are divided into the same cluster. From the perspective of system frequency and voltage control, the electrical node distance is defined by the node active power-frequency, reactive power-voltage amplitude sensitivity matrix.

$$\begin{aligned} e_{ij}^P &= G_{ii}^P + G_{jj}^P - G_{ij}^P - G_{ji}^P \\ e_{ij}^Q &= G_{ii}^Q + G_{jj}^Q - G_{ij}^Q - G_{ji}^Q \end{aligned} \quad (18)$$

where G_{ij}^P is the element of row i and column j in the active power-frequency sensitivity matrix $\mathbf{G}^P$, and G_{ij}^Q is the element of row i and column j of the reactive power-voltage sensitivity matrix $\mathbf{G}^Q$, which represents the influence of the power change of node j on the frequency and voltage of node i in the power subsystem.

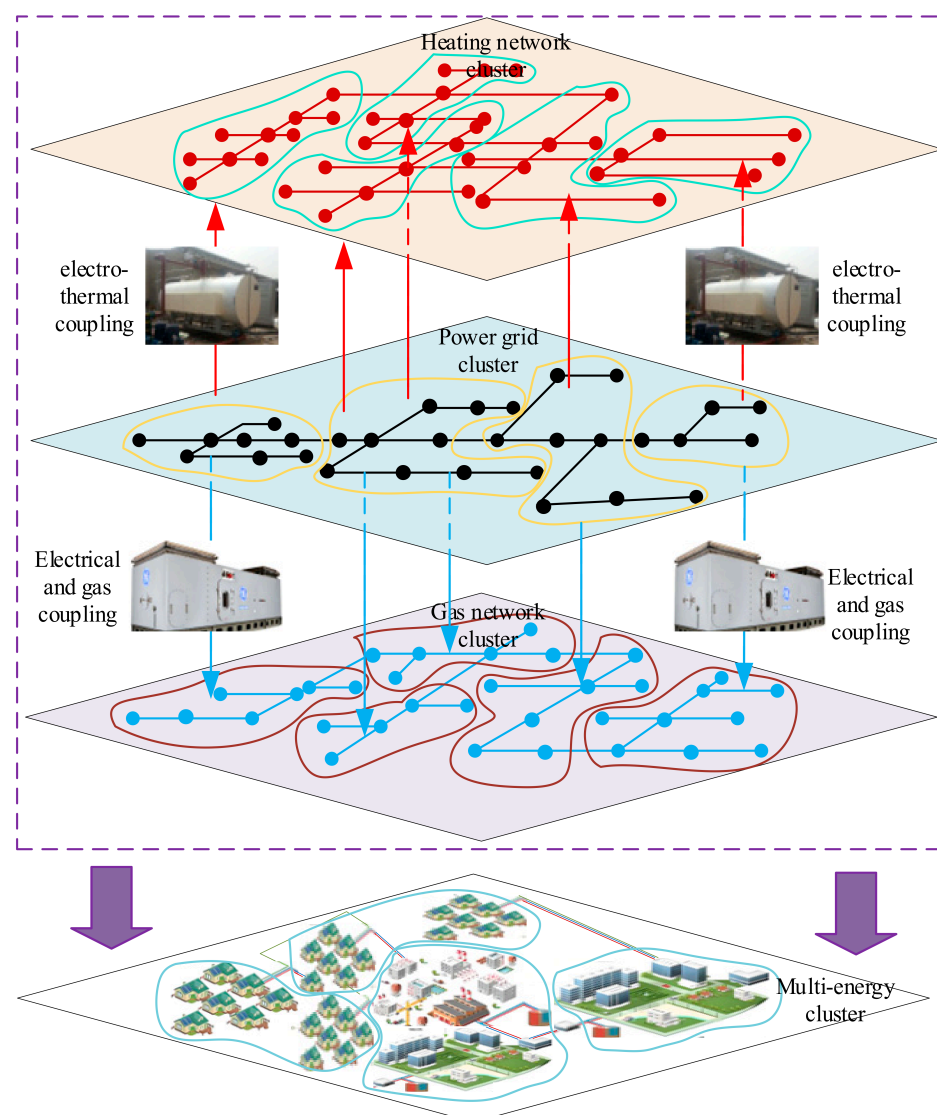


Figure 2. Multi-energy system cluster.

Considering the influence of active and reactive power in the power subsystem on the frequency and voltage of the system, the electrical distance of the system is:

$$e_{ij} = \lambda_P^e e_{ij}^P + \lambda_Q^e e_{ij}^Q \quad (19)$$

where λ_p^e is the weight of the electrical distance that affects the frequency, and λ_Q^e is the weight of the electrical distance that affects the voltage. When the active-frequency and reactive-voltage sensitivities between two nodes are larger, the coupling degree between nodes ij is closer. Therefore, the node edge weight in the power subsystem is expressed as:

$$A_{ij}^E = 1 - \frac{e_{ij}}{\max_{m,n \in \Gamma^E} e_{mn}} \quad (20)$$

where Γ^E is the set of nodes in the power subsystem.

(2) Supply and demand balance

In the power subsystem, in order to reduce the power transmission of the tie lines between the clusters, the distributed renewable energy generation, cogeneration units, and gas turbines in the power cluster system are balanced with the load in real time. The established power supply and demand balance is expressed as [20]:

$$\varphi_{x,t}^E = \begin{cases} 1 & \sum_{i \in \Pi_x^S} P_{i,t}^S \pm \sum_{i \in \Pi_x^L} P_{i,t}^L + \sum_{c \in O_x} P_{l,t}^{\text{loss}} \\ \sum_{i \in \Pi_x^S} P_{i,t}^S & \\ \frac{\sum_{i \in \Pi_x^L} P_{i,t}^L + \sum_{l \in O_x} P_{l,t}^{\text{loss}}}{\sum_{i \in \Pi_x^S} P_{i,t}^S} & \sum_{i \in \Pi_x^S} P_{i,t}^S \leq \sum_{i \in \Pi_x^L} P_{i,t}^L + \sum_{l \in O_x} P_{l,t}^{\text{loss}} \end{cases} \quad (21)$$

$$\varphi^E = \frac{1}{\Gamma_C} \sum_{x=1}^{\Gamma_C} \left(\frac{1}{\tau} \sum_{t=1}^{\tau} \varphi_{x,t}^E \right) \quad (22)$$

Among them, φ^E is the balance of supply and demand of the power subsystem, $P_{i,t}^S$ is the power output of the power cluster system x internal node i , $P_{i,t}^L$ is the load demand power at the internal node i of the power cluster system x , $P_{l,t}^{\text{loss}}$ is the line network loss in the transmission process, Π_x^S is the set of power access nodes in power cluster system x , Π_x^L is the set of load access nodes in power cluster system x , O_x is the line set of power subsystem cluster system x , Γ_C is the initial cluster number of the thermal subsystem, and τ is the number of time periods for regulation.

(3) Regulating ability index

In order to obtain the optimal control of a multi-energy system cluster, the control ability of the distributed power supply, cogeneration unit, gas turbine, and reactive power compensation devices in the power system to system frequency and voltage is evaluated. When the frequency and voltage in the power system fluctuate, the active and reactive power output of the power supply is controlled according to the change in frequency and voltage of key nodes in the system, so as to achieve stable control of the frequency and voltage of each node in the cluster system. If node i is the key node of cluster system x , the regulation index of cluster system is [21]:

$$\gamma_{x,t}^{E,P} = \begin{cases} 1 & \Delta f_{i,t} \leq J_{ij}^P \Delta P_{j,t}^S \\ \sum_{j \in \Pi_x} \frac{J_{ij}^P \Delta P_{j,t}^S}{\Delta f_{j,t}} & \Delta f_{i,t} > J_{ij}^P \Delta P_{j,t}^S \end{cases} \quad (23)$$

$$\gamma_{x,t}^{E,Q} = \begin{cases} 1 & \Delta U_{i,t} \leq J_{ij}^Q \Delta Q_{j,t}^S \\ \sum_{j \in \Pi_x} \frac{J_{ij}^Q \Delta Q_{j,t}^S}{\Delta U_{i,t}} & \Delta U_{i,t} > J_{ij}^Q \Delta Q_{j,t}^S \end{cases} \quad (24)$$

$$\gamma^E = \frac{1}{\Pi_C} \sum_{x=1}^{\Pi_C} \left(\frac{1}{\tau} \sum_{t=1}^{\tau} \omega_P^E \gamma_{x,t}^{E,P} + \omega_Q^E \gamma_{x,t}^{E,Q} \right) \quad (25)$$

where $\Delta f_{i,t}$ is the change value of the frequency of key nodes at time t in the cluster system x , $\Delta U_{i,t}$ is the change value of the key node voltage in the cluster system x at time t , $\Delta P_{j,t}^S$ is the maximum active power adjustment of the power supply at node j in the cluster system, and $\Delta Q_{j,t}^S$ is the maximum reactive power adjustment of the power supply at node j in the cluster system.

3.2. Thermal Subsystem Cluster Division Index

(1) Structural modularity index of thermal subsystem

In the heat subsystem, the pressure of the pipe network decreases due to the friction between the medium and the pipe when it is transmitted in the pipe network. Analogous to the power subsystem, the two adjacent nodes with less pressure loss in the pipe network are divided into the same cluster, and the two adjacent nodes with greater pressure loss are divided into different clusters. The loss along the way between node i and the node j in the thermal subsystem is expressed in the following mathematical model:

$$r_{h,ij} = p_{h,i} - p_{h,j} = 6.88 \times 10^{-3} \frac{K_{h,ij} (m_{h,ij})^2 L_{h,ij}}{\rho_{h,s} d_{h,ij}}, i \in \Gamma_{h,b}^s, i \in \Gamma_{h,b}^e \quad (26)$$

Among them, $p_{h,i}$ and $p_{h,j}$ are the active power input by the thermal subsystem at node i and node j at time t , respectively, $\rho_{h,s}$ is the density of the transmission medium, $K_{h,ij}$ is the pipe roughness between the nodes i and j of the thermal subsystem, $d_{h,ij}$ is the diameter of the heat subsystem transmission pipe network, $L_{h,ij}$ is the length between the heat subsystem transmission pipeline ij , $m_{h,ij}$ is the mass flow between the pipe network node i and the node j in the heat subsystem, $\Gamma_{h,b}^s$ is the heat source set with the heat pipe node i as the beginning, and $\Gamma_{h,b}^e$ is the heat source set with the heat pipe node j as the end.

According to the above analysis, the thermal distance between node i and node j in the thermal subsystem is:

$$r'_{h,ij} = \frac{K_{h,ij} m_{h,ij} L_{h,ij}}{\rho_{h,s} d_{h,ij}} \quad (27)$$

The network edge weight matrix of the thermal system is:

$$A_{ij}^H = 1 - \frac{r'_{h,ij}}{\max_{g \in \Gamma_{h,b}^s, h \in \Gamma_{h,b}^e} r_{gh}} \quad (28)$$

(2) Supply and demand balance index of thermal subsystem

In the thermal system, cogeneration units, electric boilers, and gas boilers are used as heat sources to meet the load demand. Therefore, the supply and demand balance index of the thermal system is established to represent the balance between the source and load.

$$\varphi_{x,t}^H = \begin{cases} 1 & \sum_{i \in \Gamma_{h,x}^S} H_{i,t}^S \geq \sum_{i \in \Gamma_{h,x}^L} H_{i,t}^L + \sum_{b \in \Psi_{h,x}} H_{b,t}^{\text{loss}} \\ \frac{\sum_{i \in \Gamma_{h,x}^S} H_{i,t}^S}{\sum_{i \in \Gamma_{h,x}^L} H_{i,t}^L + \sum_{b \in \Psi_{h,x}} H_{b,t}^{\text{loss}}} & \sum_{i \in \Gamma_{h,x}^S} H_{i,t}^S \leq \sum_{i \in \Gamma_{h,x}^L} H_{i,t}^L + \sum_{b \in \Psi_{h,x}} H_{b,t}^{\text{loss}} \end{cases} \quad (29)$$

Here, $\varphi_{x,t}^H$ is the supply and demand balance degree of cluster x in the thermal subsystem at time t . $\Gamma_{h,x}$ is the node set of cluster x in the thermal subsystem. $\Psi_{h,x}$ is the pipeline

set of cluster x in the thermal subsystem. $H_{i,t}^S$ is the input power of node i at time t in the thermal subsystem. $H_{i,t}^L$ is the load consumption power at node i at time t in the thermal subsystem. $H_{b,t}^{\text{loss}}$ is the thermal energy loss value of the thermal pipeline b at time t . The calculation formula for heat loss in the thermal system is as follows:

$$H_{b,t}^{\text{loss}} = \left[(T_{b,t}^{\text{in}} - T_{b,t}^{\text{out}}) / 2 - T_{h,t}^g \right] \lambda_{h,b} L_{h,b} \quad (30)$$

where $\lambda_{h,b}$ is the heat transfer coefficient of the pipeline, $L_{h,b}$ is the length of the heat pipe, $(T_{b,t}^{\text{in}} - T_{b,t}^{\text{out}}) / 2$ is the average temperature of the transmission medium in the pipeline in the thermal system, and $T_{h,t}^g$ is the ambient temperature outside the heat pipe. Therefore, the calculation model for the supply and demand balance index can be expressed as:

$$\varphi^H = \frac{1}{\Gamma_{h,C}} \sum_{x=1}^{\Gamma_{h,C}} \left(\frac{1}{\tau} \sum_{t=1}^{\tau} \varphi_{x,t}^H \right) \quad (31)$$

Among them, $\Gamma_{h,C}$ represents the initial cluster number of the thermal system and τ denotes the number of time periods for coordinated control.

(3) Regulating ability index of thermal subsystem

In the thermal subsystem, due to the inertia of the heat network transmission and the storage characteristics of the heat pipe network, the gas pipeline network can be equivalent to a virtual heat storage device in the process of system regulation and control. Therefore, the flexible heat storage regulation ability of the heat network can be used as an important index of the system control and regulation ability. The maximum output power of the heat source of the cogeneration unit, the electric boiler, and the gas boiler is $H_{x,t}^{S,\text{max}}$, and the minimum output power is $H_{x,t}^{S,\text{min}}$. The maximum climbing power of the upward output of the heat source is $\Delta H_{x,t}^{S,+}$, and the maximum climbing power output down is $\Delta H_{x,t}^{S,-}$. Therefore, the allowable transmission temperature range in the transmission process of the thermal system is:

$$H_{x,t}^{S,\text{max}} = \min \left\{ \sum_{i \in \Gamma_{h,x}} c_s m_{i,t}^{\text{in}} (T_{i,\text{max}}^{\text{su}} - T_{i,t}^{\text{re}}), \sum_{i \in \Gamma_{h,x}^S} H_{i,\text{max}}^{\text{DCR}} \right\} - \sum_{i \in \Gamma_{h,x}^S} H_{i,t}^S \quad (32)$$

$$H_{x,t}^{S,\text{min}} = \max \left\{ \sum_{i \in \Gamma_{h,x}} c_w m_{i,t}^{\text{in}} (T_{i,\text{min}}^{\text{su}} - T_{i,t}^{\text{re}}), \sum_{i \in \Gamma_{h,x}^S} H_{i,\text{min}}^{\text{DCR}} \right\} - \sum_{i \in \Gamma_{h,x}^S} H_{i,t}^S \quad (33)$$

Among them, $T_{i,\text{max}}^{\text{su}}$ represents the maximum water supply temperature at the heating pipeline node, $T_{i,t}^{\text{re}}$ represents the return water temperature at the node of the regenerative pipeline, c_s is the specific heat capacity of the transmission medium in the thermal subsystem, $H_{i,\text{max}}^{\text{DCR}}$ is the maximum output power of all heat sources at node i , and $H_{i,\text{min}}^{\text{DCR}}$ is the minimum output power of all heat sources at node i .

$$\Delta H_{x,t}^{S,+} = \min \left\{ H_{x,t}^{S,\text{max}} - \sum_{i \in \Gamma_{h,x}^S} H_{i,t}^S, \sum_{i \in \Gamma_{h,x}^S} \Delta H_{i,\text{max}}^{\text{DCR}} \right\} \quad (34)$$

$$\Delta H_{x,t}^{S,-} = \max \left\{ H_{x,t}^{S,\text{min}} - \sum_{i \in \Gamma_{h,x}^S} H_{i,t}^S, \sum_{i \in \Gamma_{h,x}^S} \Delta H_{i,\text{min}}^{\text{DCR}} \right\} \quad (35)$$

According to the above parameter analysis, the system regulation ability index is established as follows:

$$\gamma_{x,t}^{H,H} = \frac{H_{x,t}^{S,\max} - H_{x,t}^{S,\min}}{\sum_{i \in \Gamma_x^S} H_{i,\max}^{DCR} - \sum_{i \in \Gamma_x^S} H_{i,\min}^{DCR}} \quad (36)$$

$$\gamma_{x,t}^{H,\Delta H} = \frac{\Delta H_{x,t}^{S,+} - \Delta H_{x,t}^{S,-}}{\sum_{i \in \Gamma_x^S} \Delta H_i^{DCR,+} - \sum_{i \in \Gamma_x^S} \Delta H_i^{DCR,-}} \quad (37)$$

$$\gamma^H = \frac{1}{\Gamma_C} \sum_{x=1}^{\Gamma_C} \left(\frac{1}{\tau} \sum_{t=1}^{\tau} \omega_H^{\gamma} \gamma_{x,t}^{H,H} + \omega_{\Delta H}^{\gamma} \gamma_{x,t}^{H,\Delta H} \right) \quad (38)$$

Among them, ω_H^{γ} is the weight coefficient of the output power of all heat sources in the thermal system and $\omega_{\Delta H}^{\gamma}$ is the weight coefficient of the climbing rate of all heat sources in the thermal system.

3.3. Gas Subsystem Cluster Division Index

(1) Structural modularity index of gas subsystem

In the gas subsystem, when the gas is transmitted in the pipeline network, the pressure of the pipeline network decreases due to friction with the pipeline. Analogous to the thermal subsystem, the two adjacent nodes with smaller pressure loss are divided into the same cluster, and the two adjacent nodes with larger pressure loss are divided into different clusters. The loss along the path between node i and node j in the gas subsystem is a , and its mathematical model is:

$$r_{g,ij} = p_{g,i} - p_{g,j} = 6.88 \times 10^{-3} \frac{K_{g,ij} (m_{g,ij})^2 L_{g,ij}}{\rho_{g,s} d_{g,ij}}, i \in \Gamma_{g,b}^s, i \in \Gamma_{g,b}^e \quad (39)$$

where $p_{g,i}$ and $p_{g,j}$ are the active power input by the gas subsystem at node i and node j at time t , respectively. $\rho_{g,s}$ is the density of gas. $K_{g,ij}$ is the pipe roughness between the nodes i and j of the gas subsystem. $d_{g,ij}$ is the diameter of the gas subsystem transmission pipe network. $L_{g,ij}$ is the length between the gas subsystem transmission pipeline ij . $m_{g,ij}$ is the mass flow between the pipe network nodes i and j in the gas subsystem. $\Gamma_{g,b}^s$ is the heat source collection with the gas pipeline node i as the starting end. $\Gamma_{g,b}^e$ is the heat source collection with the gas pipeline node j as the end.

According to the above analysis, the thermal distance between node i and node j in the gas subsystem is:

$$r'_{g,ij} = \frac{K_{g,ij} m_{g,ij} L_{g,ij}}{\rho_{g,s} d_{g,ij}} \quad (40)$$

The edge weight matrix of gas system network is:

$$A_{ij}^G = 1 - \frac{r'_{g,ij}}{\max_{g \in \Gamma_{g,b}^s, h \in \Gamma_{g,b}^e} r_{gh}} \quad (41)$$

(2) Gas subsystem supply and demand balance index

In the gas system, the gas supply from sources such as electric gas should meet the load demand; the supply and demand balance index of the gas system is therefore established to represent the balance between the source and the load.

$$\varphi_{x,t}^G = \begin{cases} 1 & \sum_{i \in \Gamma_{g,x}^S} G_{i,t}^S \geq \sum_{i \in \Gamma_{g,x}^L} G_{i,t}^L \\ \frac{\sum_{i \in \Gamma_{g,x}^S} G_{i,t}^S}{\sum_{i \in \Gamma_{g,x}^L} G_{i,t}^L} & \sum_{i \in \Gamma_{g,x}^S} G_{i,t}^S \leq \sum_{i \in \Gamma_{g,x}^L} G_{i,t}^L \end{cases} \quad (42)$$

Among them, $\varphi_{x,t}^G$ is the supply and demand balance degree of cluster x in the gas subsystem at time t , $\Gamma_{g,x}$ is the node set of cluster x in the gas subsystem, $G_{i,t}^S$ is the input power of node i in the gas subsystem at time t , and $G_{i,t}^L$ is the load consumption power at node i at time t in the gas subsystem.

Therefore, the calculation model for the supply and demand balance index can be expressed as:

$$\varphi^G = \frac{1}{\Gamma_{g,C}} \sum_{x=1}^{\Gamma_{g,C}} \left(\frac{1}{v} \sum_{t=1}^v \varphi_{x,t}^G \right) \quad (43)$$

where $\Gamma_{g,C}$ represents the initial cluster number of the gas system and v denotes the number of time periods for coordinated control.

4. Cluster Division Method of Multi-Energy System Based on the Louvain Algorithm

The Louvain algorithm is a general community discovery algorithm that does not consider the physical characteristics and operational constraints of the energy system.

In the improved algorithm proposed in this paper, the specialized energy system model is deeply integrated. The unique ‘distance’ of the energy system is defined: when calculating the structural modularity, the simple topological connection weight is not used; rather, ‘electrical distance’, ‘thermal distance’, and ‘gas distance’ are used, which conform to the physical characteristics defined. These distances are based on actual physical quantities such as power-frequency sensitivity and pipeline pressure loss.

Operational constraints are introduced: in the process of partitioning, the feasibility and economic constraints of energy system operation are indirectly considered through supply and demand balance and adjustment capability indicators, such that the divided clusters are not only closely connected but also have good independent operation potential.

The core improvement of the algorithm proposed in this paper is the enhancement of the standard Louvain algorithm from a simple topology community discovery tool to an integrated energy system planning and operation analysis tool that integrates the characteristics of multi-energy network structure, operation balance constraints, and the cross-energy flow coupling relationship. The division results not only address the tightness of the network connection, but also the optimal comprehensive performance of the cluster in terms of the self-balancing of energy supply and demand, adjustment flexibility, and multi-energy complementarity.

The Louvain algorithm is divided into two stages: modularity optimization and network aggregation, and iterates repeatedly. In the first stage, each node in the weighted network is initialized as an independent cluster. Then, according to the direction of the increase in the modularity function, the corresponding modularity gain, $\Delta\rho$ is calculated after node i moves to cluster y , as shown in Equations (44)–(46). Node i is then divided into the cluster with the largest positive $\Delta\rho$. If all the $\Delta\rho$ are negative, then node i remains in place. In this way, all nodes are continuously merged until the modularity value is maximum.

$$\rho_1 = \frac{\sum_{inside} + 2k_{i,inside}}{2a} - \left(\frac{\sum_{total} + k_i}{2a} \right)^2 \quad (44)$$

$$\rho_1 = \frac{\sum_{inside} + 2k_{i,inside}}{2a} - \left(\frac{\sum_{total}}{2a} \right)^2 - \left(\frac{k_i}{2a} \right)^2 \quad (45)$$

$$\Delta\rho = \rho_1 - \rho_2 \quad (46)$$

In the formula, $\sum_{inside}$ represents the sum of edge weights in cluster y , and k_i is the sum of all edge weights connected to node i . $k_{i,inside}$ is the sum of edge weights connected to node i in cluster y , and $\sum_{total}$ represents the sum of edge weights connected to all nodes in cluster y .

In the second stage of network aggregation, a new network is constructed based on the cluster division results of the first stage, and a cluster is used as a new node. The connection between the two clusters is used as a new edge weight, and the first-stage process is repeated to optimize the modularity at a higher level. Finally, the cluster partition scheme that satisfies the maximum modularity function is obtained.

The Louvain algorithm divides the network into clusters by maximizing the modularity. In the initial stage, each node in the system is initialized as a separate cluster, and the node set is set according to the direction of increasing modularity. The corresponding modularity gain $\Delta\rho$ is calculated after node i moves to cluster y . The specific calculation model is shown in Equations (47) and (48). The node is moved to the cluster with the largest $\Delta\rho$ value. The calculation formula of $\Delta\rho$ is as follows:

$$\Delta\rho = \left[\frac{\sum_{in} + 2k_{i,in}}{2m} - \left(\frac{\sum_{tot} + k_i}{2m} \right)^2 \right] - \left[\frac{\sum_{in} + 2k_{i,in}}{2m} - \left(\frac{\sum_{tot}}{2m} \right)^2 - \frac{k_i}{2m} \right] \quad (47)$$

Among them, m is the sum of the node weights in the system. $\sum_{in}$ is the sum of all edge weights in the cluster system. k_i is the sum of edge weights connected to node i . $k_{i,in}$ is the sum of all edge weights connected to node i in the cluster system. $\sum_{tot}$ is the sum of edge weights connected by all edge nodes in the cluster system.

In order to realize the cluster division of multi-energy system, according to the cluster division index of the power subsystem, the cluster division index of the thermal subsystem and the cluster division index of the gas subsystem in a multi-energy system, the system is divided into two stages. Firstly, the single-level division of the power subsystem, the single-level division of the thermal subsystem, and the single-level division of the gas subsystem are carried out. Considering the regulation ability of each subsystem and the balance between energy supply and demand, the optimization goal for establishing the initial cluster is as follows:

$$\begin{aligned} \Omega_a^E &= v_\rho^E \rho^E + v_\varphi^E \varphi^E + v_\gamma^E \gamma^E \\ \Omega_a^H &= v_\rho^H \rho^H + v_\varphi^H \varphi^H + v_\gamma^H \gamma^H \\ \Omega_a^G &= v_\rho^G \rho^G + v_\varphi^G \varphi^G \end{aligned} \quad (48)$$

Among them, Ω_a^E is the comprehensive performance of the initial cluster of the power subsystem. Ω_a^H is the comprehensive performance of the initial cluster of the thermal subsystem. Ω_a^G is the comprehensive performance of the initial cluster of the gas subsystem. ρ^E is the modularity index of the power subsystem. ρ^H is the modularity index of the thermal subsystem. ρ^G is the modularity index of the gas subsystem. v_ρ^E is the power subsystem modularity index weight coefficient. v_φ^E is the weight coefficient of the supply and demand

balance index of the power subsystem. v_{γ}^E is the weight coefficient of the regulation ability index of the power subsystem. v_{ρ}^H is the weight coefficient of the modularity index of the thermal subsystem. v_{φ}^H is the weight coefficient of the supply and demand balance index of the thermal subsystem. v_{γ}^H is the weight coefficient of the regulation capacity index of the thermal subsystem. v_{ρ}^G is the weight coefficient of the modularity index of the gas subsystem. v_{φ}^G is the weight coefficient of supply and demand balance index of gas subsystem.

In the multi-energy system composed of electric heating and gas coupling equipment, due to the long transmission time inertia of heat and gas, the demand for electric energy should be met first in the cluster division process. When the multi-energy cluster is carried out during the second stage of electric heating and gas coupling, the cluster members of the power subsystem are adjusted according to the initial division results of the thermal and gas subsystems. The optimization objective is expressed as:

$$\Omega_b^E = \Omega_a^E + v_{\varepsilon}^{EH} \varepsilon^{EH} + v_{\varepsilon}^{EG} \varepsilon^{EG} + v_{\varepsilon}^{HG} \varepsilon^{HG} \quad (49)$$

Among them, Ω_b^E is the optimization goal of the multi-energy system cluster, v_{ε}^{EH} is the weight coefficient of electro-thermal coupling index, ε^{EH} is the electro-thermal coupling index, v_{ε}^{EG} is the weight coefficient of electrical coupling index, ε^{EG} is the electrical coupling index, v_{ε}^{HG} is the weight coefficient of gas–heat coupling index, and ε^{HG} is the gas–heat coupling index.

For an electricity–heating–gas integrated energy system with n nodes, the specific steps to realize the cluster division of the three levels of the power grid and heating network are as follows.

Step 1: The optimization objectives for the initial cluster division of the heating network, power grid, and gas network are constructed, respectively.

Step 2: Each node in the integrated energy system is initiated as a separate cluster; that is, the number of clusters is equal to the number of nodes.

Step 3: For any node i , node j is randomly selected from other nodes and combined with them to form new clusters $C_H(i, j)$ and $C_P(i, j)$ at the heat network and power grid levels, respectively. In order to ensure the logicity of the cluster division results, the adjacency matrix is used to preliminarily determine whether there is a direct connection between the heating network where nodes i and j are located and the cluster at the grid level. Two clusters with at least one direct connection have the opportunity to merge.

Step 4: The changes in the optimization objectives $\Delta\rho_{H,im}$ and $\Delta\rho_{P,im}$ before and after the merger are calculated, and the cluster numbers of the heating network and the grid level corresponding to $\max\Delta\rho_{H,im}$ and $\max\Delta\rho_{P,im}$ are recorded. If $\max\Delta\rho_{H,im} > 0$ $\max\Delta\rho_{P,im} > 0$, then node i chooses to join the heat network (power grid) cluster of the node j corresponding to $\max\Delta\rho_{H,im}$ ($\max\Delta\rho_{P,im}$). Otherwise, it remains unchanged.

Step 5: Repeat steps 3 and 4 until all nodes belong to the heating network cluster and the grid cluster no longer change.

Step 6: The heat network and power grid cluster structure found in step 5 are compressed, respectively, and the formed cluster is regarded as a new node.

Step 7: Return to step 3, until the optimization objectives of the entire heating network and the power grid no longer change, the cluster partitioning process stops, and the optimal cluster partitioning result at the single network level is obtained.

Step 8: Considering the coupling phenomenon of source-side energy output, the initial grid cluster division results are adjusted. The required heat energy under the heat network cluster division is used as the actual heat of the coupling network in the thermoelectric coupling index, and the optimization goal $\rho_{P,im} = \rho_{P,im}^{\text{update}}$ for adjusting the cluster division at the grid level is reconstructed by combining the modularity index and the supply-and-

demand matching index. The optimization goal for cluster division at the heating network level is given by $\rho_{H,im} = \rho_{H,im}^{\text{first}}$.

Step 9: Repeat steps 2 to 7 to obtain the adjusted optimal power grid cluster division results.

Through the above modeling analysis, in order to equip the integrated energy system cluster system with a strong supply and demand balance adjustment ability, the multi-energy system cluster optimization process shown in Figure 3 is adopted:

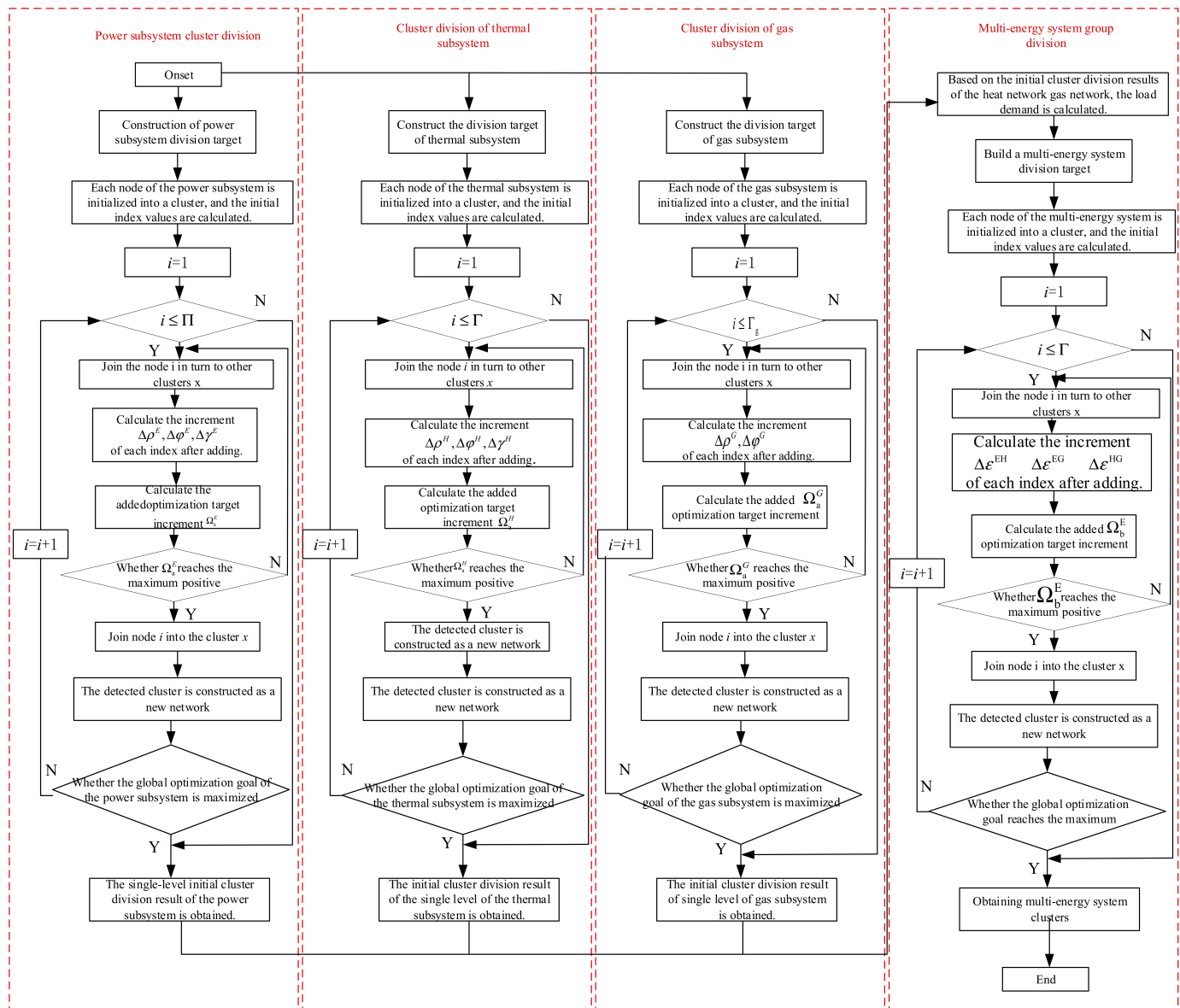


Figure 3. Multi-energy system cluster optimization flow chart.

5. Simulation Verification

In order to verify the effectiveness of the method proposed in this paper, the grid structure of the system is used as an example system for parameter identification of the generative adversarial network. The actual equipment parameters and operation data in the integrated energy system are used as reference data. Because the three subsystems of electricity, heat, and gas are modeled separately in the modeling process of the integrated energy system, there are differences in the control variable units of each subsystem during the operation of the integrated energy system. Therefore, it is necessary to convert the

number of different energy subsystems per unit value for the parameter identification of the multi-source microgrid system. Before parameter identification, the cluster division of the multi-energy system is first carried out. Table 1 shows the cluster division results of the multi-energy system under different coupling strengths of electricity, heating, and gas systems. The cluster division results are shown in Figures 4 and 5.

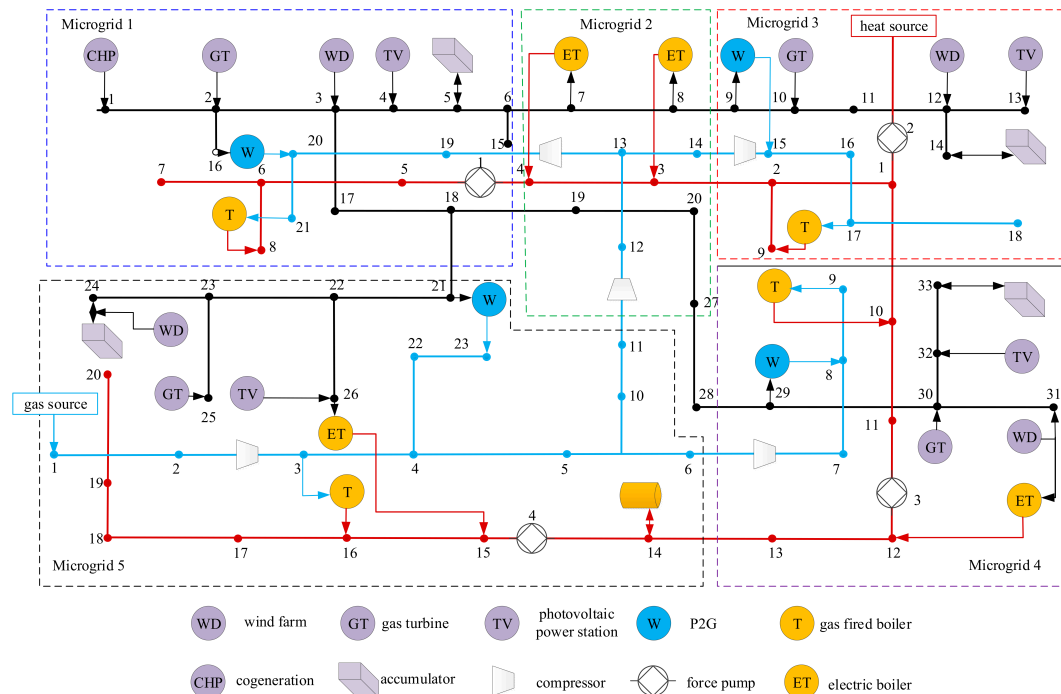


Figure 4. Multi-energy microgrid cluster system division.

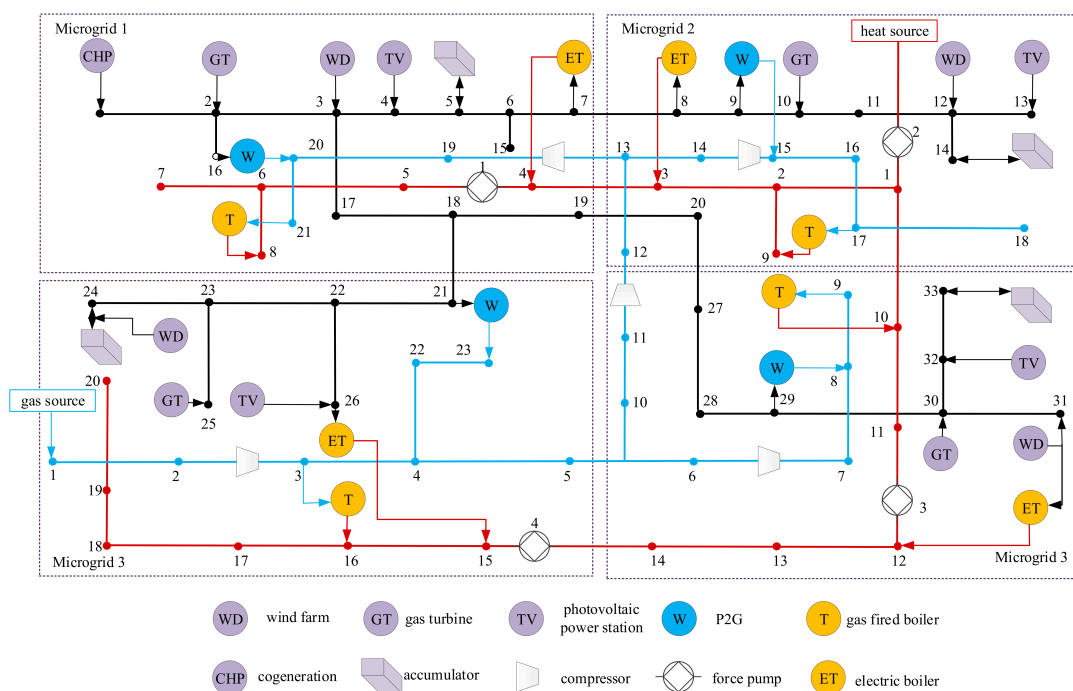


Figure 5. Multi-energy microgrid cluster system partition.

Figure 5 is used as the simulation system for verification, and the electrical, thermal, and gas energy interactions between the microgrids in the integrated energy system are shown in Figures 6–8.

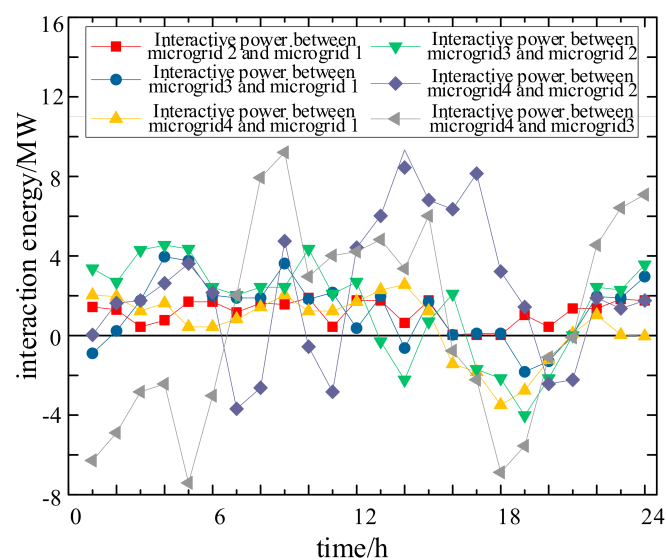


Figure 6. Interactive power between microgrids.

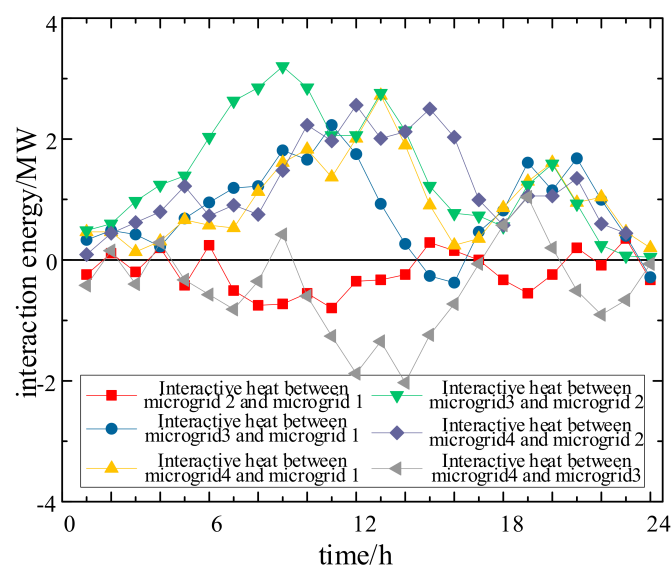


Figure 7. Interactive power between heating networks.

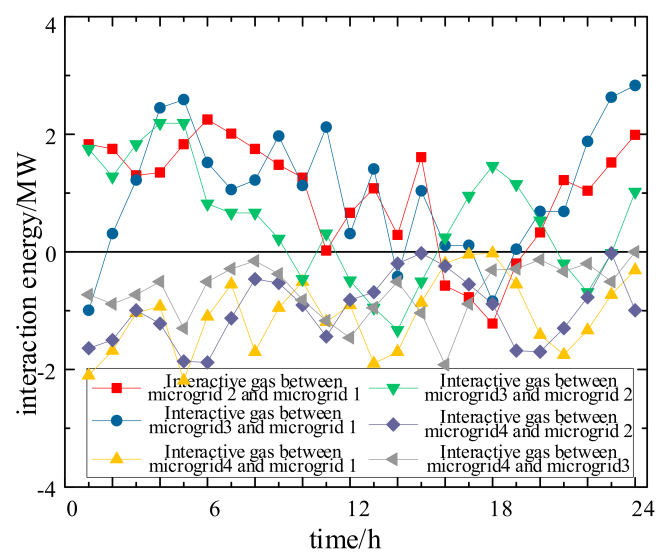


Figure 8. Interactive power between gas networks.

The interaction energy between microgrid 1 and other networks is 7.1 MW, and the energy purchased from the energy network is 2.1 MW. The energy purchase capacity is reduced by 17.84%, and the energy interaction frequency is increased by 47.32%. The interaction energy between microgrid 3 and other networks is 4.3 MW, and the energy purchased from the energy network is 1.4 MW. The energy purchase capacity is reduced by 25.73%, and the energy interaction frequency is increased by 41.12%. The interaction energy between microgrid 4 and other networks is 5.1 MW, and the energy purchased from the energy network is 2 MW. The energy purchase capacity is reduced by 8.97%, and the energy interaction frequency is increased by 13.03%.

The energy scheduling results for each energy microgrid are shown in Figures 9–14, respectively.

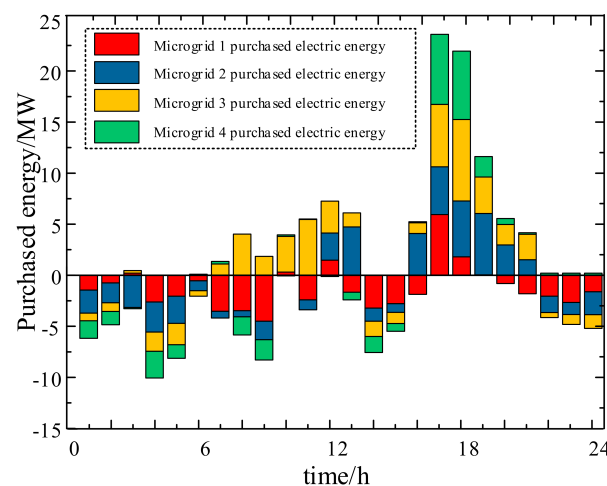


Figure 9. Electricity purchased by the microgrid.

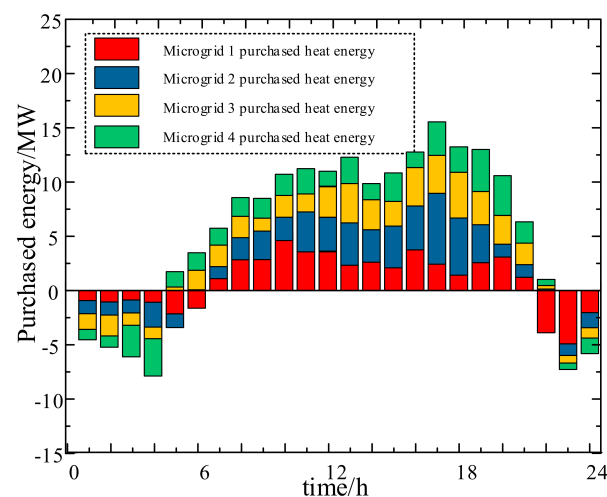


Figure 10. Heat energy purchased by the heat network.

As shown in the diagram, the supply and demand for electricity, gas, and heat are in a power-balance state in each microgrid within the cluster system. Among them, the supply side of electricity, gas, and thermal energy in each microgrid mainly comes from the output of system energy supply equipment, energy purchase, and energy release of energy storage equipment. The load demand side of electricity, gas, and thermal energy mainly comprises the system's own energy consumption load, energy sales, the energy consumption of various energy conversion devices, the charging demand of energy storage equipment, and the charging demand of energy storage ships. From 22:00–06:00, each

microgrid in the cluster system is in a state of low power output. During this period, the electricity output from renewable energy generation cannot meet the consumption of all energy conversion equipment and energy storage equipment. The shortage of electric energy can be compensated by purchasing electricity from the energy network. Part of the electricity purchased is coordinated and supplied to seawater desalination equipment, pyrolysis furnaces, P2G devices, and gas-making devices. At the same time, the large-capacity power storage device is charged during this period to meet the demand of various types of load during the peak period of system power consumption, thus reducing the cost of purchasing electricity from the energy network by the cluster system. According to the multi-type load demand of each microgrid in the cluster system, each microgrid in the cluster considers the time-of-use electricity price to choose to purchase electricity storage from other microgrids during the trough period to meet the demand for electricity load during its peak period. While improving the energy utilization efficiency of each microgrid, this also reduces the operating cost of the cluster system. In addition, from Figure 14, it can be seen that each microgrid cluster purchases electricity from other microgrids or energy networks between 22:00–06:00 and between 14:00 and 17:00 during the valley period of electricity consumption, thereby reducing the cost of purchasing electricity from energy networks during the peak period of energy consumption and improving the real-time power utilization efficiency of the system throughout the scheduling period.

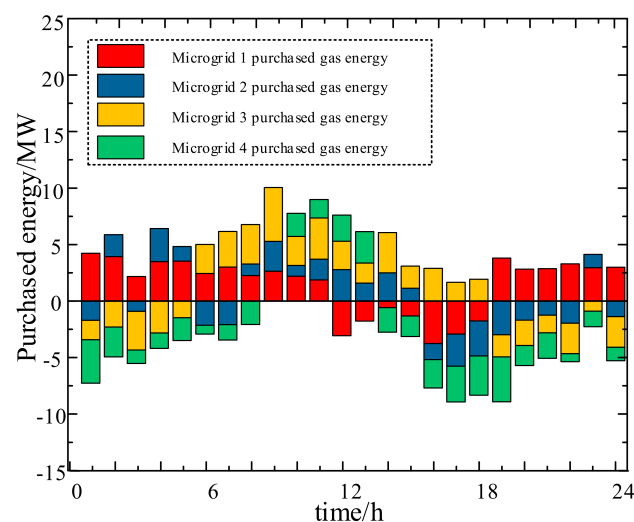


Figure 11. Gas energy purchased by network.

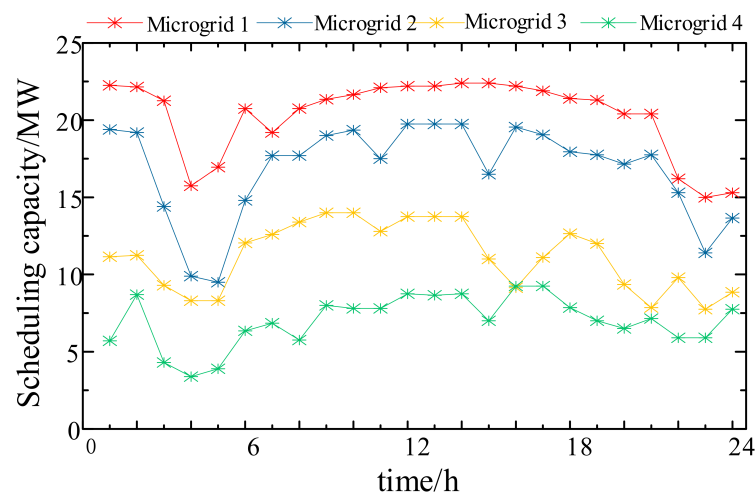


Figure 12. Microgrid power scheduling.

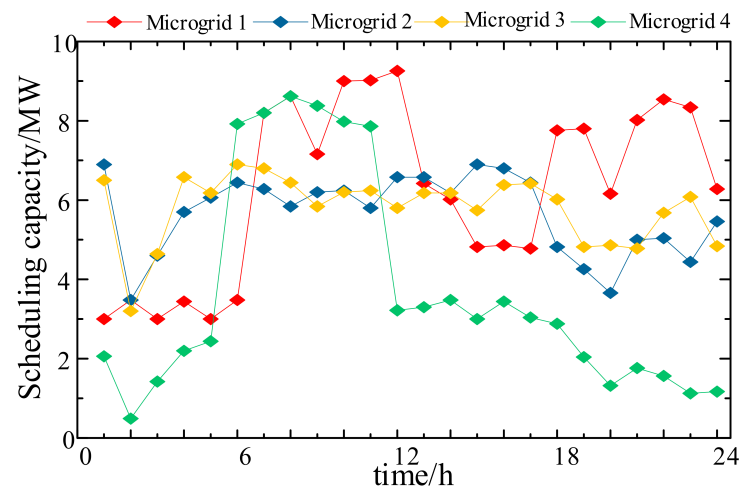


Figure 13. Gas energy scheduling of each microgrid.

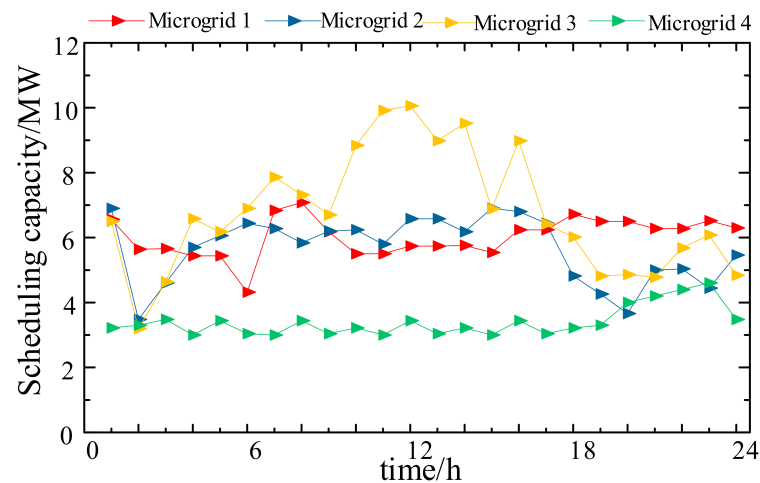


Figure 14. Thermal energy scheduling of each microgrid.

6. Conclusions

The cluster optimization of the integrated energy system in the park, based on demand response, demonstrates that, by integrating multi-type demand response mechanisms, exploiting the flexible adjustment resources on the demand side of the park cluster, and combining complementary energy trading with multi-energy collaborative scheduling among the parks, the output fluctuations of distributed renewable energy can be effectively suppressed, the overall load curve can be smoothed, and the local consumption capacity of the park cluster for clean energy, such as wind and solar energy, can be significantly improved. At the same time, the overall operating cost and carbon emission of the system can be reduced, and the comprehensive energy utilization efficiency and energy supply reliability can be improved. In the future, it remains necessary to further deepen the research on the improvement of user participation, multi-scenario uncertainty processing, and intelligent scheduling technology to better support the balance of supply and demand in the park.

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