

A Reliability Assessment of an Integrated Energy System Based on Coupling Energy Flow and Thermal Inertia

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Abstract—With the wide application of integrated energy systems (IES), the degree of coupling between different types of energy sources is further strengthened, and the mechanism of fault development tends to be complicated. Therefore, in order to improve the accuracy and practicability of the reliability assessment of IESs, a sequential simulation reliability assessment method considering multi-energy flow and thermal inertia is proposed in this paper. In this method, the IES structure model is constructed with the combined cooling, heating and power (CCHP) unit as the core equipment, combining with the new energy source to realize the comprehensive energy power flow calculation considering any loss. Then, a load reduction optimization model is established, considering the importance of load and operational economy, in the system status analysis. Furthermore, the heat supply reliability index is corrected taking into account the transmission delay characteristics and terminal thermal inertia. A case study based on the 20-node and the analysis of the influence factors demonstrates the validity of the proposed method.

Index Terms—Combined cooling, heating and power (CCHP), integrated energy system, multi-energy flow calculation, reliability assessment, thermal inertia.

NOMENCLATURE

GT	Subscript denoting the gas turbine generator.
WHB	Subscript denoting the waste heat boiler.
LB	Subscript denoting the lithium bromide unit.
HP	Subscript denoting the heat pump.
EB	Subscript denoting the electrical boiler.
D	Subscript denoting the distributed photovoltaic.
H	Superscript denoting the conversion to heating power.
C	Superscript denoting the conversion to cooling power.
P	The electrical power of the system.
Φ	The thermal power of the system.
Ψ	The cooling power of the system.
E	The economic cost of the load.
R	The reduction of the load.
η	The efficiency coefficient of the energy conversion.
λ	The average failure rate.

μ	The average repair rate.
S	The supply capacity of the natural gas flow.
$G_{\max}$	The maximum local light intensity.
k_1, k_2	The shape parameters of the Beta distribution.
A	The incidence matrix of thermal pipe networks.
m	The matrix of the distribution of the flow in the pipes.
T_{si}, T_{sj}	The temperatures of the inflow node and outflow node of the supply water network.
T_{ri}, T_{rj}	The temperatures of the inflow node and outflow node of the return water network.
T_{en}	The environmental temperature.
T_{hi}	The initial indoor temperature.
ξ	The thermal conductivity of unit pipe.
d_{ij}	The length of the pipe from i -th node to j -th node.
C_p	The specific heat of the circulating water.
ρ	The density of indoor air.
c	The specific heat capacity of air.
V	the volume of indoor air.
h	The surface heat transfer coefficient of convective heat transfer between building and air.
a	The area of the building surface.
χ	The thermal reserve coefficient of the building surface.
l	The length of the pipes.
ν_w	Velocity of the water flow.
$S_{L,i}$	The reliability status of the i -th load node.
t_p	The allowable time of temperature change considering the storability of the buildings.
t_r	The duration of the energy recovery.
q	The heat dissipation per unit length of radiator through natural convection.
t_u	The duration of the temperature recovery.
AITC	The average interruption times of customer.
AIHC	The average interruption hours of customer.
RS	The reliability of service.
t_{fi}	The duration of i -th power failure.
t_s	The annual standard energy supply time.
N_{fi}	The number of users affected during i -th failure period.
N	The total number of system users.

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I. INTRODUCTION

THE importance of an integrated energy system (IES) has been increasingly recognized with the industrial

goal of energy saving, emission reduction and energy stress reduction [1]. Through the multi-energy coupling link comprehensive utilization, an IES can not only break through the system and technology barriers of the traditional energy supply systems, but also improve the energy supply reliability of the system by interflow substitutability and complementarity [2]. Meanwhile, these new techniques bring extra uncertainties and threats to the reliability of a power system [3]. More specifically, the stability of an IES may be influenced by the high interdependency between the subsystems. In some scenarios, some component failures can affect key coupling nodes and cause large-scale cascading problems, which have been a potential risk for system operations. Also, considering the fundamental purpose of the IES, analyzing the quality of the energy supply is an important way to measure basic value of the system. Actually, with the further understanding of its operation characteristics and coupling structures, an improved reliability evaluation method still remains to be proposed, which has very little research reported on this aspect. Therefore, considering the characteristics of the IES, establishing comprehensive reliability indexes and research assessment methods has become an significant problem to be solved in the planning and operation of the system.

In previous studies for reliability assessment of the IES, four primary categories were given significant attention, including component reliability modeling, fault state analysis, reliability index construction and the evaluation method. In terms of component reliability modeling, the two-state Markov chain is widely used to characterize the reliability of the basic equipment in electrical, thermal and gas networks [4]. Furthermore, reference [5] established the availability model for a gas unit, comprehensively considering the influence mechanism with the failure of the gas equipment itself and the failure of other subsystems. Regarding the fault state analysis, most studies used failure consequence analysis to traverse the effects of each component failure on various loads within the system and quantified the resulting impact based on load shedding strategies. During the process, it's important to take advantage of the variation of different energy forms to reduce energy loss. To be specific, there are several models concerning fault load reduction of an IES: one is based on the objective function that targets the sum of the reductions in electricity, gas, or heat load [6], [7]; the other is to optimize the load reductions with the minimum operating cost of the system [8], [9]. Considering the complexity of energy diversity, a priority-based load shedding strategy was formulated to ensure the energy consumption in multi-energy buildings [10], which refined the emergency treatment and improved the reliability. Also, based on the coupling between different energy forms, the minimization of conflicting costs was considered [11].

For the calculation of the assessment indexes, reference [12] introduced the traditional power system reliability indexes including the system average interruption frequency index (SAIFI) and the system average interruption duration index (SAIDI) to the heating and gas supply subsystems to form an index system. Considering the diversity of application scenarios, new index systems are brought up with strong pertinence and refinement. In [13], considering the impact

of connecting multi-energy storage systems, two reliability indexes are introduced, including loss of frequency probability and loss of duration probability to describe the characteristics of the system. Also, considering the thermal inertia of the terminal building [14], [15], the status change of the system is in time-delay. Combined with the thermal characteristics of the building's exterior, the heat transfers are modeled in detail and arranged [16], [17]. In literature, it can be largely found that the instant state and temperature recovery time determine the change of the users' heating temperature. While the influence of coupling subsystems is not currently considered in reliability evaluations, the detailed analysis remains to be discovered.

In terms of the evaluation method, the reliability assessment of traditional power systems primarily includes the analytical method and simulation method. The analytical method is adopted to access the reliability of the electricity-gas coupling system [18], considering that increasing the energy system size and the complexity of coupling between different subsystems, the practicability and accuracy of the method will be affected. Thus, the Monte Carlo simulation method is introduced to achieve the assessment of the IES [19], [20]. The method can comprehensively analyze the influence of the failure of different subsystems and consider their randomness [21], which provides an effective method to quantify their reliability.

Comparing the current methods for the reliability evaluation of IES, we conclude that the following problems still remain to be improved: First, the research primarily involves concerns about the temperature change of the thermal terminals, lacking any consideration about the actual network topology and the heat network transmission loss. This simplification means it can hardly reflect the impact of the transmission networks on the reliability, which may cause inaccurate results. Second, load shedding strategies are mostly formulated from the perspective of energy suppliers, ignoring the differences in users' demand for energy supply reliability. Also, considering the judgment of the users' heating reliability, the evaluation based on a fixed failure evaluation temperature tends to be impractical. Third, due to the thermal inertia and delay of transmission networks, the change of the system status at the moment of failure has a time lag. Furthermore, the users' thermal temperature is jointly determined by the duration of the failure and the current status, which has a significant impact on the reliability. However, most of relevant studies lack the timing analysis of the fault process and the accurate calculation of the operational status, which cannot deeply reflect the characteristics. Therefore, considering the different types of energy interruptions of users, the characteristics of each subsystem, and their multi-energy complementarity, under the failure to establish the comprehensive reliability evaluation method, has become a significant goal.

After the analysis of all the different aspects, this paper aims at establishing an accurate and efficient method for IES reliability assessment. Considering the space-time coupling between subsystems, based on the existing research, this paper proposes an IES sequential simulation reliability evaluation method considering multi-energy flow and thermal inertia. The main contributions are concluded as:

1) A multi-energy flow model for simulating electric-thermal system operation and a load shedding optimization model considering load importance and operational economy are established.

2) According to the different characteristics of multi-energy flow, the thermal network transmission delay and its terminal thermal inertia are used to correct the thermal reliability indexes.

3) Combining a multi-energy flow calculation with sequential Monte Carlo, the IES reliability evaluation method is proposed. With the consideration of network topology, transmission delay, terminal thermal inertia and reliability requirements of users, this method improves the accuracy of the IES reliability assessment and provides technical support for the operation and design of the actual system.

II. IES MODEL DESCRIPTION

The core structure of the IES flexibility lies in the combined cooling, heating and power unit (CCHP), which is combined with the gas turbine generator (GT), waste heat boiler (WHB) and lithium bromide unit (LB). On this basis, the joint configuration with ground source heat pump (HP) is considered to achieve the decoupling of cold/heat and power supply according to the flexible operation of the unit. And the electrical boiler (EB) is configured to handle the peak load and serve as a heat source backup in case of fault of the generator set. In addition, a distributed photovoltaic (PV) is connected to the grid to locally consume renewable energy. The basic structure of the system is shown in Fig. 1.

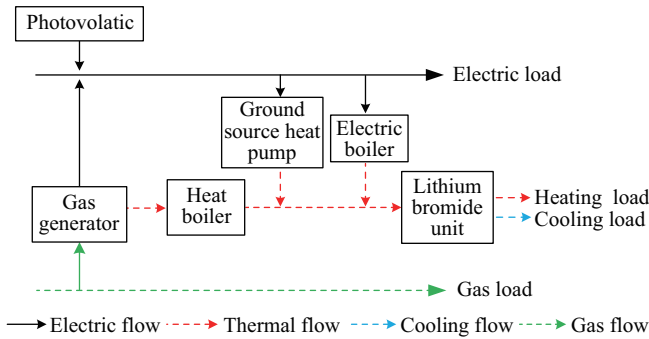


Fig. 1. Schematic diagram of an integrated energy system.

A. Model for Equipment and Operating Principles

1) Gas turbine generator: The gas turbine generator uses high-temperature and high-pressure gas generated by natural gas combustion to produce electricity. And the recoverable medium with low temperature heat is absorbed by the waste heat boiler to produce heat. Considering the energy conversion characteristics, the operating model of the gas turbine generator is established:

$$\begin{cases} P_{GT} = \eta_{GT}^E S_{GT} \\ \Phi_{GT} = \eta_{GT}^H S_{GT} \end{cases} \quad (1)$$

where P_{GT} and Φ_{GT} are the output electrical power and thermal power respectively; S_{GT} denotes supply capacity of

the natural gas flow; η_{GT}^E , η_{GT}^H are the electricity production coefficient, and heating coefficient of the gas turbine generator respectively.

2) Waste heat boiler: The equipment can use waste gas in the production process to heat water to a certain temperature to achieve heat energy recovery. The production process can be characterized as:

$$\Phi_{WHB} = \eta_{WHB} \Phi_{GT} \quad (2)$$

where Φ_{WHB} , η_{WHB} represent the output thermal power and the recovery efficiency of waste heat boiler.

3) Electric heating equipment: The equipment including ground source heat pump and electrical boiler can obtain energy through heat exchange from the power system. And the relationship can be expressed as:

$$\Phi_{HP} = \eta_{HP} P_{HP} \quad (3)$$

$$\Phi_{EB} = \eta_{EB} P_{EB} \quad (4)$$

where, Φ_{HP} , Φ_{EB} are the output thermal power of the heat pump and electrical boiler; P_{HP} , P_{EB} are the input electrical power of the equipment; η_{HP} , η_{EB} are the coefficients which indicate the efficiency of the conversion.

4) Lithium bromide unit: The energy of each heat source is transmitted to the heat station where it is equipped with an absorption type lithium bromide unit at the end of the pipe network. During the heating period in winter, the heat exchange between the first and second pipe networks is directly performed, and in the summer the demand for cooling can be satisfied through the lithium bromide unit with the secondary pipe network, so the corresponding model can be established according to the capacity mode of the unit in different seasons:

$$\Phi_{LB} = \eta_{LB}^H \Phi_{HN} \quad (5)$$

$$\Psi_{LB} = \eta_{LB}^C \Phi_{HN} \quad (6)$$

$$\Phi_{HN} = \Phi_{WHB} + \Phi_{HP} + \Phi_{EB} \quad (7)$$

where Φ_{HN} is the input thermal power which is absorbed from heat conversion equipment such as a heat hump; Φ_{LB} , Ψ_{LB} are the heating power and cooling power of the lithium bromide unit respectively which are output for users; η_{LB}^H , η_{LB}^C represent the coefficients which indicate the conversion efficiency of the heating and cooling process.

5) Distributed photovoltaic: With the increasing proportion of new energy being connecting to the systems, considering the integrating of new energy sources is of a great significance for the operational analysis of an IES. On the one hand, a distributed photovoltaic can provide a new source of power and increase the abundance of the grid. On the other hand, its stochastic fluctuation characteristics may bring potential dangers to the operating status. In order to effectively characterize this feature, a multi-time sampling method is adopted to calculate the PV output power. According to reference [22], the Beta distribution is used to describe its corresponding output characteristics, which is shown in (8):

$$\varphi_{\nu}(G) = \frac{\Gamma(k_1 + k_2)}{\Gamma(k_1)\Gamma(k_2)} \left(\frac{G}{G_{\max}} \right)^{k_1-1} \left(1 - \frac{G}{G_{\max}} \right)^{k_2-1} \quad (8)$$

where $G_{\max}$ represents the maximum local light intensity; G represents the local intensity; $\Gamma(x)$ represents that a random variable x that is gamma-distributed; k_1 and k_2 are the shape parameters of the Beta distribution. Considering the various weather conditions, classification samplings are carried out. And the curves are randomly chosen based on the possibility of weather in different seasons, which are included in the appendix.

6) The operating principle of the electric flow: Based on the equipment model of the IES, considering the transmission balance of the energy flow of each node of the system, the operational energy flow balance model is established for the electric and thermal subsystem respectively. The IES is based on the regional power grid and is connected to the external power grid through a medium voltage line to ensure the reliability of the power supply in the event of system failure. Therefore, the electric operation condition is fixed by the heat setting. Due to the differences between the operational mode of heating and cooling, it is necessary to establish a balance model between the heating energy flow and cooling energy flow, which is expressed as:

$$\begin{cases} P_{DN,i} + P_{D,i} + P_{GT,i} - P_{HP,i} - \\ P_{EB,i} - P_{L,i} - P_i = 0, & i = 1, 2, \dots, n_p \\ \Phi_{LB,j} - \Phi_{L,j} - \Phi_j = 0, & j = 1, 2, \dots, n_\Phi \\ \Psi_{LB,k} - \Psi_{L,k} - \Psi_k = 0, & k = 1, 2, \dots, n_\Psi \end{cases} \quad (9)$$

where $P_{DN,i}$ denotes the electrical power injected by the 10 kV distribution network at the i -th node; $P_{L,i}$ is the electric load at the i -th node; $\Phi_{L,j}$, $\Psi_{L,k}$ are the thermal load of the j -th node and cooling load of the k -th node respectively; $P_{D,i}$ is the injected electrical power of the photovoltaic; P_i represents the outflow electrical power of the i -th node; Φ_j , Ψ_k are the injected thermal power and cooling power of the nodes; n indicates the different node sets including electric, thermal and cooling network respectively; other coefficients represent the output of the equipment which have been introduced.

B. Model for Multi-energy Flow Calculation

Due to the time-series correlation of the thermal network state, it is necessary to perform a co-simulation to extract the operating state of the system during failure to analyze the energy supply reliability index. In this paper, electric and thermal coupling flow are applied to quantify the system status of each period. And the status parameters include node voltage, branch power, circulating water temperature, pipeline flow and water pressure, etc. In order to simulate the practical condition, the operational mode is adopted for the flow calculation. During this process, the thermal flow is calculated first to obtain the distribution of the heating flow and the temperature of the circulating water. Thus, the thermal power from the heat source required to maintain the temperature of the heating water is determined. Finally, the equivalent power load of the electric-heat transfer equipment in the electric subsystem is obtained by the model of the device at the coupling node, and the power flow of the electric subsystem is calculated. Based on the various functions in the

process, the multi-energy flow calculation can be divided as thermal flow, electric-thermal coupling flow and electric flow.

1) Thermal flow: The thermal network model involves hydraulic circulation and the heat exchange process. In this paper, high temperature circulating water is considered as the heat medium in the thermal network. Ignoring the small volume changes caused by the differences of the temperature between the supply and return pipes, the circulating water networks can be equivalent to a pipe network for hydraulic calculation, and the flow balance equation is used to establish a hydraulic model for the radial thermal network, which is expressed as:

$$Am = m_q \quad (10)$$

where A is the incidence matrix of the thermal pipe branch and node; m is the matrix of the heating water flow in the pipes; m_q represents the increment of the injected heating water from the coupling nodes.

The temperature of the circulating water at each node is analyzed in the model to reflect the energy exchange in the thermal network under the transmission loss. The target thermal node's temperature depends on the temperature of the upper node, the ambient temperature, the pipe flow rate, as well as the energy loss characteristic of the pipe, which is shown as:

$$T_{sj} = (T_{si} - T_{en}) \exp\left(\frac{-\xi d_{ij}}{C_p m_{ij}}\right) + T_{en} \quad (11)$$

where T_{si} , T_{sj} are the temperatures of the inflow node and outflow node in the supply water network; T_{en} represents the environmental temperature; ξ indicates the thermal conductivity of the unit pipe; d_{ij} denotes the length of the pipe from i -th node to j -th node; C_p is the specific heat of the circulating water; m_{ij} represents the heating water flow in the pipes.

Similarly, the model of the return water network temperature can be determined by:

$$T_{rj} = (T_{ri} - T_{en}) \exp\left(\frac{-\xi d_{ij}}{C_p m_{ij}}\right) + T_{en} \quad (12)$$

where T_{ri} , T_{rj} are the temperature of the inflow node and outflow node of the return water network.

The heat medium is flowing into the return water network after the heat exchange at the load point. The water temperature change caused by the physical process is primarily related to the thermal load and water rate, which is characterized by the specific heat capacity model:

$$\Phi_{L,j} = C_p m_l (T_{sj} - T_{ri}) \quad (13)$$

where m_l represents the water flow passing the load node. For the nodes with multiple ports involving the mixture process, the temperature of the water after mixing can be calculated by the law of conservation of heat.

$$\sum (m_{out} T_{out}) = \sum (m_{in} T_{in}) \quad (14)$$

where m_{in} is the volume of inflow; T_{in} is the temperature of the inflow. The return water temperature of the heat source is obtained according to the heat flow of the heat network, and

the circulating water has to be heating in the heat source to maintain the balance of the system.

2) Electric-thermal coupling flow: The nodes configured with a combined heat and power unit, ground source heat pump and electrical boiler are regarded as the coupling node of the network, and the set of the electric heating equipment as the load of the power subsystem. When the heat production of each device is calculated through the thermal network balance, the electrical power consumed by each electric heating equipment can be obtained from the model shown in (3) and (4), which is regarded as the equivalent distribution load.

3) Distribution network flow: In the grid, electric sources include the power grid and photovoltaic, and the load primarily includes the conventional load and equivalent electrical load of the coupling equipment. In this paper, the nodes connected to the higher voltage power grid are regarded as the balance nodes, and the equivalent model of the multiple equipment connecting is considered to establish the balance of the power system [23].

$$\begin{cases} P_i - \sum_{j=1}^n [e_i (G_{ij}e_j - B_{ij}f_j) + f_i (G_{ij}f_j + B_{ij}e_j)] = 0 \\ Q_i - \sum_{j=1}^n [f_i (G_{ij}e_j - B_{ij}f_j) - e_i (G_{ij}f_j + B_{ij}e_j)] = 0 \end{cases} \quad (15)$$

where P_i , Q_i are the active and reactive powers injected into the i -th node; e_i , f_i are the real and imaginary parts of the i -th node voltage respectively; G_{ij} , B_{ij} are the conductance parameters between i -th node and j -th node, and the parameters of the susceptance.

III. THE MODIFIED SEQUENTIAL RELIABILITY ASSESSMENT METHOD FOR THE IES

A. Model for Component Reliability

The two-state model is widely used in power system reliability assessment methods, and is applied to characterize the operating state of the components in the electric and thermal subsystems. Furthermore, the normal and fault states are characterized by two parameters: component failure rate λ and repair rate μ . The components' status sequence can be obtained by simulation sampling of the time to failure (TTF) and the time to repair (TTR). According to the current reliability assessment theory, the sample values of each state duration are generally subject to an exponential distribution [24].

$$TTF = -\frac{1}{\lambda} \ln \sigma_1 \quad (16)$$

$$TTR = -\frac{1}{\mu} \ln \sigma_2 \quad (17)$$

where σ_1 , σ_2 are the random numbers obeying the uniform distribution between 0 to 1.

B. System Fault States Analysis

1) The failure analysis of the independent electric system: When the components of the electric subsystem are faulty,

the evaluation method based on the minimal path is used to traverse all the electrical loads in the system, and the power supply status of each load point under the fault condition can be analyzed [25]. In the definition, the path represents the set consisting of a directed arc and an undirected arc connecting any two nodes. If one path can no longer form a connection when any arc is removed, the path is called the minimum path. Considering the application in the electrical system, two scenarios will be discussed.

a) The Faulty Component is on The Minimum Path

According to the connectivity analysis, the faulty component will cause the load power supply to be interrupted, and the branch of the component needs to be isolated by the switching operation. This operation will cause the load to be powered off until the faulty component is repaired; when the switching is considered, the load can be transferred to an alternate line via the tie switch.

b) The Faulty Component is Not on the Minimum Path

After searching for the nearest circuit breaker upstream of the faulty element, if the circuit breaker is on the minimum path of the load, the isolation operation of the faulty component will cause a short-term power outage to the load, otherwise the faulty component will not cause the load to be interrupted.

Based on the analysis, the implication can be expressed as:

$$\beta_j = \prod_{i \in s} \beta_i \quad (18)$$

where β_j is the energy supply status of the j -th load node, and the value 1 is working as well as 0 in the faulty component. s represents the set of the nodes on the minimum path as well as the additional components.

2) The failure analysis of the thermal system considering thermal inertia: In order to understand the reliability of the heat load in the thermal subsystem, it is necessary to analyze the temperature change process of the load. The lumped parameter model of unsteady heat conduction is used to analyze the variation of indoor average temperature with time. And the energy conservation relationship of building load can be shown by the following equation.

$$\rho c V \frac{dT}{dt} = -ah(T - T_{en}) \quad (19)$$

where ρ is the density of the indoor air; c is the specific heat capacity of air; V is the volume of indoor air; h is the surface heat transfer coefficient of convective heat transfer between the building and outdoor air; a represents the area of the building surface. The temperature change of the load is primarily affected by factors, such as the building envelope structure and outdoor temperature. The influence of the envelope on the temperature change process can be simplified as the effect of the building thermal reserve coefficient χ , and its model is shown as follows.

$$\chi = \frac{\rho c V}{ah} \quad (20)$$

The greater the reserve coefficient χ , the better the heat storage ability of the material, and logically, the stronger its ability to withstand temperature fluctuations. Therefore, the

network terminal exhibits the thermal inertia of the indoor temperature drop in the winter and the indoor temperature rise in the summer, and the actual power supply fault time on the user side lags behind the component failure time. The parameter is based on the national building climate zoning standard, which divides the outdoor temperature of the heating area into 4 intervals, and defines the reference value of the heat storage coefficient in the heating zones.

According to (19), the minimum standard temperature and the maximum standard temperature are respectively set for the central heating in winter and cooling in summer. Considering the heat storage coefficient of different loads and the environmental temperatures, the time required for the indoor temperature to change to the standard can be calculated. To reflect the delay caused by the thermal inertia of the building, the duration of this period can be defined as temperature change time t_p :

$$t_p = \chi \ln \frac{T_{hi} - T_{en}}{T_p - T_{en}} \quad (21)$$

where T_p is the standard temperature including the minimum criterion temperature and the highest criterion temperature; T_{hi} is the initial indoor temperature of the building.

The thermal network is primarily composed of the heat source, pipeline, valve and compensator. When the heat source equipment fails, the heat load has to be reduced as the heating power is insufficient. And the failure of the pipeline and valve will also cause the interruption of the heating energy flow. The fault location and repair work of the component starts from the moment when the fault occurs, and the fault is repaired after the TTF , and the heat energy is transmitted to the user after the delay t_c when the user heat supply is restored again. The specific mathematical expression is shown in (22):

$$\begin{cases} t_r = TTF + t_c \\ t_c = l/v_w \end{cases} \quad (22)$$

where, t_r is the energy recovery time; l is the length of the pipes; v_w is velocity of the water flow.

If the energy recovery time is less than the allowable temperature change time t_p , this means the user's indoor temperature does not deviate from the standard temperature range when the power is restored. Then the load point is regarded as a normal state, otherwise it is recorded as a fault.

$$S_{L,i} = \begin{cases} 1, & t_p - t_r > 0 \\ 0, & t_p - t_r < 0 \end{cases} \quad (23)$$

where $S_{L,i}$ is the reliability status of the i -th node.

C. The Model for IES Load Shedding Optimization

When the components fail and the energy supply cannot be adequately guaranteed, load reduction is needed to maintain the stable operation. Through the initial multi-energy flow calculation, the power shortage in different subsystems is obtained. On the premise of obtaining better operational economy in the system, the supply to the pricey load can be maintained by reducing the output power of the coupling equipment. Meanwhile, considering the important degree of

different loads, the subsystem will also give priority to the reliability of the load points with higher importance levels to realize the higher value of the energy. After the repeated multi-energy flow calculations ensuring the constraint conditions, the load shedding, considering the stable and economic operation of the system, is realized. And the data about the energy supply are recorded for reliability assessment.

1) The objective function: This function considers the energy consumption price of electricity, heat and cold and the relative importance of electricity load, and takes the economy of the equivalent load reduction as the optimization object.

$$\min f = \sum_{i=1}^{n_p} E_{p,i} \nu_i R_{p,i} + \sum_{j=1}^{n_\Phi} E_{\Phi,j} R_{\Phi,j} + \sum_{k=1}^{n_\Psi} E_{\Psi,k} R_{\Psi,k} \quad (24)$$

where ν_i is the relative importance coefficient of the electrical load; $E_{p,i}$, $E_{\Phi,j}$, $E_{\Psi,k}$ represent the economic price of the electric, thermal and cooling load; $R_{p,i}$, $R_{\Phi,j}$, $R_{\Psi,k}$ are the reduction amounts of the load.

2) The constraint condition: Based on the multi-system coupled operational energy flow model in modeling, constraint equations can be established for the load reduction.

$$\begin{cases} P_{DN,i} + P_{D,i} + P_{GT,i} + R_{p,i} - P_{HP,i} - \\ P_{EB,i} - P_{L,i} - P_i = 0, & i = 1, 2, \dots, n_p \\ \Phi_{LB,j} + R_{\Phi,j} - \Phi_{L,j} - \Phi_j = 0, & j = 1, 2, \dots, n_\Phi \\ \Psi_{LB,k} + R_{\Psi,k} - \Psi_{L,k} - \Psi_k = 0, & k = 1, 2, \dots, n_\Psi \end{cases} \quad (25)$$

In addition, the load reduction optimization model also includes the upper and lower limits of each node voltage, branch power, line flow, load reduction, and unit output.

D. Corrected Reliability Indexes of the IES

Quantified indexes are the foundation of reliability assessment. In the study of this article, the traditional adequacy indexes are corrected according to the delay characteristics of system network. Specifically, the average interruption times of customer (AITC), the average interruption hours of customer (AIHC), and the reliability of service (RS) are used as reliability indexes, and some details are explained in (26), which can be defined as:

$$AITC = \frac{\sum N_{fi}}{N} \quad (26)$$

$$AIHC = \frac{\sum t_{fi}}{N} \quad (27)$$

$$RS = \left(1 - \frac{AIHC}{t_s}\right) \times 100\% \quad (28)$$

where t_{fi} , N_{fi} are the duration of each failure period and the number of users affected respectively; N is the total number of system users; t_s is the annual standard energy supply time.

The failure consequences of the thermal network components show the delay characteristics, which makes it impossible to directly use the sample values to calculate the indexes. It

is for this reason that the heat load on the network is thermally inert and the differences between the transmission speed of the cold/heat energy flow with the electricity also brings about the delay of the users' power supply recovery time. This section takes into account the thermal storing of the building, the weather and other factors to correct the IES reliability indexes. The process simulation can be implemented by establishing a temperature recovery model by the law of conservation of thermodynamic energy.

$$qvt_u^2 = \alpha cpV(T_p - T_f) \quad (29)$$

$$t_r = \chi \ln \frac{T_{hi} - T_{en}}{T_f - T_{en}} \quad (30)$$

where, q is the heat dissipation per unit length of the radiator through natural convection; v is the speed of the circulating water; t_u denotes the duration of the temperature recovery; α is the heat loss coefficient.

Based on (29), (30), the temperature recovery time t_u can be expressed explicitly as:

$$t_u = \sqrt{\frac{\alpha cpV(T_p - T_{en} - (T_{hi} - T_{en})/e^{t_r/\chi})}{q\nu}} \quad (31)$$

Therefore, if the thermal component fails to cause the heating process to be interrupted, the time when the user's indoor temperature actually deviates from the standard temperature range is recorded as the statistical data, which is primarily composed of the energy recovery time t_r , the allowable temperature change time t_p , and the temperature recovery time t_u . And the expression is:

$$t_f = t_r - t_p + t_u \quad (32)$$

where t_f is the interruption time of the thermal supply after correcting.

E. Connections Between Each Module

In order to clarify the proposed IES reliability evaluation method, the connections between each module need to be introduced in detail, which primarily includes parameter transfer and calculation analysis. And the specific contents are shown in this section.

1) Based on (16), (17), the sampling of the component status can be accomplished for analysis. Taking the electric system as an example, the information about the power failure element i and its duration t is recorded.

2) Based on the information of the fault component from the previous step, the node set q which is affected by the failure of the element is determined by the minimum path method, and the further impact on the energy flow is analyzed,

a) Based on the judgement standard of the minimum path, the energy supply and consumption of the nodes will be affected, which can be respectively expressed as:

$$\begin{cases} (P_{DN,i} + P_{D,i} + P_{GT,i} + P_{in,ij}) = 0, & i \in s \\ (P_{HP,i} + P_{EB,i} + P_{L,i} + P_{out,ij}) = 0, & i \in s \end{cases} \quad (33)$$

b) According to (1)–(6), the characteristics of the thermal flow are further obtained. For example, the thermal power of

the heat pump can be expressed as (34), when the electric flow is affected,

$$\Phi_{HP} = \eta_{HP} \left(P_0 - \sum_{i \in q} P_{HP,i} \right) \quad (34)$$

Combined with the basic physical characteristics, the initial multi-energy flow calculation is realized to obtain the distribution of the comprehensive flow.

3) Based on the operational mode and status parameters, the power deficit is calculated for different systems. Furthermore, considering the importance and type of each load node, the optimization load shedding model is carried out. The process can be shown as,

$$\begin{cases} R_p = R_{DN} + P_D + P_{GT} - (P_{HP} + P_{EB} + P_L) \\ R_\Phi = \Phi_L - \Phi_{LB} \\ R_\Psi = \Psi_L - \Psi_{LB} \end{cases} \quad (35)$$

According to the importance degree and the prices, some nodes are selected for load shedding. And combined with the constraint conditions, the optimization operation of the system is realized by reducing the specific load.

4) The fault data are gathered for calculation during the process. Also, the corresponding reliability index is corrected.

F. The Modified Sequential Monte Carlo Simulation Method Considering the Thermal Inertia

In this paper, the sequential Monte Carlo simulation [26] is realized, combined with the multi-energy flow calculation. Based on the system state sampling, state analysis and indicator statistics, the evaluation is showed in Fig. 2, and the main steps are also explained.

1) Components status sampling: During the simulation period, considering the two-state Markov model, random sampling for each component is repeated. And the corresponding failure details are extracted for the deep analysis.

2) Flow calculation: According to the thermal power flow model proposed in this paper, the load of the electric-thermal coupling node is defined. Then, the flow of the distribution network is calculated considering the network topology, local electric load and the sampling results of the PV.

3) Optimization of the load shedding: Combined with the importance of the load points and flow characteristics, the loads of different types are analysed respectively. Based on the results of step 2, the supply of the multi-energy system can be obtained.

4) Boundary conditions judgement: Considering that the operational status of the system flow has changed after load shedding, it's necessary to analyze the boundary conditions of the IES.

5) Load point reliability indexes calculation: Based on the fault occurrence moment and time of the duration, the power supply interruptions are counted. Furthermore, considering the qualification results of step 3, the reliability indexes are calculated.

6) Reliability indexes correcting: Based on the delay characteristics of the heat exchange and pipelines transmission, the thermal system reliability indexes are corrected.

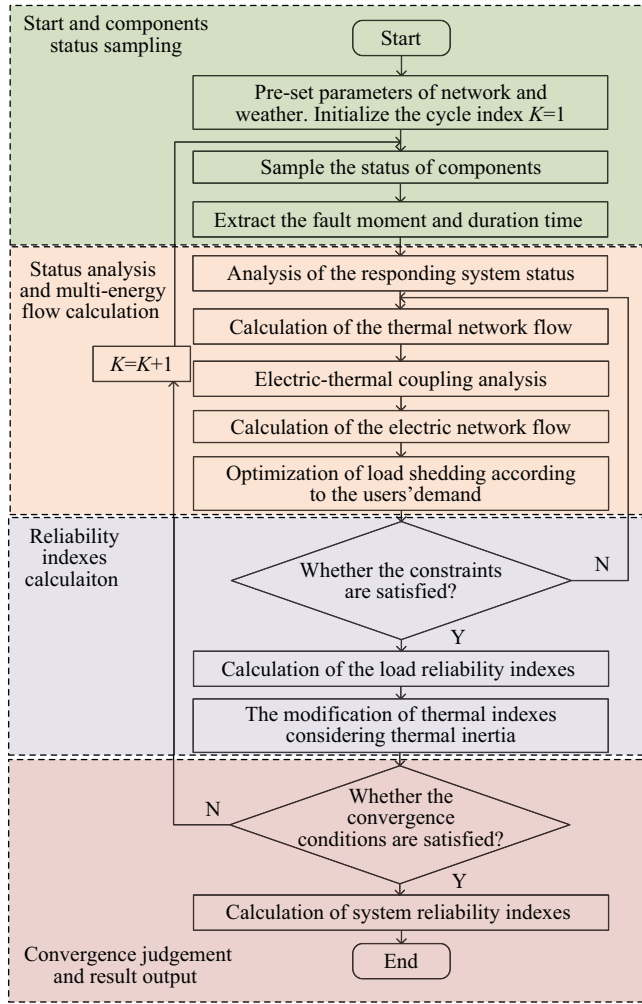


Fig. 2. The reliability evaluation.

7) Convergence judgment: When the variance coefficient of the reliability induces less than the given value or the number of simulated samples, K reaches the maximum number of samples, and the cycle is terminated. Otherwise, step 1 is reperformed for the generation and analysis of the next state.

8) System induces calculation: The corresponding indexes of each load point are counted to form a system reliability assessment.

IV. CASE STUDY

In order to verify the reliability assessment method proposed in this paper, an IES with a 10-node power distribution network system and a 10-node thermal network is introduced. The basic network structure and energy supply equipment are integrated as shown in Fig. 3. The system is connected to the 10 kV city grid and natural gas network.

There are nine load points and three customer types in this system, including residential, commercial and industrial. The electrical, cold and heat load data of the system are shown in Table I. In addition, the important degree of load is primarily established by the analytic hierarchy process, which can combine the qualitative and quantitative characteristics and

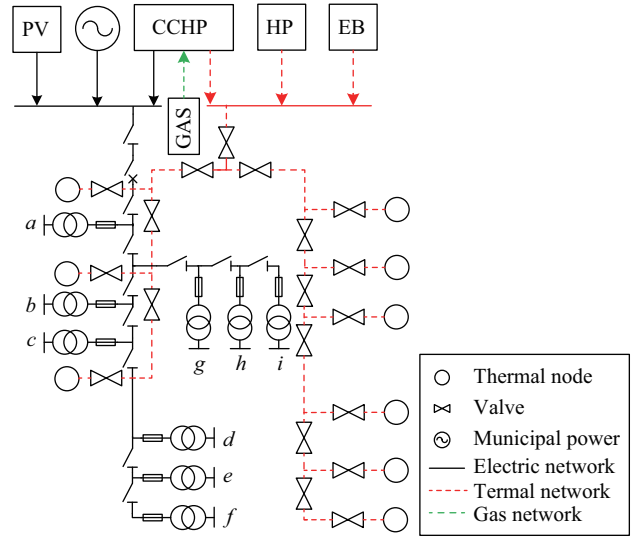


Fig. 3. Network structure of IES.

TABLE I
LOAD SETTING

Node	Type	Electric/heating/ cooling load (MW)	Importance degree	Price of the heating/cooling (yuan/(kW·h))
a	Residential	0.2/0.24/0.4	1.00000	0.477/0.140
b	Residential	0.3/0.36/0.6	1.00000	0.477/0.140
c	Residential	0.4/0.48/0.8	1.00965	0.477/0.140
d	Commercial	0.7/1.05/1.3	1.38786	0.597/0.200
e	Commercial	0.8/1.2/1.4	1.38786	0.597/0.200
f	Commercial	0.9/1.35/1.5	1.45157	0.597/0.200
g	Industrial	1.2/1.8/2.0	1.09881	0.508/0.200
h	Industrial	1.3/1.95/3.2	1.09881	0.508/0.200
i	Industrial	1.4/2.1/2.5	1.28443	0.508/0.200

weigh the relative importance of each element to provide the preconditions for the optimization load shedding model.

The system's electrical demand period is the whole year, the planned heating period is from Nov. 1st to Mar. 31st, the heating temperature standard is at least 16°C, the planned cooling period is from June 1st to Sept. 30th, and the cooling temperature standard is up to 28°C. And the related operating parameters including load change curves are shown in the appendix.

A. The Reliability Assessment Results of the IES

The resulting analysis of the system is completed based on the following three scenarios.

Scenario I: The traditional Monte Carlo simulation method is adopted to evaluate the IES with independent subsystems for electrical, thermal and cold uncoupling supply.

Scenario II: The traditional Monte Carlo simulation method is adopted to evaluate the IES with joint subsystems of electrical, thermal and cold coupling supply.

Scenario III: The simulation method combined with the multi-energy flow and Monte Carlo is adopted to evaluate the IES with joint subsystems of electrical, thermal and cold coupling supply, and establish the statistical heating reliability index with the temperature changing process.

Based on the convergence criteria, the duration of the sequential Monte Carlo simulation is set as 1,000 years after

repeated calculations. And the results concerning reliability indexes and the simulation time of each scenario are shown in Table II.

TABLE II
RESULT OF THE RELIABILITY INDEXES AND SIMULATION TIME

Index	Energy type	AITC (time/year)	AIHC (h/year)	RS (%)	Simulation time (s)
Scenario I	Electric	0.28695	0.76115	99.9913%	306.15
	Heating	2.60714	30.77572	99.1508%	
	Cooling	2.89873	19.64091	99.3274%	
Scenario II	Electric	0.10955	0.24804	99.9972%	1216.32
	Heating	1.36326	13.51166	99.6298%	
	Cooling	1.12414	12.16878	99.6124%	
Scenario III	Electric	0.10955	0.24804	99.9972%	1411.38
	Heating	0.40276	5.05479	99.8615%	
	Cooling	0.47453	4.94338	99.8307%	

1) Comparison of the reliability indexes in scenario I and II: It can be seen from Table I that compared with the traditional mode, the reliability of IES is obviously improved based on the energy complementarity. The AITC of electrical power decreases from 0.28695 times/year to 0.10955 times/year, and AIHC drops from 0.76115 h/year to 0.24804 h/year. Also, the system power supply reliability is increased from 99.9913% to 99.9972%. The improvement of the reliability indexes is primarily due to the operational strategy of reducing the electric-heat transfer equivalent load when the outputs of the internal electric supplies are insufficient. And the improvement of the heating/cooling reliability primarily results from the energy complementarity containing various energy supply modes such as electric-heat, gas-heat and so on. Also, it can be seen that the calculation process of the multi-energy flow greatly increases the simulation time required, while the corrections of the thermal inertia also further adds a certain amount to the computation.

2) Comparison of the reliability indexes in scenario II and III: After the indexes are revised based on the multi-energy flow method and thermal delay characteristics, the AITC decreases from 1.36326 times/year to 0.40276 times/year, and the AIHC decreases from 13.51166 h/year to 5.05479 h/year. It can be seen that the reliability indexes are better than those under the traditional reliability assessment method. In fact, the corrected indexes more accurately depict the user's consumption comfort. The reliability indexes are more intuitively compared with the specific data of the faults, as shown in Fig. 4.

There are 7,461 times of failures of components in IES during the simulation period. In scenario II, there are 11,983 interruptions of heating and 12,231 interruptions of cooling. While, there are 3,599 interruptions of heating and 5,213 interruptions of cooling in scenario III, and the heating/cold failure conversion rates are 30.03% and 42.62%, respectively. The reason for the differences between the conversion rates of the heating/cooling failure is the difference in the temperature standard and the heating/cooling speed of the pipes. By contrast, the delay characteristics of the thermal network transmission and load will have a great impact on the system reliability evaluation, and the traditional reliability indexes are relatively conservative and do not reflect the reliability status of the terminal user.

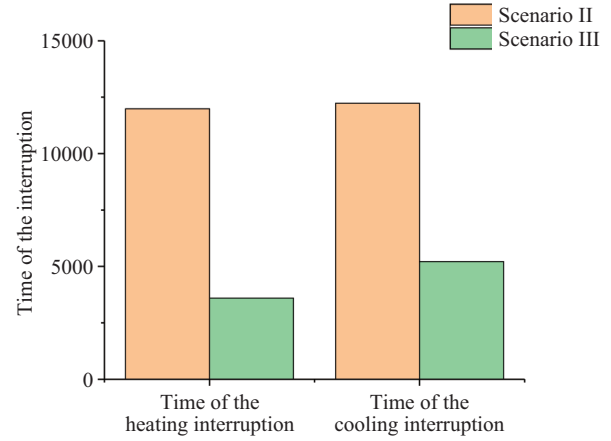


Fig. 4. Compare of the statistical results between the scenarios.

B. Impact of Load Shedding Strategy

Considering the differentiated importance of the electrical load and the price of energy consuming, the load with higher relative importance and energy price will have a better reliability guarantee. The reliability indexes of each node are shown in Fig. 5. The commercial electricity price is higher than the industrial, and the residential electricity price is the lowest. Therefore, the priority is given to the power consumption of nodes d, e, and f in the load reduction, which logically shows the best adequacy of the electric supply. As for different types of loads, nodes c, f, and i have the highest degree of importance in their own load types, and the index AITC all show the lowest value among the same type nodes. Generally, the analysis process proves that IES can realize the reliability guarantees of differentiation by considering the loads of different importance and energy prices.

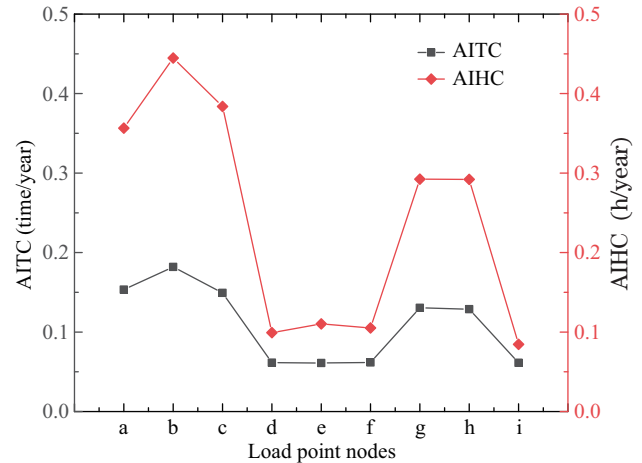


Fig. 5. Reliability indexes of each power load node.

C. Impact of Energy Supply Standard

In this paper, the terminal use heating temperature deviates from the energy supply standard, and is set as the reliability criterion. And based on the thermodynamic characteristics, the temperature change process is modeled to achieve statistical index quantification. Therefore, in addition to the buildings'

thermal reserve coefficient and outdoor temperature, the assessment results are also greatly affected by the energy supply standard.

In order to analyze the influence of differentiated demand, the minimum standard temperature T_p of winter heating is set as a variable, and the results are collected for each node when T_p changes from 10°C to 30°C. Through, marking every three points, the trend of change is shown in Fig. 6.

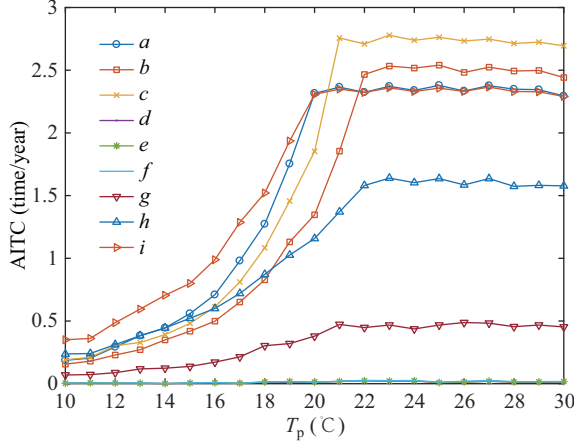


Fig. 6. The trend of indexes considering the changing of the heating temperature.

It can be seen that as the minimum standard temperature rises in winter, the value of the AITC becomes larger. The reason is that when the user's acceptable heating fluctuation range becomes stricter, the reliability of the system is worse. After T_p reaches 22°C, the index value tends to be stable. That's because that the heating demand is so strict that the user temperature drop caused by any component failures will be judged as the terminal user experiencing a fault. On this condition, the assessment results of each load point approach the value of scenario II. In addition, due to the difference prices in the load shedding model, each load point shows differentiated features.

This section verifies that the reliability assessment method can take into account the differential energy demand considering the different types of loads. For example, when the users have different requirements for the minimum heating temperature, the energy supply reliability can be more accurately evaluated.

D. Impact of Thermal Reserve Coefficient

Different types of users in the system have different thermodynamic characteristics, and the building thermal reserve coefficient of the thermal load is an important parameter. In this section, the reserve coefficient is set as a variable to simulate the heating reliability index of each load point, as shown in Fig. 7.

It can be seen that with the continuous increase of the thermal reserve coefficient, the AITC shows a non-linear trend of decline and continuously approaches 0. The reason is that the improvement of load heat storage performance will make the time allowed for the outdoor temperature to drop lower,

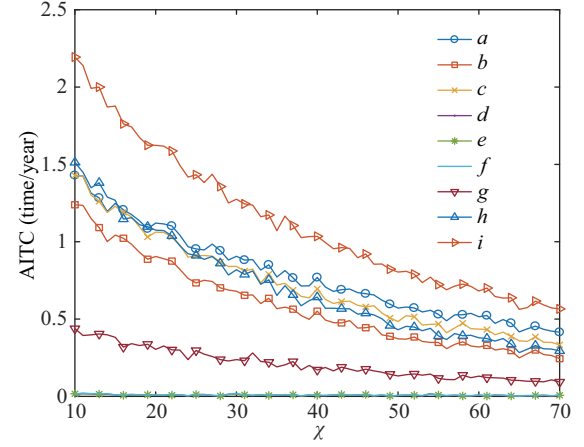


Fig. 7. The trend of the indexes considering the changing of the reserve coefficient χ .

and it is gradually lower than the heating interruption time caused by component failure. Until χ reaches a certain critical value, the failure of any component will not cause temperature of the each terminal to drop below the standard temperature. However, when χ decreases to 0, which means the load does not have the ability to store heat, it can be considered that any component's failure leading to the interruption of heating will cause the user to experience a fault. The reliability index AITC in this case is consistent with the unmodified results in scenario II.

V. CONCLUSION

This paper studies the reliability assessment of an IES considering the combined operation of electrothermal coupling equipment, such as a cogeneration unit and ground source heat pump. A comprehensive power flow operational model, considering multi-energy flow, is established based on IES typical equipment. Thereafter, considering the influence of random component faults, an economic optimal load reduction model based on the relative importance of electrical load is established. Also, taking into account the delay characteristics of the heat network transmission and the thermal inertia, the reliability evaluation index of the thermal network is corrected. Finally, combining the multi-energy flow with the Monte Carlo simulation, the IES reliability evaluation method is proposed. Through adopting this method, the reliability indexes of the IES can be obtained. In addition, the impact of the load shedding priority, heating standard and thermal reserve coefficient is verified in this case. Several conclusions are summarised as follows:

APPENDIX A

1) Compared with the traditional mode, the IES that realizes the mutual response and energy flow between the subsystems greatly improves the reliability of the energy supply.

2) Considering the pipeline transmission delay in the thermal network and the thermal inertia in the thermal terminal, the assessment can be carried out based on the moment when the user actually experiences the temperature deviation

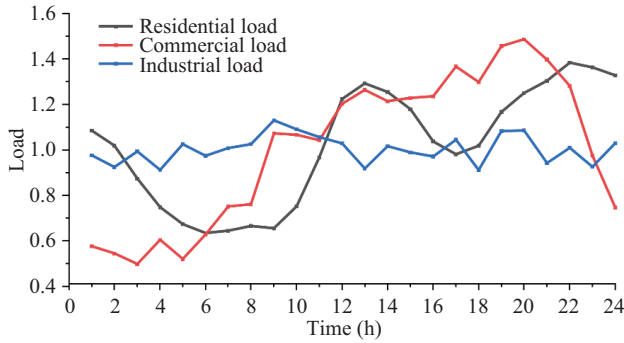


Fig. A1. The chart of the load in spring.

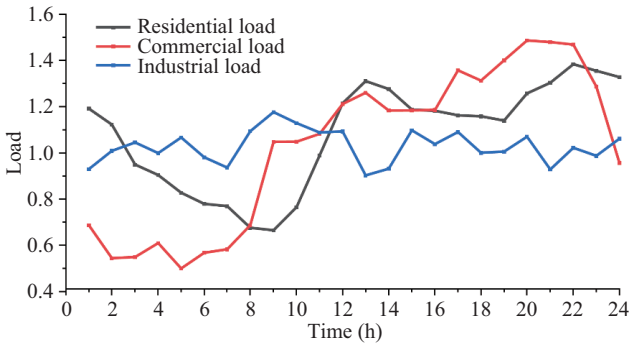


Fig. A2. The chart of the load in summer.

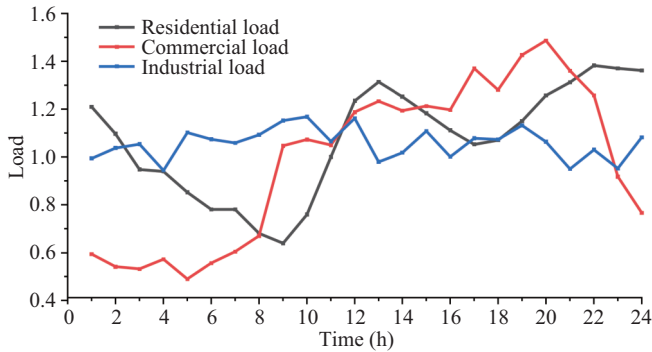


Fig. A3. The chart of the load in autumn.

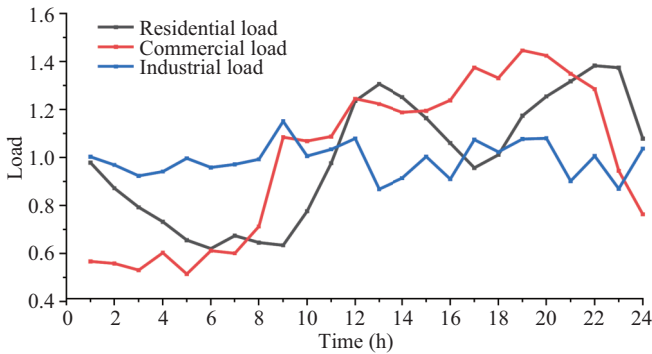


Fig. A4. The chart of the load in winter.

from the standard temperature, which can more accurately evaluate the reliability of the IES thermal subsystem. Also, this correction is in line with the concept of an IES which

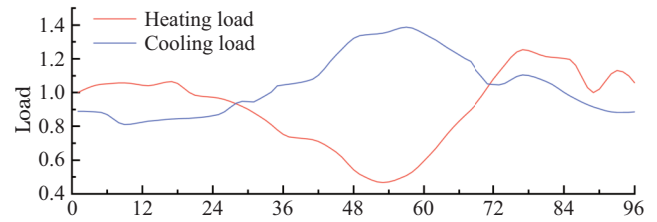


Fig. A5. Thermal system load during the heating/cooling period.

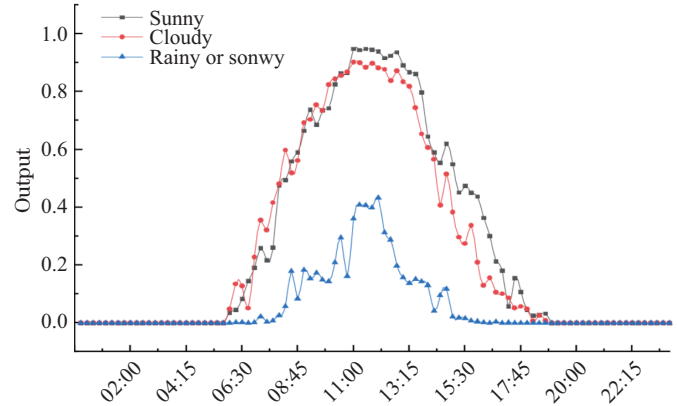


Fig. A6. The output curves of the PV in different weather conditions.

considers the different energy demand of users.

3) The reliability of the system is evaluated combined with multi-energy power flow and the Monte Carlo method, and various external factors are analyzed to verify its feasibility and rationality, which provides technical support for an IES reliability evaluation with multi-energy flow.

Considering the multi-stage structure of thermal networks, further analysis can be performed to simulate more accurately, and the demand of the IES user can also be refined.

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