Optimal device capacity planning and strategy determination in an integrated energy system to promoting IES integration considering reliability value

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[Correction added on 30-April-2021, after first online publication: right parenthesis of equation (26) is deleted]

Abstract
This paper proposes a novel framework for optimal planning of integrated energy system (IES) that takes into account its reliability value, which aims at promoting the power grid and IES to share the responsibility of the user's energy-supply reliability by market mechanism, thus promoting IES integration. First, an IES grid-connected electricity purchase price estimation model considering reliability is established, based on price theory and reliability theory, to quantify the reliability incremental value of IES. Then, a two-layer collaborative planning model, containing optimal equipment capacity configuration and strategy determination in the upper layer and optimal operation simulation and IES incremental reliability value in the lower layer, is established to coordinate the reliability guarantee capability of distribution network and IES while maximize the profit of IES. Among them, a practical approach of IES probabilistic reliability calculation is studied, considering double uncertainty and time-series matching of generation and demand, aiming at reducing the complexity of electricity price calculation embedded in planning model. Next, the intelligent krill herd algorithm and MILP are implemented to solve the model. Finally, a case is studied to verify the effectiveness of the model, and analyse the impact of load growth rate and user reliability requirements on the planning results.

1 | INTRODUCTION

In order to promote renewable energy (RE) consumption and improve energy utilization efficiency, countries around the world are vigorously developing integrated energy system (IES), aiming to meet the users' multiple types and grades energy demands through multiple energy coupling and cascade utilization [1]. At the same time, in the event of the external power or gas grid failure, the internal multi-energy coupling of terminal IES improves energy supply reliability guarantee capability of energy system [2] and reduces the deep dependence of energy supply reliability on the reliability of the external energy network, which is of great significance for ensuring the safety of critical loads under low probability high loss events [3]. With the increasing widespread application of IES at the end of energy supply path, the power supply capacity and reliability value of them will gradually increase. Under these conditions, the electricity sale power of the power grid will decrease and the utilization rate of power grid equipment will reduce, which eventually leads to an increase in the overall electricity price of user and is not conducive to the integration of IES. How to coordinate the reliability capability of the power grid and the terminal IES and carry out personalized configuration based on this has become an urgent problem to be solved.

The existing research objects of IES mainly include multi-regional systems [4], regional systems [5, 6] and terminal systems [7]. Among them, the terminal system can meet the demand of users on-site and promote the consumption of distributed RE, while improving the energy utilization efficiency, operational reliability, and economy of the energy system. It has weak market barriers, relatively mature products, broad application prospects and promotion value. In recent years, preliminary research results have been achieved in the study of IES planning. Ref. [8] establishes a novel multi-objective optimization model...
for IES design with electric, thermal and cooling subsystem to simultaneously optimize the economic, technical and environmental objectives. Ref. [9] utilizes exergy efficiency to measure the energy utilization level of IES and establishes an IES multi-objective planning model with economy and exergy efficiency as the goal. In view of the flexibility of IES operation, most references at this stage adopt the modelling method of integration of operation and planning [10]. The upper layer is a multi-objective nonlinear equipment optimization configuration model, and intelligent algorithms are often adopted for this layer, such as Strength Pareto Evolutionary Algorithm 2 (SPEA2) [11]. The lower layer is a single-objective nonlinear operation optimization model, some of which are solved directly by intelligent algorithms [12], and others convert nonconvex into convex [13], using mathematical methods [11] or solvers [14] to solve. Some references further consider the uncertainty of the system, and use robust and multi-scenario methods for planning [15]. Additionally, the IES can provide users with multiple energy through energy coupling and cascade utilization [8, 9], reduce environmental pollution [8], improve energy efficiency [9], and improve energy supply reliability. The first three effects can be reflected in the planning through the objective function [8, 9]. As for the latter one, there have some related researches of reliability evaluation approach of IES [16, 17]. A systematic IES energy supply reliability analysis method integrating stochastic model to give comprehensive knowledge under different, coupled uncertainties has been proposed [16]. A framework to assess the reliability of energy hub based on its elements and input energy carriers has been contributed [17]. However, these methods are not applicable in planning because of its calculation complexity. Although ref. [18] plans IES with reliability as a constraint, it failed to consider the coordination of the reliability ability of distribution network and terminal IES, in other words, the utilization of reliability value of IES, which leading to the low investment utilization rate and investment redundancy of overall energy system. And it is not conducive to terminal operators to invest in the construction of IES under the existing market mechanism. Therefore, the economic quantification and utilization of IES’s contribution to energy supply reliability is less involved, and it cannot be repaid through other means.

Furthermore, electricity is also a kind of commodity. The price of high reliability electricity should be high, and vice versa, according to the principle of market value. The IES purchasing electricity from power grid is a market behaviour. The IES and grid jointly complete the supply of energy to users and also jointly shoulder the responsibility of ensuring reliability. Reasonable pricing should take their respective costs and responsibilities as the basis, so as to achieve the goal of reducing overall energy supply costs. Therefore, the electricity price between the two should include both power supply costs and reliability costs. How to reasonably set the electricity price is also an important research topic for the future integration of micro-grid, IES, energy storage, EV, RE etc. into the grid, and there are some newly published relative researches. An optimal parking lot (PL)-based charging infrastructures allocation method to facilitate the efficient integration of plug-in electric vehicles (PEVs) is proposed, considering the uncertain implications of incentive policy on PEV owners’ charging behaviours and its effects in PL planning [19]. A comprehensive planning model, containing the placement of advanced metering infrastructures, the installation of renewable generation units along with the relevant pricing strategy for the demand side, for enhancing renewable energy sources integration into multi-energy system by utilizing the flexibility of a price-based demand response program is studied [20]. However, the relevant research of IES integration considering its reliability value has been rarely found.

Currently, Locational Marginal Price (LMP), as a mature electricity market pricing theory [21], has been used in many foreign electricity markets, such as PJM, MISO, CAISO, ERCOT, Europe, Australia and New Zealand. It has been successfully applied in the electricity market. LMP is defined as the system marginal cost of meeting the new unit load demand of a node, including the marginal cost of power generation, the cost of marginal loss and the cost of transmission congestion [22]. Node electricity price is a feasible way of introducing reliability into the electricity price mechanism [23]. This pricing method can provide a reference for IES grid-connected point pricing.

For this reason, this paper proposes an optimal capacity planning method of IES that coordinate the energy supply reliability capability of distribution network and IES to promoting IES integration based on the reliability-considered pricing method of the IES grid-connected point in the future. The innovative work of this article mainly includes:

a. Based on price theory and reliability theory, an IES grid-connected electricity purchase price estimation model considering reliability from the perspective of the growth of load and network investment strategy is established, which is used to set reasonable price for the connection point of IES according to the reliability level of the power purchased by IES, so as to quantify the reliability incremental value of IES.

b. A two-layer collaborative planning model, containing optimal equipment capacity configuration and storage equipment strategy determination in the upper layer and optimal operation simulation and IES incremental reliability value in the lower layer, is established to coordinate the reliability guarantee capability of distribution network and IES while maximize the profit of IES.

c. A practical model solution method of IES probabilistic reliability calculation is studied, adopting MCL clustering algorithm to transfer the double uncertainty of equipment failure and RE output and the time-series matching of RE and multi-demands to multiple probabilistic deterministic scenarios, aiming at reducing the complexity of electricity price calculation embedded in planning model.

d. The adaptive intelligent krill herd algorithm adopting linearly decreasing random diffusion and mixed integer linear programming method is implemented to solve the model based on simulation.
The rest of this paper is organized as follows: Section 2 presents the IES structure and storage equipment operation strategy. Section 3 establishes reliability-considered IES grid connection point electricity price estimation method based on electricity pricing theory. Optimal double-layer IES equipment capacity planning model considering the reliability incremental value of IES is provided in Section 4. Solution approach for the planning model is presented in Section 5. Sections 6 and 7 respectively present the case studies and conclusion.

2 | IES STRUCTURE AND STORAGE EQUIPMENT OPERATION STRATEGY ANALYSIS

As the terminal energy coupling supply system of the energy pipe network, IES is a typical energy load demand system (The proposed IES model is shown in Figure 1, including combined cooling-heating-power system CCHP, electric refrigerator EC, electric-heat equipment EH, electricity storage ES, heat storage HS, cold storage CS, photovoltaic PV, wind power WIND and other equipment, as well as electricity, heat and cold loads). The proposed IES can be partitioned into five parts: energy pipe network (power network and gas grid), energy production equipment (CCHP, PV and WIND), energy conversion equipment (EC and EH), energy storage equipment (ES, HS, CS) and multiple demands (electric load, heat load and cold load). The energy flow can be seen from Figure 1.

In order to ensure that the energy storage equipment has sufficient capacity to participate in failure recovery when the system fails so that play the role of improving the energy supply reliability, the lower operation limit percentage of the energy storage device’s state of charge \( \mu_{\text{XS, min}} \) (X represent Electricity E, Heat H or Cold C) needs to be set. That is to say, during normal operation, the state of charge of the energy storage equipment is at least \( \mu_{\text{XS, min}} \) of the total capacity, and the remaining \( 1 - \mu_{\text{XS, min}} \) of the total capacity participates in the operation optimization; in the event of a failure, at least \( \mu_{\text{XS, min}} \) of the energy storage capacity participates in the failure recovery. The selection of \( \mu_{\text{XS, min}} \) plays a decisive role in the influence of storage on overall reliability value of IES. Thus, the storage operation strategy \( \mu_{\text{ES, min}}, \mu_{\text{HS, min}}, \mu_{\text{CS, min}} \) are adopted as variables to be optimized while equipment capacity planning.

3 | IES GRID CONNECTION POINT ELECTRICITY PRICE ESTIMATION METHOD

3.1 | Domestic and foreign transmission and distribution power pricing methods

At present, there are two main types of pricing methods for transmission and distribution prices: comprehensive cost pricing method based on accounting costs and marginal cost pricing method based on microeconomic principles. The comprehensive cost method is based on cost accounting and allocates accounting costs to various users. Stamp method, trend tracking method and contract path method fall into this category. The principle of the comprehensive cost pricing method is relatively intuitive, easy to implement, and able to ensure the balance of power grid revenue and expenditure. Meanwhile, its price cannot reflect the scarcity of grid resources, which is not conducive to form incentive price signals and achieve the optimal allocation of grid resources. As for marginal cost method, it only reflects the changes in the operating cost of the power grid, and cannot guarantee the balance of the power grid’s revenue and expenditure. In the electricity market environment, the traditional same-grid-same-price mechanism not only has price discrimination, but also cannot guide potential market participants to make reasonable consumption. Therefore, the node electricity price came into being. Due to the large degree of load dispersion, complex structure, and inseparable investment characteristics of the distribution network, the node price pricing method of the transmission grid brings difficulties to the cost allocation of the distribution network, and may not be applied to the pricing of the distribution network node.

As the first country to formulate pricing methods on the power distribution side, the United Kingdom’s pricing methods mainly include a cost-sharing model based on the stamp method, a cost-sharing model based on the flow and a long-term incremental cost method. Among them, the core idea of the long-term incremental cost model is to obtain the node electricity price by calculating the annual incremental cost of the total investment of the system caused by the influence of the change of the injected power of the node on the investment years of all components [24]. This method avoids facing the problem of the large load dispersion of the distribution network and the increase in complexity of the node electricity price calculation model using the power flow-based distribution network investment cost allocation method caused by the access of distributed generations (DGs). Moreover, the forward-looking cost of each component of the power grid can be considered to reflect the degree of utilization of the power grid by each node, and the investment cost can be effectively recovered.
3.2 | Reliability-considered pricing method of IES grid connection point

This paper refers to the long-term incremental cost method based on the pricing method of transmission and distribution prices [23], and proposes a reliability-considered pricing method for IES grid connection point electricity purchase reliability requirements and the distribution network’s requirements for effective recovery of investment costs. This method is proposed based on quantitative evaluation of the impact of load growth on regional power supply reliability and power outage losses and the system component investment strategy.

3.2.1 | Quantification of the influence of load growth on the average outage time of nodes

In a multi-section and multi-connection distribution system, for any feeder, in order to share the load of the faulty feeder through the action of the tie switch when the adjacent feeder fails, the feeder must have a certain transfer margin. The effective operation rate $\eta$ is an index to distinguish the ability of a feeder to share the load of the corresponding section and effectively switch when the adjacent feeder fails. It is equal to the ratio of the feeder load current, including the transferred load when the adjacent feeder fails, to the short-time allowable current of the feeder. $\eta \leq 100\%$ indicates that the feeder has a transfer margin and is called appropriate feeder. The margin of the distribution system in a certain area can be expressed by the appropriate feeder ratio $q$, which is equal to the ratio of the number of appropriate feeders to the total number of feeders in the area.

As the load increases, the margin of the power distribution system will decrease, manifesting as $\eta$ increase and $q$ decrease, which affects reliability. Assuming that the load of the power distribution area and the value of $\eta$ conform to the normal distribution, the appropriate feeder rate in year $y + 1$ can be obtained from the appropriate feeder rate in year $y$ and the annual load growth rate of the distribution network $\varphi$ through Equation (1) [25].

$$q_{y+1} = (1 + \varphi) q_y - K_1 \varphi$$  \hspace{1cm} (1)

where $K_1$ is a normal number depending on the failure rate of the distribution line.

With the decrease of the appropriate feeder rate of the regional distribution network, the number of sections that can be inversely fed by the adjacent feeder will decrease, and the average annual outage time $U_i$ of the load node will increase. The impact of load growth on the value of $U_i$ is related to the degree of automation, that is, the higher the level of system automation, the smaller the ratio of the time required to complete the load transfer to the time required to repair the fault point, the greater the impact of $q$ on $U_i$. On the premise that the calculated $q_{y+1}$ and known $q_y$ and load node $i$ annual average outage time of year $y U_{i,y}$, the average outage time of node $i$ in the $y+1$ year can be calculated:

$$U_{i,y+1} = U_{i,y} \left[1 - (q_{y+1} - q_y) / q_y K_2 \right]$$  \hspace{1cm} (2)

where $K_2$ is a parameter depending on the level of power distribution automation.

3.2.2 | System component investment strategy

In order to take into account the reliability requirement of IES grid connection point and to reasonably ensure the effective recovery of grid investment costs in the electricity price calculation of the long-term incremental cost, two grid investment strategies are adopted:

1. When the average annual outage time of the load node $i$ $U_{i,y}$ exceeds the reliability requirement of IES grid connection point $U_i^*$, that is, when the reliability of the power purchase required by IES cannot be guaranteed, new investment will be triggered.

2. When the expected power outage loss of node $i$ in year $y$ $EDC_{i,y}$ exceeds the amortized annual cost of the node $i$ in year $y A_{i,y}$, new investment will be triggered.

The calculation formula of node expected power outage loss is expressed as follows:

$$\begin{align*}
EDC_{i,y} &= p \cdot EENS_{i,y} \\
EENS_{i,y} &= D_{i,y} \cdot U_{i,y}
\end{align*}$$  \hspace{1cm} (3)

where $EDC_{i,y}$ is the expected power outage loss of node $i$ in year $y$, $p$ is the unit power outage loss; $EENS_{i,y}$ is the expected power shortage of node $i$ in year $y$; $D_{i,y}$ is the average load of node $i$ in year $y$.

The annual cost of the load node is the allocation of the annual value of the total investment cost of the distribution network according to the load ratio. The total investment cost $B$ of the distribution network is composed of two parts: construction investment cost and operating cost [26]. Thus the equations of the annual cost of load node are expressed as:

$$\begin{align*}
A_{i,y} &= A_{i,\phi} \cdot \eta_{AF} (l) \\
A_{i,\phi} &= B \cdot D_{i,y} / \sum_{i=1}^{n} D_{i,y} \\
B &= R_{inv} + R_{op} \\
\eta_{AF} (l) &= \left[ d(1 + d^l) \right] / \left[ (1 + d^l) - 1 \right]
\end{align*}$$  \hspace{1cm} (4)

where $A_{i,y}$ is the amortized annual cost of the node $i$ in year $y$; $A_{i,\phi}$ is the total cost of the distribution system where the load node $i$ is located; $\eta_{AF}$ is the annuity factor, which is the coefficient that allocates the investment cost to each year of the investment life; $n$ is the total number of load nodes for which
the cost is allocated; \(B_{\text{inv}}\) and \(B_{\text{op}}\) are respectively construction investment cost and operating cost of the distribution network; \(d\) is the discount rate; \(l\) is the life of the grid components.

3.2.3  Electricity price calculation method

From the beginning of the calculation year, using known parameters \((q_{ij}, U_{ij,\text{in}}, \varphi)\) and Equations (1)–(4) to calculate \(U_{ij,\text{E}_{\text{inv}}}, E_{\text{DC}_{ij}}, \text{and} A_{ij}, (j = 1, 2, 3,...)\) until one of the system component investment strategies is met, then the year when load node \(i\) triggers investment is \(T_i = y - 1\).

Therefore, the equivalent initial annual average power outage time considering the load growth rate \(U_{ij,\Delta}\) and the investment time of node \(i\) after injecting new unit power on the basis of the original load \(T_{i,\text{inject}}\) can be calculated as:

\[
U_{ij,\Delta} = A_{ij}/[pD_{ij,\text{in}}(1 + \varphi)^T]
\]

\[
T_{i,\text{inject}} = \{\ln(A_{ij}/pU_{ij,\Delta}) - \ln(D_{ij} + \Delta D_{ij})\}/\ln(1 + \varphi)
\]

Then the present value of the investment cost before and after the unit power is injected into node \(i\), the annual incremental investment cost and the node electricity price of the distribution network can be calculated.

\[
\begin{align*}
C_{\text{PV},i} & = A_{ij}/(1 + d)^T \\
C_{\text{PV},i,\text{inject}} & = A_{ij}/(1 + d)^{T_{i,\text{inject}}} \\
\Delta C_i & = (C_{\text{PV},i,\text{inject}} - C_{\text{PV},i}) \cdot \eta_{\text{AF}} (l) \\\n\rho_i & = \Delta C_i/\Delta D_{\text{in}}
\end{align*}
\]

The sum of the node electricity price of the distribution network \(\rho_i\) and other costs of per unit electric energy \(\kappa\) (including the marginal cost of power generation, the cost of marginal loss, and the cost of transmission congestion) is the price of electricity sold at the node \(i\) of the distribution network. And when the node \(i\) is grid connection point of IES, the node price is the IES grid connection point electricity purchase price \(p_r\).

\[
p_r = \rho_i + \kappa
\]

4  OPTIMAL DOUBLE-LAYER IES EQUIPMENT CAPACITY PLANNING MODEL

In order to promote IES integration considering reliability value, an IES grid-connection point electricity purchasing pricing method considering reliability is proposed, in which high reliability electricity has high price and vice versa, in the above. Under certain conditions of the reliability electricity price mechanism at the grid connection point and user demand, low cost is an important factor for IES to achieve the optimal economy, and the cost includes investment and operating costs. Among them, the operating cost depends on two factors, the energy purchase price and energy consumption. If the equipment configuration capacity is large, the investment cost is high, however, the electricity price is relatively low, so the operating cost is low; on the contrary, the low investment cost leads to the high operating cost. Therefore, the equipment configuration method proposed in this article is to find the lowest point of comprehensive cost between investment and operating cost.

To this end, this paper establishes a two-layer IES optimal equipment capacity model based on the entire life cycle of equipment investment, with the goal of maximizing IES’s annual profit, including configuration and strategy plan layer and operation layer. The upper layer is the IES equipment capacity configuration and storage strategy optimization model. After configuring the equipment capacity that meets the generation-demand sufficiency and determining storage equipment operation strategy, the configuration plan and strategy is used to calculate the connection point reliability requirement of IES which is passed to the IES grid-connected point electricity price estimation model to estimate the IES power purchase price, and then the obtained electricity price, configuration plan and storage strategy is passed to the lower layer. The lower layer is an operation optimization model that takes into account the reliability incremental value, which maximizes the annual operating income of IES and returns it to the upper layer. The upper layer calculates the equivalent annual value of the total profit of the configuration and strategy plan. The plan with the best equivalent annual value of the total profit is the plan to be sought.

4.1  Upper-layer capacity allocation and strategy optimization model

4.1.1  Objective function

The upper-layer aims at configuring the IES equipment capacity and obtain the operation strategy of storage equipment of IES, thus the decision variables are \(\delta_{\text{CCHP}}, \delta_{\text{EC}}, \delta_{\text{EH}}, \delta_{\text{ES}}, \delta_{\text{HS}}, \delta_{\text{CS}}, \) respectively representing the capacity of CCHP, EC, EH, ES, HS, and CS to be configured, of which the first three units are kW, the unit of the latter three is kWh, and the storage operation strategy \(\mu_{\text{ES},\min}, \mu_{\text{HS},\min}\) and \(\mu_{\text{CS},\min}\) representing the lower limit percentage of ES, HS and CS’s state of charge while normal operation.

The upper-layer model takes the maximum annual value of the IES operator’s total profit as the goal, thus the objective function is the difference between the annual net operating revenue \(R_{\text{profit}}\) and the entire life cycle construction investment equivalent annual cost \(C_{\text{invest}}\) of IES:

\[
\max f = R_{\text{profit}} - C_{\text{invest}}
\]
Among them, $R_{\text{profit}}$ can be expressed specifically as the sum of the product of day operation income and the number of days in each type of typical day:

$$R_{\text{profit}} = \sum_{\epsilon = 1}^{3} R_{\text{profit},\epsilon} \cdot \text{days}_\epsilon$$

where $\epsilon = 1, 2, 3$ respectively represent three typical daily load scenarios that are adopted in the operation optimization in the lower layer: transition season, cooling season and heating season; $R_{\text{profit},\epsilon}$ is the daily operating income of typical day $\epsilon$, obtained by optimization of the lower-layer operation; days$_\epsilon$ is the number of days in typical day $\epsilon$.

Furthermore, $C_{\text{inv}}$ contains three parts: equipment investment cost, maintenance cost and residual value, the annual value of above three parts is denoted as $C_{\text{inv}}$, $C_{\text{main}}$ and $C_{\text{res}}$, thus $C_{\text{inv}}$ can be expressed as:

$$C_{\text{inv}} = C_{\text{inv}} + C_{\text{main}} - C_{\text{res}}$$

Among them, $C_{\text{inv}}$ can be specifically expressed as:

$$C_{\text{inv}} = \sum_{\xi = 1}^{N_{\text{type}}} K_{\xi} \cdot S_{\xi} \cdot \eta_{\text{AF}}(\lambda_{\text{IES}})$$

where $N_{\text{type}}$ is the number of types of equipment, a total of six types of equipment to be planned, $\xi = 1, 2, 3, ..., 6$ respectively representing CCHP, EC, EH, ES, HS, GS; $K_{\xi}$ is the construction investment cost per unit capacity of the equipment $\xi$, its unit is yuan/kW or yuan/kWh; $S_{\xi}$ is the configuration capacity of the equipment of the category $\xi$; $\lambda_{\text{IES}}$ is the expected life of IES equipment, which is 20 years. $C_{\text{main}}$ and $C_{\text{res}}$ take 5% [27] and 3% [11] of equipment investment cost equivalent annual value respectively.

### 4.1.2 Constrains (multi-energy supply reliability)

In order to comprehensively evaluate the reliability of IES energy supply relatively, the average energy supply availability rate ASAI and the lack of energy expected LOEE are selected as IES reliability indicators so that the reliability of IES energy supply is described from the perspective of time and energy respectively. According to the user’s energy reliability requirements, there are lower bounds to average energy supply availability rate ASAI and upper bounds to the lack of energy supply expected LOEE of three types energy supply.

$$\begin{cases} \text{ASAI}_m \geq \text{ASAI}_{m,\text{demand}} \\ \text{LOEE}_m \leq \text{LOEE}_{m,\text{demand}} \end{cases}$$

where $m = 1, 2, 3$ respectively represent electricity, heat and cold energy; ASAI$_{m,\text{demand}}$ and LOEE$_{m,\text{demand}}$ are the energy supply availability requirement of the $m$-th energy of IES users.

### 4.2 Connection point reliability requirement calculation of IES

According to power system reliability theory, there are two types of reliability evaluation methods: simulation method and analytical method [28]. Due to the randomness of energy, simulation method is more commonly used in IES reliability evaluation, whose accuracy comes at the cost of efficiency, while the analytical method is more effective for systems with certainty, fewer components, or low component failure probability. Besides, the reliability assessment for the purpose of calculating electricity prices in the planning stage should meet the principles of high calculation efficiency and robustness.

To this end, this paper proposes an IES reliability analysis evaluation method that combines the scenario method and the failure mode effect analysis method (FMEA). First, based on the annual time series RE generation and multi-demand characteristics (photovoltaic-wind power output and multi-energy loads), clustering of scenarios is carried out to convert the uncertainty into multiple probabilistic deterministic scenarios. Then, the probability of each IES failure scenario is determined according to each IES failure scenario and the IES component reliability model. At last, according to the combination of different generation-demand scenarios and failure scenarios, FMEA is used to analyse the consequences of failures and calculate reliability indicators.

#### 4.2.1 IES reliability index calculation method

1. **Markov clustering method of offline generation-demand multi-scene generation and probability determination:** Markov clustering algorithm (MCL) is an iterative algorithm that interweaves matrix expansion and inflation steps. Matrix expansion is to continuously exponentiate the transition matrix to achieve longer random walks, while matrix inflation improves the possibility of high-probability transitions and reducing low-probability transitions. Since nodes in the same cluster have higher weights and transition probabilities, the inflation operator makes them more inclined to stay in the same cluster, thus limiting the degree of random walking. The annual time series wind power output, photovoltaic output and multi-energy load set is transformed into five-dimensional coordinate axis point set. The corresponding parameters of each cluster centre represent the typical scene parameters of each cluster. Through continuous iteration, $N_L$ optimal typical scenes are obtained, and the probability of each scene $P_\lambda(x = 1, ..., N_L)$ can be calculated.

2. **IES failure scenario generation and its probability determination:** The time duration to be evaluated is set to one year, and the various devices in the IES and the two type of energy network are regarded as components in the IES system. The two-state model shown in Figure 2 are adopted by each component.
IES has a total of \( N_C \) components, therefore, there are a total of \( 2^{N_C-1} \) failure scenarios. The probability of the \( \mu \)-th failure scenario \( P_u \) can be expressed as:

\[
P_u = \prod_{k=1}^{N_{C,S}} P_k \prod_{k=1}^{N_{C,F}} Q_k
\]

where \( N_{C,F} \) is the number of failed components in the \( \mu \)-th state scenario; \( P_k \) and \( Q_k \) are the working and failure probabilities of the \( \mu \)-th component respectively; \( \mu_k, \lambda_k \) and \( r_k \) are the repair rate, failure rate and average repair time of the \( \mu \)-th component respectively; \( k = 1 \) represents the distribution network.

3. Failure consequence analysis based on FMEA: Through analyzing the IES energy coupling supply relationship, it is possible to determine the failure consequences of each combination scenario of generation-load scenario and the IES fault scenario. Taking the CCHP failure as an example, the CCHP failure will affect the supply of electricity, heat, and cold. Among them, the electric load can be supplied by photovoltaic, wind power, and distribution network, and ES is used as a backup with energy storage of at least \( \mu_{ES,min} \) of its total capacity; the heat load is supplied by EH when the electric load is surplus and can meet the EH output constraint, and HS is used as a backup with energy storage of at least \( \mu_{HS,min} \) of its total capacity; the cold load is supplied by EC when the electric load has a surplus and can meet the constraints of EC output, and CS is used as a backup with energy storage of at least \( \mu_{CS,min} \) of its total capacity. According to the above failure consequence analysis method, the supply of load \( m \) in the combination scenario of \( \mu \)-th generation-load scenario and the \( \mu \)-th IES fault scenario \( I_{C,S,F,m} \) (0 means lack of supply, 1 means normal supply) and energy shortage in the same scenario \( P_{C,S,F,m} \) can be determined.

4. Reliability index calculation: Based on the above probability scenario generation and failure consequence analysis results, these two reliability indicators can be calculated as:

\[
\begin{align*}
\text{ASA}_m & = 1 - \sum_{x=1}^{N_t} \sum_{n=1}^{2^{N_t}-1} P_x P_n I_{C,S,F,m} \\
\text{LOEE}_m & = \sum_{x=1}^{N_t} \sum_{n=1}^{2^{N_t}-1} P_x P_n P_{C,S,F,m}
\end{align*}
\]

4.2.2 IES grid connection point reliability requirement calculation

Under the premise of a certain IES capacity configuration plan, set multiple grid-connected power reliability levels, and calculate IES energy supply reliability indicators from low grid-connected power reliability level to high grid-connected power reliability level, until the user reliability requirements are met, and then the grid-connected power reliability requirement \( U_{cut} \) can be determined, which is the calculation basis of grid-connected electricity price.

4.3 Lower-layer operation optimization model

4.3.1 Objective function

The lower-layer operation optimization model aims at the highest single-day operating income of IES operators. By optimizing and dispatching the output of each device (CCHP, EC, EH, ES, HS, CS) in IES at different time periods, it can meet the demand of multi-energy loads, at the same time, obtain the electric power purchased from the distribution network and the amount of natural gas purchased from the gas network per period of time. The decision variables are \( P_{CCHP}^t, P_{EC}^t, P_{EH}^t, P_{chES}^t, P_{disES}^t, P_{chHS}^t, P_{disHS}^t, P_{chCS}^t, P_{disCS}^t, P_{EN}^t \). The operating income \( R_{profit} \) is the difference between the energy sales revenue \( R_{sell} \) and the energy purchase cost \( C_{buy} \), thus the objective function is as follows:

\[
\max R_{profit} = R_{sell} - C_{buy}\tag{16}
\]

Among them, \( R_{sell} \) can be expressed as the sum of the revenue from electricity, heat, and cold sales \( R_e, R_h, R_c \), while \( C_{buy} \) is twofold, containing gas and electricity purchase cost \( C_g \) and \( C_c \).

\[
R_{sell} = R_e + R_h + R_c = \gamma_e \sum_{t=1}^{24} L_e^t + \gamma_h \sum_{t=1}^{24} L_h^t + \gamma_c \sum_{t=1}^{24} L_c^t\tag{17}
\]

\[
C_{buy} = C_g + C_c = \lambda_g \sum_{t=1}^{24} V_{CCHP}^t + \rho_g \sum_{t=1}^{24} P_{EN}^t\tag{18}
\]

where \( \gamma_e, \gamma_h \) and \( \gamma_c \) are respectively the prices of electricity, heat, and cold sales. \( L_e^t, L_h^t \) and \( L_c^t \) are respectively the electricity, heat and cold loads during \( t \) period; \( \lambda_g \) is gas purchase price; \( V_{CCHP}^t \) and \( P_{EN}^t \) are respectively IES gas purchase amount and electricity purchase power during \( t \) period.

4.3.2 Constraints

1. Energy conversion constraints: According to the input and output characteristics of energy production, conversion and...
storage equipment, there are equality constraints on the input and output of CCHP, EC, EH, ES, HS and CS.

\[
\begin{align*}
    P_{\text{cCCHP}} &= P_\text{cCCHP} \\
    P_\text{EC} &= P_\text{hCCHP} \\
    P_\text{EH} &= P_\text{hEH} \\
    P_\text{ES} &= P_\text{hES} \\
    P_\text{HS} &= P_\text{hHS} \\
    P_\text{CS} &= P_\text{hCS}
\end{align*}
\]

where \( P_{\text{cCCHP}}, P_{\text{EC}}, P_{\text{EH}} \) and \( P_{\text{CS}} \) are the CCHP output electric power, heat power, cold power and input power during \( t \) period, respectively; \( \eta_{\text{CCHP}}, \eta_{\text{EC}}, \eta_{\text{EH}} \) are CCHP gas-to-electricity efficiency, gas-to-heat efficiency and refrigeration coefficient, respectively; \( V_{\text{CCHP}} \) is CCHP natural gas consumption during \( t \) period; \( \beta \) is the low calorific value of natural gas, taking 10.8 kWh/m\(^3\) in this paper; \( \Delta t \) is the time length of each period, taking 1 h in this paper; \( K_0 \) and \( K_t \) are the heat and cold production scheduling factors of CCHP respectively; \( P_{\text{EC}} \) and \( P_{\text{EH}} \) are the EC output cold power and input electrical power during \( t \) period respectively; \( \eta_{\text{EC}} \) and \( \eta_{\text{EH}} \) are the EC refrigeration coefficient and the EH electric-to-heat efficiency respectively; \( P_{\text{hEC}} \) and \( P_{\text{hEH}} \) are respectively EH output thermal power and input electrical power during \( t \) period; \( X \) can be \( E, H \) and \( C \), respectively represent the energy stored by ES, HS, CS; \( X_t \) is energy storage of XS during \( t \) period; \( X_{\text{dis}} \) is charge and discharge power during \( t \) period respectively; \( \eta_{\text{dis}} \) and \( \eta_{\text{ch}} \) are charge and discharge efficiency respectively.

2. Energy balance constraints:

\[
\begin{align*}
    I_{\text{cEC}} &= P_{\text{cEC}} + P_{\text{hEC}} + P_{\text{EC}} \\
    I_{\text{cEH}} &= P_{\text{cCCHP}} + P_{\text{PV}} + P_{\text{WIND}} + P_{\text{EN}} + P_{\text{disES}} \\
    I_{\text{cEH}} &= P_{\text{hCCHP}} + P_{\text{hEC}} + P_{\text{disCS}} \\
    I_{\text{cEH}} &= P_{\text{hCHP}} + P_{\text{hEH}} + P_{\text{disHS}}
\end{align*}
\]

where \( P_{\text{PV}} \) and \( P_{\text{WIND}} \) are respectively photovoltaic and wind power output during \( t \) period.

3. Equipment output constraints:

\[
\begin{align*}
    P_{\text{cCCHP}}^\text{min} &\leq P_{\text{cCCHP}} \leq P_{\text{cCCHP}}^\text{max} \\
    P_{\text{hEC}}^\text{min} &\leq P_{\text{hEC}} \leq P_{\text{hEC}}^\text{max} \\
    P_{\text{hEH}}^\text{min} &\leq P_{\text{hEH}} \leq P_{\text{hEH}}^\text{max} \\
    0 &\leq P_{\text{EN}} \leq P_{\text{EN}}^\text{max}
\end{align*}
\]

where \( P_{\text{cCCHP}}^\text{min}, P_{\text{cCCHP}}^\text{max}, P_{\text{hEH}}^\text{min} \) and \( P_{\text{EN}}^\text{max} \) are respectively the lower limit of CCHP electric output, EC cold output, EH heat output and the upper limit of electric power purchased from distribution network.

4. Energy storage operation constraints: The generalized energy storage system model is adopted for three type of energy storage output modelling, and its constraints include cycle start and end constraints, upper and lower limit constraints, and energy charge and discharge power constraints. The expression is as follows:

\[
\begin{align*}
    X_{t}^{24} &= X_{t}^{1} \\
    \mu_{\text{XS},\text{min}} + S_{\text{XS}} &= X_{t}^{1} \leq \mu_{\text{XS},\text{max}} \\
    0 &\leq X_{t}^{\text{disXS}} \leq \mu_{\text{XS},\text{max}} - S_{\text{XS}}
\end{align*}
\]

where \( X_{\text{min}} \) is the lower limit of energy storage; \( \mu_{\text{XS},\text{max}} \) is 0–1 variable ensuring that energy storage charges and discharges during different periods of time, 1 means energy storage is charging during period \( t \), and vice versa; \( P_{\text{EN},\text{max}} \) and \( P_{\text{disXS},\text{max}} \) are respectively the upper limits of charge and discharge power.

5. Solution method for the planning model

The upper layer of the model is a multi-variable and multi-constrained single objective nonlinear programming (NLP) problem, and the lower layer is a mixed integer linear programming (MILP) problem. The overall simulation process is based on MATLAB R2018a software. In order to realize the nesting of the upper and lower layers, the upper layer usually chooses the intelligent algorithm. In this paper, the self-adaption krill herd (KH) algorithm is adopted, and the lower layer chooses CPLEX solver to solve. Among them, the generation-demand scene clustering is performed offline, and the grid-connected point reliability requirement calculation and electricity price calculation are embedded in the planning model for online solution, which improves the practicality of the method.

5.1 Solution for the upper layer

The KH algorithm is a simulation of the foraging activity of krill swarms. Compared with other intelligent optimization algorithms, it has the advantages of fewer control parameters, easy implementation, and strong nonlinear optimization performance in continuous space [29]. Among them, each individual krill represents a potential solution in the solution space (assumed to be \( D \)-dimensional), and the krill food is the global optimal solution that the algorithm needs to find. Under comprehensive guidance of food information and surrounding krill information, the algorithm iterates in the dimensional solution space and updates the krill position until the final output is the optimal solution. The position movement of each individual krill is composed of three parts, and its \( \tau \)-th movement can
be expressed as follows:

\[ X_v (t) = N_v^\text{local} (t) + F_v (t) + R_v (t) \]  

(23)

\[
\begin{cases}
N_v^\text{local} (t) = N_v^\text{max} (\alpha_v^\text{local} (t) + \alpha_v^\text{target} (t)) + \mu N_v (t - 1) \\
F_v (t) = v_i \left( \beta_v^\text{food} (t) + \beta_v^\text{best} (t) \right) + \mu f_v (t - 1) \\
R_v (t) = R^\text{max} (1 - iter/\text{iter}\_\text{max}) \delta_v (t)
\end{cases}
\]

(24)

where \( N_v^\text{local} (t) \), \( F_v (t) \) and \( R_v (t) \) represent the three kinds motion vectors of the \( t \)-th step of krill individual \( v \) caused by the guidance of other krill individuals, food guidance and physical random diffusion respectively. The guiding movement vector \( N_v^\text{local} (t) \) is not only attracted locally by the surrounding krill individuals, but also by the current optimal global individual. \( N_v^\text{max} \) is the maximum guiding speed; \( \alpha_v^\text{local} (t) \) is the motion vector of the individual \( v \) attracted by the surrounding krill individuals; \( \alpha_v^\text{target} (t) \) is the motion vector of the individual \( v \) attracted by the current optimal individual; \( \mu \) is the inertial weight of the two before and after guided movements, \( \mu \in [0, 1] \). The foraging movement vector \( F_v (t) \) consists of two parts: food guidance and foraging experience. \( v_i \) is the foraging speed; \( \beta_v^\text{food} (t) \) is the attraction of food to individual \( v \); \( \beta_v^\text{best} (t) \) is the attraction of the individual \( v \)'s historically optimal fitness value to individual \( v \); \( \mu \) is the inertia weight of the two foraging movements before and after. The physical diffusion vector \( R_v (t) \) is a random search process. \( R^\text{max} \) is the maximum diffusion speed; \( \delta_v (t) \) represents the current random direction vector, each of which is a random number in the interval \([-1, 1]\). As the number of iterations increases, the krill group gradually moves to the optimal solution, and the influence of guided movement and foraging movement is gradually reduced. Thus, the corresponding random diffusion should gradually decrease as the position of the krill becomes better. Therefore, a term that makes the random diffusion part linearly decrease iteratively is added in the third equation in Equation (24), shown as Equation (25).

\[ R_v (t) = R^\text{max} (1 - iter/\text{iter}\_\text{max}) \delta_v (t) \]

(25)

where \( \text{iter} \) is the current iteration number; \( \text{iter}\_\text{max} \) is the maximum iteration number.

The algorithm steps are as follows: ① Initial population; ② Calculate fitness value; ③ Update the optimal position of the individual krill, the optimal position of krill herd and the optimal fitness value; ④ Use 3 kinds of movement formulas to update the position of each individual krill, with random movement before and after guided movements, \( \mu \) is the termination condition is met; ⑤ if it is satisfied, output the result, otherwise repeat steps ②, ③, ④, ⑤.

### 5.2 Solution for the lower layer

Linear programming (LP) is an important branch of operational research method, which is a mathematical method to assist people in scientific management. The operation optimization problem of IES presented in this paper is a typical mixed integer linear programming problem (MILP). The mixed integer linear programming problem consists of a linear objective function for solving the maximum or minimum value, a linear system of equations, and constraints for each optimization variable [30]. The mixed integer linear programming problem presented in this paper is described as follows:

\[
\begin{align*}
\max & \quad c^T x \\
\text{s.t.} & \quad Ax \geq b \\
& \quad \mathbf{x}_{\min} \leq x_i \leq \mathbf{x}_{\max}, \quad i \in I \\
& \quad x_j \in \{0, 1\}, \quad j \in I
\end{align*}
\]

(26)

where \( c \) is objective function; \( A \) is a coefficient matrix of simultaneous linear equations; \( b \) is the value of simultaneous linear equation; \( x_i \) and \( x_j \) are continuous variables and shaping variables, respectively. And CPLEX solver is used via YALMIP and MATLAB to solve the lower layer MILP problem.

The specific process of solving the overall model is shown in Figure 3.
6 CASE STUDY

6.1 Test systems and parameters

The simulation calculation takes a science-technology park in North China as an example. The structure of the distribution network in the park is shown in Figure 4. Transformer faults can be eliminated through regular maintenance and therefore are not considered. According to the reliability parameters of the components of the distribution network and FMEA, the initial reliability parameter of the IES grid connection point in F1 is obtained as a failure rate of 0.12 times/a, and the initial average outage duration is 3.393h. F1 initial annual total load is 10,000 kW, and IES grid-connected point load accounts for 30% of distribution feeder F1. The allocated fixed investment of F1 is 87.12 million yuan. \( q_0 \) is 0.5, \( \varphi \) is 1.2%. Electricity price calculation parameters \( K_1 \), \( K_2 \), \( p_d \) and \( d \) are 2.7, 2, 35.455 yuan/kWh, 0.067 and 40 years respectively. Thirteen grid-connected reliability levels are set, and the average annual power outage time (h) is respectively 18.2, 9.5, 5.9, 4, 2.9, 2.2, 1.8, 1.4, 1.2, 1, 0.9, 0.8, 0.7. Other cost per unit electricity is 0.3 yuan/kWh. The terminal IES structure constructed by the park operator is shown in Figure 1, and the equipment reliability data is shown in Table 1. The failure rate and repair time of the main gas pipeline is adopted as the gas network reliability parameters. The annual output curves of photovoltaic and wind power are shown in the Figure 5. The parameters of the equipment to be configured are shown in Table 2. According to the climate characteristics of the area, the whole year is divided into three typical days: cooling season, heating season and transition season, which is shown in Table 3, and the corresponding load curves are shown in Figure 6. Table 4 is the price of energy purchase and sale of IES. The energy supply reliability requirements of IES user are:

\[
\text{ASAI}_{m_{\text{demand}}} = 0.9999, \quad \text{LOEEm}_{m_{\text{demand}}} = 10 \text{ MWh/a}
\]

| Typical days | Transition season | Cooling season | Heating season |
|--------------|------------------|---------------|---------------|
| Year-round duration | March to June, September to November, 183 days in total | June to August, 92 days in total | January to February, December, 90 days in total |

| TABLE 1 IES equipment reliability data |
|---------------------------------------|
| Equipment     | Failure rate \( \lambda \) (Times/a) | Fault repair time \( r \) (h) |
|---------------|----------------------------------------|-------------------------------|
| CCHP          | 4                                      | 24.00                         |
| EC            | 0.4                                    | 2.00                          |
| EH            | 0.4                                    | 10.00                         |
| PV            | 0.4                                    | 20.00                         |
| WIND          | 0.4                                    | 20.00                         |
| ES            | 0.05                                   | 50.00                         |
| HS            | 0.05                                   | 50.00                         |
| CS            | 0.05                                   | 50.00                         |
| Distribution network | /                          | /                             |
| Natural gas network   | 0.9                                    | 20.00                         |

| FIGURE 4 Distribution network structure |

| TABLE 2 IES parameter table |
|-----------------------------|
| Equipment     | Capacity (kW or kWh) | Unit capacity construction cost/ (yuan/kW or yuan/kWh) | Energy conversion efficiency |
|---------------|----------------------|-----------------------------------------------------|-------------------------------|
| CCHP          | –                    | 6000                                                 | CHP: e:35% h-c:50% GB:0.8     |
| EC            | –                    | 1500                                                 | 4                             |
| EH            | –                    | 2700                                                 | 4                             |
| ES            | –                    | 2500                                                 | 0.9                           |
| HS            | –                    | 500                                                  | 0.9                           |
| CS            | –                    | 1000                                                 | 0.9                           |
| WIND          | 335                  | /                                                    | /                             |
| PV            | 550                  | /                                                    | /                             |

| FIGURE 5 Photovoltaic output and wind power annual output curve |

| TABLE 3 Classification of typical days |
|---------------------------------------|
| Typical days | Transition season | Cooling season | Heating season |
|--------------|------------------|---------------|---------------|
| Year-round duration | March to June, September to November, 183 days in total | June to August, 92 days in total | January to February, December, 90 days in total |
Result analysis

Calculation results and analysis

Set the population $n_{pop}$ = 50, the maximum iteration number $iter_{max}$ = 200. The capacity of each equipment is optimally configured between $[1,10000]$, the operation strategy of each energy storage device is optimally configured between $[0.001,0.8]$, and the iteration number of convergence is about 80 generations. The optimization result is: the average annual power outage time of IES power purchase is 2.2 h/a, that is, the average power availability rate is 0.99975, the power purchase price is 0.5402 yuan/kWh, and the annual value of the total profit is 6.8647 million yuan, of which the investment cost is 1.7171 million yuan, equipment residual value is 86.865 thousand yuan, and operating income is 8.5475 million yuan. The optimized configuration scheme is shown in Table 5. The operation strategies of energy storage are respectively 0.7184, 0.3456 and 0.1051.

In order to compare the difference of configuration results under different electricity price mechanisms, the above configuration method is named as method 1, and setting method 2 adopts the existing same-network-same-price electric energy trading market mechanism to optimize the configuration. The IES power purchase availability rate is 0.9999, and the IES power purchase price is 0.6545 yuan/kWh, and the optimized configuration plan is shown in Table 6. The operation strategies of energy storage are respectively 0.001, 0.0017 and 0.0056. The annual value of total profit is 6.7793 million yuan, of which investment cost is 1.6336 million yuan, equipment residual value is 81,679 yuan, and operating income is 8.3802 million yuan.

Although the investment cost of method 1 is 83,500 yuan higher than that of method 2, due to the lower power purchase reliability and electricity price, operating income and total profit have been significantly improved, increasing by 167,300 yuan and 85,400 yuan respectively. It shows that the adoption of reliability-considered electricity prices can effectively encourage operators to build their own terminal IES systems and increase equipment redundancy through the increase in operator profit, reducing the reliability requirement for power purchase from the distribution network. The increase in IES profit comes from the increase in its own investment and the reduction in the

| Table 5: Device configuration results |
|-----------------|-----------------|-----------------|
| Equipment       | Capacity (kW)   | Equipment       | Capacity (kWh) |
| CCHP            | 858             | ES              | 22             |
| EC              | 2525            | HS              | 5037           |
| EH              | 2635            | CS              | 1              |

| Table 6: Device configuration results under same electricity price for the whole network |
|-----------------|-----------------|-----------------|
| Equipment       | Capacity (kW)   | Equipment       | Capacity (kWh) |
| CCHP            | 923             | ES              | 1              |
| EC              | 2522            | HS              | 1              |
| EH              | 3109            | CS              | 1              |
reliability requirement for the purchase electric energy, while the distribution network reduces the reliability of power supply and delays investment according to the reliability requirements of IES, and reduces the annual investment cost by 32.24%, which is on the premise of guaranteeing its own profit. Thus the electricity price is lowered to achieve the purpose of sharing the responsibility for the energy supply reliability of users between the distribution network and IES through a market mechanism, and effectively improve the asset utilization rate of the distribution network.

6.2.2 The effect of load growth rate on configuration results

In the above electricity price calculation method, the load growth rate of the distribution network is taken as 1.2%, and the electricity price characteristics of the grid connection point will change when the load growth rate is different, as shown in Figure 7. When the load growth rate increases, the overall gradient of the stepped electricity price characteristics decreases and the high-reliability electricity price is relatively low, but when it is between 0.4% and 1.2%, the low reliability electricity price increases with the increase of annual load growth, and the increment is relatively large, and when it is between 1.2% and 2%, low reliability electricity price decreases with the increase of annual load growth, and the decrement is relatively small. According to the characteristics of different electricity price curves, different reliability levels of the grid connection point are set up. Table 7 shows the configuration results under different load growth rates, and Figure 8 shows the changes in power purchase reliability, electricity price, and total profit with load growth rates.

It can be seen from Figures 7, 8 and Table 7 that when the value is smaller (\(\varphi = 0.4\%\)), the low-reliability electricity price effect is obvious, that is, the low-reliability electricity price is lower, and the low-reliability electric energy and high-redundancy configuration are more economical. CCHP and ES have relatively larger capacity. As a buffer device for low-reliability electric energy, ES can improve the reliability of electric energy through charging and discharging, as to supply power for EC, EH, other electric energy supply equipment and users, and ensure the reliability of EC cooling supply, EH heating supply and user power supply. CCHP serves as a backup energy supply path for electricity, cold and heat, ensuring the reliability of the three energy generations. At this time, due to the significant effect of low electricity prices, although the equipment capacity is larger, the total profit is still higher.

When it is larger (\(\varphi > 0.4\%\)), the low-reliability electricity price effect is not obvious, and the overall reliability of the configuration of electric energy is higher. The configuration result is a balance between the reliability of electricity purchase and the capacity of equipment configuration, and the overall trend of total profit is increasing with \(\varphi\) increasing. Except for \(\varphi = 1.6\%\), the reliability of purchased electricity has little change, so the investment in equipment configuration has little change, and thus the electricity price has a greater impact on the total profit. High electricity prices will result in low total profit, and low electricity prices will result in high total profit. When \(\varphi = 1.6\%\), electricity purchase reliability is relatively high, due to the characteristics of electricity prices, the electricity purchase price difference between \(\varphi = 1.6\%\) and \(\varphi = 1.2\%\) is small, while the investment in configuration equipment is relatively small, thus the total profit is higher.
TABLE 8  IES device configuration results under different user reliability requirements

| ASAI     | CCHP  (kW) | EC  (kW) | EH  (kW) | ES  (kWh) | HS  (kWh) | CS  (kWh) |
|----------|------------|----------|----------|-----------|-----------|-----------|
| 0.9999   | 858        | 2525     | 2635     | 21.90     | 5037      | 1         |
| 0.9997   | 437        | 3251     | 3018     | 1         | 950       | 1         |
| 0.9995   | 379        | 2544     | 3107     | 1         | 1         | 1         |
| 0.9993   | 244        | 2503     | 2948     | 1         | 1         | 1         |
| 0.9991   | 270        | 2522     | 2947     | 1         | 1         | 1         |
| 0.9989   | 236        | 2432     | 2921     | 1         | 1         | 1         |
| 0.9987   | 144        | 2325     | 2652     | 1         | 1928.74   | 1         |
| 0.9985   | 1          | 2548     | 3107     | 1         | 1         | 1         |
| 0.9983   | 73         | 2360     | 2961     | 1         | 1         | 1         |
| 0.9981   | 240        | 2424     | 2829     | 1         | 1         | 1         |
| 0.9979   | 237        | 2218     | 2730     | 1         | 1         | 1         |
| 0.9977   | 188        | 2192     | 2636     | 1         | 962.75    | 1         |
| 0.9975   | 239        | 1980     | 2596     | 1         | 428.62    | 1         |
| 0.9973   | 280        | 1929     | 2410     | 1         | 961.77    | 1         |

FIGURE 9  Changes in investment, power price and profits under different user reliability requirements

6.2.3  The impact of user reliability requirements on configuration results

When IES users have different energy reliability requirements, the configuration results and effects of the model proposed in this article are different. Assuming that electric, heat and cold users have the same energy reliability requirements, Table 8 shows the equipment configuration results under different user reliability requirements (average energy supply availability rate ASAI). Figure 9 shows the changes in investment, electricity price, and profit under different user reliability requirements.

In the equipment configuration results of different user reliability requirements, the heat supply path equipment (CCHP, EH, HS) and the cold supply path equipment (CCHP, EC, CS) show obvious complementary characteristics. Among them, the CCHP can combine cooling, heating and power supply, EC refrigeration efficiency is relatively high and its economy is better, therefore, CS configuration result is always the minimum.

The optimized configuration result is a balance between the reliability of power purchase and the capacity of equipment configuration. The electricity purchase price characteristics are that electricity prices increase stepwise with the improvement of electricity purchase reliability. The higher the reliability of electricity purchase, the denser the gradient and the faster the growth speed under certain load growth rate. As Figure 9 shown, when the ASAI is greater than 0.9975, the reliability of power purchase will increase stepwise with the increase of users’ energy reliability requirements, the price will increase stepwise, the operating profit will decrease stepwise, the length of the step will gradually shorten, and the speed of change will gradually increase. Under the same power purchase reliability, the equipment investment cost increases with the increase of user energy reliability requirements. In addition, the investment cost of the section with higher power purchase reliability has increased rapidly. As a result, the total profit will decrease at an accelerated rate as the user energy reliability requirements increase.

When the ASAI is less than 0.9975, the total profit changes less. This is because users have low energy reliability requirements. IES can meet user electric load requirement by purchasing electricity with lower reliability and price from distribution network. To meet users’ cold and heat energy needs, certain energy conversion equipment needs to be configured. Although the equipment configuration capacity decreases as the reliability requirements decrease, and the investment cost decreases, when the average annual power outage time of power purchase is greater than 18.2 h, the power purchase price no longer decreases, and the operating income decreases with the decrease in reliability requirements. Therefore, when the reduction in operating income is greater than the reduction in equipment investment, the total profit no longer increases with the reduction in user reliability requirements.

7  CONCLUSIONS

Aiming at the redundancy configuration problem of the terminal IES and distribution network, this paper proposes a method for estimating the electricity price at the IES grid connection point considering reliability, and establishes the optimal IES equipment capacity configuration model taking into account its reliability value. The simulation results verify the validity of the model and draw the following conclusions:

1. The implementation of IES grid-connected point electricity price, proved as an efficacious incentive mechanism, can effectively stimulate terminal operators to improve the self-guarantee ability of power supply reliability by constructing IES and configuring equipment redundant capacity, thus promote IES integration. The operating income and total profit have been significantly improved by 167,300 yuan and 85,400 yuan respectively. By this means, the dependence on the reliability of grid power was reduced, the grid redundancy was decreased, the grid annual investment cost is
reduced by 32.24% and the utilization of power grid assets was improved. Thereby coordinating the reliability of IES and power grid was efficaciously achieved, and the purpose of sharing the responsibility between IES and distribution network for the user's energy supply reliability through the market mechanism was realized, so as to reduce the energy cost of end users.

2. Under the IES grid-connected point electricity price mechanism, the higher the user's reliability requirements, the larger the capacity of the configured energy coupling supply equipment, and the total profit of operators increases with the decrease of reliability requirement of users; When the reliability requirement is certain, the higher the annual network load growth rate within a certain range is, the smaller the electricity price gradient is, the lower the electricity purchase price of IES is, and the greater the total profit of operators is.

**NOMENCLATURE**

Indices and Sets

| X | Index for energy storage types |
| c | Index for typical days Index for time period of one day |
| i | Index for load nodes |
| k | Index for IES components |
| m | Index for energy types |
| u | Index for IES fault scenario |
| x | Index for source-load scenes |
| y | Index for investment years |
| z | Index for types of IES equipment |

Parameters

| B<sub>inv</sub> | Construction investment cost of distribution network |
| B<sub>op</sub> | Operating cost of distribution network |
| K<sub>1</sub> | A normal parameter depending on the failure rate of the distribution line |
| K<sub>2</sub> | A parameter depending on the level of distribution automation |
| L<sub>e</sub>, L<sub>h</sub>, L<sub>c</sub> | The electricity, hot and cold loads |
| N<sub>G</sub> | The total number of IES components |
| N<sub>type</sub> | The number of types of equipment |
| P<sub>min</sub><sup>cEC</sup> | The lower limit of EC cold output |
| P<sub>chXS</sub>, P<sub>disXS</sub> | The upper limits of charging power of storage |
| P<sub>cut</sub> | Energy shortage |
| P<sub>chXS</sub>, P<sub>disXS</sub> | The upper limits of discharging power of storage |
| P<sub>min</sub><sup>eCCHP</sup>, P<sub>max</sub><sup>eCCHP</sup> | The upper limit of power purchased from distribution network |
| P<sub>min</sub><sup>hEH</sup> | The lower limit of EH heat output |
| P<sub>PV</sub>, P<sub>WIND</sub> | Photovoltaic and wind power output |
| X<sub>min</sub> | The lower limit of energy storage capacity |
| l<sub>IES</sub> | Expected life of IES equipment |
| Y<sub>e</sub>, Y<sub>h</sub>, Y<sub>c</sub> | The prices of electricity, heat and cold |
| η<sub>CCHP</sub>, η<sub>MC</sub> | CCHP refrigeration coefficient |
| η<sub>AF</sub> | Annuity factor |

| η<sub>ch</sub>, η<sub>dis</sub> | Charging and discharging efficiency of storage |
| η<sub>EC</sub> | EC refrigeration coefficient |
| η<sub>eCCHP</sub> | CCHP gas-to-electricity efficiency |
| η<sub>hEICH</sub> | EH electric-to-heat efficiency |
| η<sub>h−eCCHP</sub> | CCHP gas-to-heat efficiency |
| λ<sub>g</sub> | Gas purchase price |
| Δ<sub>t</sub> | Time length of each period |
| x | Other costs per unit electric energy |
| A | Cost of distribution network |
| B | Total investment cost of distribution network |
| d | Discount rate The life of the distribution network components |

| days | The number of days |
| n | The total number of load nodes for which the cost is allocated |
| p | Unit power loss |
| r | Average repair time Construction cost of per unit capacity |
| β | Low calorific value of natural gas |
| λ | Failure rate |
| μ | Repair rate |
| φ | Annual load growth rate of the distribution network |

Variables

| C<sub>g</sub>, C<sub>e</sub> | Gas purchase cost and electricity purchase cost |
| C<sub>inv</sub> | Equipment investment cost |
| C<sub>invest</sub> | Equivalent annual cost of the IES operator's entire life cycle construction investment |
| C<sub>mai</sub> | Maintenance cost |
| C<sub>PV</sub> | The present value of the investment cost |
| C<sub>res</sub> | Residual value of the equipment |
| N<sub>f</sub> | The number of IES failure components |
| N<sub>L</sub> | The number of optimal typical source-load scenes |
| P<sub>CCHP</sub> | CCHP output cold power |
| P<sub>CCHP</sub> | CCHP input power |
| P<sub>eEC</sub>, P<sub>eEC</sub> | EC output cold power and input electric power |
| P<sub>chXS</sub>, P<sub>disXS</sub> | Energy storage charge and discharge power |
| P<sub>cut</sub> | Energy shortage |
| P<sub>CCHP</sub> | CCHP output electric power |
| P<sub>EN</sub> | Electricity purchase power |
| P<sub>hCCHP</sub> | CCHP output hot power |
| R<sub>EH</sub>, P<sub>EH</sub> | EH output thermal power and input electrical power |
| R<sub>e</sub>, R<sub>h</sub>, R<sub>c</sub> | Income from electricity, heat, cold sales |
| R<sub>profit</sub> | Annual net operating income of the IES operator |
| R<sub>sell</sub> | Income from energy sales of IES |
| V<sub>CCHP</sub> | IES gas purchase amount |
| n<sub>XS</sub> | 0–1 variable ensuring energy storage charges and discharges during different periods of time |
\( \mu_{XS,\text{min}} \): The lower operation limit percentage of the energy storage device’s state of charge

\( \text{ASAI} \): Average energy supply availability rate

\( \text{LOEEE} \): Lack of energy expected

\( D \): Average load of node

\( EDC \): Load node expected outage loss

\( EENS \): Expected power shortage

\( I \): The supply condition

\( P \): The probability of each scene/working probability

\( Q \): Failure probability

\( S \): Configuration capacity of the equipment

\( T \): The investment year

\( U \): Average annual outage time of load node

\( X \): Energy storage

\( \rho \): Node electricity sell price

\( q \): Appropriate feeder ratio of distribution network

\( \eta \): Effective operation rate of distribution network

\( \rho \): Node electricity price

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