Multi-scenario comprehensive benefit evaluation model of a multi-energy micro-grid based on the matter-element extension model

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Abstract
Integrated energy systems and multi-energy micro-grids are complex multi-agent collaborative optimization projects. According to the operating structure and characteristics of the multi-energy system, considering the externality, economy and other factors, a scientific and effective comprehensive evaluation are important decision supports to ensure its implementation and promote its development. Therefore, this paper proposes a comprehensive benefit evaluation model of a multi-energy micro-grid based on the matter-element extension model. With the research trends and practical requirements of multi-energy micro-grid benefit evaluation, an evaluation index system covering energy efficiency indicators, economic indicators, reliability indicators, and renewable energy consumption indicators has been constructed, and uncertainties have been resolved in cloud model and fuzzy set theory. Based on the advantages of the performance evaluation information, the system operation scenarios in the process of planning scheme formation are fully considered, and then a matter-element-extensible multi-attribute decision-making model is proposed to evaluate the comprehensive benefits of multi-energy micro-grids. Finally, the feasibility of the above method is verified by comparing the comprehensive benefit evaluation results of the multi-energy micro-grid under different planning scenarios. In addition, a certain decision-making reference is provided for the formation of a multi-energy micro-grid configuration scheme.

KEYWORDS
comprehensive benefit evaluation, matter-element extension model, multi-energy micro-grid, multiple attribute decision

1 | INTRODUCTION
With the large-scale development and utilization of a series of clean energy programs, such as wind and photovoltaic power, it has become an inevitable trend to flexibly coordinate the optimization of the entire process of investment and operation of multi-energy systems and build a new generation of efficient, clean, safe, and low-carbon modern energy
systems. However, the energy subsystems in the multi-energy system are characterized by strong coupling, low energy conversion efficiency, and significant uncertainties arising from renewable availability and demand-side behaviors, which bring huge challenges to the benefits of the multi-energy micro-grid system. As an important realization of an integrated energy system in terms of the distribution network/user, a multi-energy micro-grid can realize the complementary utilization of a multi-energy micro-grid by relying on a heat pump, gas turbine, cold, heat, and electricity triple supply equipment, and has broad application prospects. As a necessary link in the construction and operation of the integrated energy system, a reasonable planning and allocation scheme are crucial to promoting the development of the integrated energy system. As a result of the need to consider more physical constraints in the planning stage, the planning objective is often relatively simple, it is impossible to achieve a comprehensive evaluation and comparison of all the planning schemes. Therefore, the establishment of a comprehensive benefit evaluation index system for the multi-energy micro-grid and a further comparison of alternative planning schemes are of great practical significance for the formation of a more reasonable and scientific multi-energy micro-grid configuration scheme.

Up to now, many scholars have studied the key technologies and planning optimization of integrated energy systems. Xie et al. considered the traffic flow guidance for electric and nonelectric vehicles in the urban transportation network, proposed a novel optimal planning framework that takes into account the coupling of transportation, natural gas, and active distribution networks, the research results show that when both charging and routing guidance are considered the energy losses will decrease by at least 5.6%. Farhad et al. considered the impact of combined heat and power(CHP) unit and electric-to-gas unit on the collaborative planning of the electric-to-gas hybrid integrated energy system, and proposed a collaborative planning scheme of the electric-to-gas hybrid integrated energy system with investment cost, operating cost and minimum energy shortage as the planning objectives. Jin et al. aimed at the design of distribution network planning schemes under different scenarios, the original dual optimization model was adopted to find the optimal decision variables and scene parameters, which improved the economy and reliability of the planning scheme. Wang et al. proposes an expansion planning model for multi-energy system integrating active distribution network, natural gas network, and energy hub; and the positive impact of active network managements on expanding multi-energy system is originally investigated. Ren et al. on the basis of natural gas system considers absorption chiller energy storage device, ground source heat pump, gas turbine, etc and designs a hybrid energy subsystem integrating solar energy and geothermal energy. Talebi et al. considered the centralized heat storage device, designed the mixed community heating energy system, compared it with the traditional energy system, and designed a variety of scenario optimization schemes. Xie et al. presented a novel multi-objective model of active distribution network planning to find the final scheme with optimal alternative, location, size and operational strategy for the candidate distribution lines, transformer substations, distribution generations, static var compensators (SVCs) and on-load tap changers (OLTCs). Scheller et al. considered the access of renewable energy such as wind power and photovoltaic to comprehensive energy system, established a mixed-integer linear programming model, and proposed a scheduling optimization strategy scheme. Wei et al. interval variables were adopted to deal with the uncertainty of renewable energy access to multi-energy systems, and chaotic search optimization algorithm was adopted for multi-objective planning and optimization of multi-energy systems with the lowest investment cost and risk. For integrated energy system or multi-micro-energy network of comprehensive benefit evaluation index and evaluation method study, due to the complexity of system and the influence of uncertainty factors on the project operation, from the traditional qualitative indexes and subjective evaluation method have been developed to all kinds of multiple attribute decision-making method and intelligent algorithm, is widely used in the field of energy system of comprehensive evaluation. Zeng et al. pointed out the problems facing the current comprehensive benefit evaluation by combing the current comprehensive energy system benefit evaluation index systems and evaluation methods. Chen et al. took the power distribution system as the research object and put forward a universal index system for the evaluation of the regional comprehensive energy system from four dimensions, namely the energy category, conversion equipment, distribution network, and users. Song et al., using five aspects (the index, cascade utilization of energy efficiency indicators, economic indicators, reliability index, and environmental index), built the pluripotent distributed energy sources system with a complementary comprehensive evaluation index system, but the index is too simple in terms of the definition of some indexes and the traditional power system evaluation index, and it lacks cohesion. Tian et al. put forward the concepts of the extended system, global system, transmission extended system, and local extended system, and analyzed the relationship between energy consumption ratio and energy utilization efficiency using two energy efficiency evaluation indexes. Wei et al. proposed an energy efficiency evaluation index system based on DPSR in combination with a real business situation. This system covers the multi-dimensional index of enterprise energy efficiency and can reveal the complete causal chain of enterprise energy efficiency caused by the internal and external environment. Zhang et al. studied the comprehensive energy evaluation method for the park micro-grid, and built a multi-attribute
decision-making model of the comprehensive energy system through VIKOR. The index calculation was combined with the system operation to some extent, but the impact analysis of the single index on the final evaluation result was lacked. Yang et al.\textsuperscript{23} considered the operation of the integrated energy system in the context of the conversion of old and new kinetic energy, building an improved dynamic data analysis model, and conducting a comparative study on the operation scheme of the integrated energy system. Nicholas Good et al.\textsuperscript{24} introduced a DMES interactive energy modeling and evaluation framework, identified the transaction energy price signals of different energy participants and evaluates the comprehensive energy efficiency through the modular value mapping method. However, in the traditional fuzzy comprehensive evaluation method, the membership function is used to replace each piece of fuzzy information, which is subjective to some extent, and the randomness of each evaluation information is ignored. In order to overcome the above problems, some researchers introduced the cloud model and the matter-element extension model to replace the membership function in evaluation methods. Li et al.\textsuperscript{25} organized the characteristics of cloud models and solved the randomness and fuzziness of qualitative indicators. Ma et al.\textsuperscript{26} proposed an efficient energy efficiency evaluation method to evaluate the energy efficiency of users according to the voting strategy. The proposed KNN energy efficiency classification method has various advantages including ease of operation and accurate classification, and has a strong application value and promotion prospects. Huang et al.\textsuperscript{27} considered the comprehensive energy-saving rate and the permeability of renewable energy sources index, as well as investment from the government, power grids, operators, and users to build the regional integrated energy system efficiency evaluation index system, in order to reduce the influence of uncertainty factors. They proposed the matter-element extension model for comprehensive evaluation, but its project investment evaluation index is too simple and lacks certain vital elements related to energy such as energy efficiency indexes. Table 1 summarizes the main differences between this paper and the state of the art.\textsuperscript{17-27} In this table, symbols “√” and “×” respectively indicate whether a particular aspect is considered or not.

Based on the above literature review, it can be seen that considerable research efforts have been done for the comprehensive assessment of power system performance. However, unlike conventional electricity power systems, the multi-energy micro-grids correspond to a complex dynamic system and there are many factors affecting the performance of such system.\textsuperscript{28,29} At the same time, there are many types of evaluation model and evaluation indices, each of which has its unique advantages and disadvantages. Therefore, considering the differences in indicators and system operation situations, a concrete analysis can be only performed based on the feature of actual problem,\textsuperscript{30} that is, the selection of evaluation indicators and evaluation methods must focus on the problem of fuzziness and randomness of multiple indexes between treatments, and thus, to eventually obtain evaluation results in accordance with the practicality of the project.

To fill in the above knowledge gap, this paper proposes a comprehensive benefit evaluation model of a multi-energy micro-grid based on the matter-element extension model. Compared with existing literatures, the main contributions of this paper can be summarized as follows:

1. In order to comprehensively and scientifically evaluate the multi-energy micro-grid system, combined with the actual project operational characteristics, from the four dimensions of energy efficiency, economy, reliability, and renewable energy consumption, we constructed the

| Approach | Multi-energy | Quantitative evaluation | Fuzziness and randomness | Objective evaluation | Multi-attribute decision-making and intelligent algorithms |
|----------|--------------|-------------------------|-------------------------|---------------------|-------------------------------------------------------|
| 17       | √            | ×                       | ×                       | √                   | ×                                                     |
| 18       | √            | √                       | ×                       | √                   | ×                                                     |
| 19       | √            | √                       | ×                       | ×                   | ×                                                     |
| 20       | ×            | √                       | ×                       | ×                   | x                                                     |
| 21       | ×            | √                       | ×                       | √                   | x                                                     |
| 22       | √            | ×                       | ×                       | √                   | √                                                     |
| 23       | √            | √                       | ×                       | ×                   | √                                                     |
| 24       | √            | ×                       | ×                       | √                   | x                                                     |
| 25       | √            | √                       | √                       | ×                   | √                                                     |
| 26       | √            | √                       | ×                       | √                   | √                                                     |
| 27       | √            | ×                       | √                       | √                   | √                                                     |
| Proposed approach | √ | √ | √ | √ | √ |
comprehensive benefit evaluation index system for the multi-energy micro-grid;
2. In the process of evaluation index assignment calculations, we considered the system planning operation scene in the process of index calculation, which can reflect the actual application requirements of the system;
3. According to the problems of system at all levels and the incompatible contradictions of processing needs, we used the matter-element extension model to improve the multi-level fuzzy comprehensive evaluation method to evaluate system comprehensive benefits, to seize the key impact indicators, and to effectively solve the randomness and uncertainty problem in the system performance evaluation; this can be achieved on the level of single index analysis; it can also analyze the feasibility of the plan or project as a whole, so as to realize a global optimal evaluation target;
4. In order to verify the effectiveness of the proposed model, we selected typical demonstration projects for the example analysis, and through comparing the different planning systems in terms of comprehensive benefits, the matter-element extension model is shown to improve the multi-level fuzzy comprehensive evaluation method by providing a better energy system efficiency evaluation of the micro-network and improving the effectiveness of evaluation results based on a bottom-up analysis of different schemes.

The structure of this paper is as follows: Section 1 reviews the selection of indicators for the efficiency evaluation of multi-energy micro-grid systems and the research trends of the evaluation methods. In Section 2, the proposed evaluation index system for the comprehensive benefits of multi-energy micro-grid system is described. In Section 3, the proposed evaluation method based on the matter-element extension model is presented. The numerical studies are conducted in Section 4 and finally Section 5 presents the conclusions of the paper.

2 | DESIGN OF INDICATOR SYSTEM FOR COMPREHENSIVE EVALUATION OF MULTI-ENERGY MICRO-GRIDS

Compared to the traditional active power distribution lines and micro-grids, multi-energy micro-networks are required to coordinate between different types of energy system optimization (using complementary features between different the types of energy and power system), improve the utilization efficiency of terminal area energy, renewable energy capacity, energy supply reliability, and system running economy. However, the strong coupling among the different energy subsystems in a multi-energy micro-grid, the uncertainties associated with renewable energy availability, and the unstable conversion efficiency among the energy equipment in the system may bring great challenges to the comprehensive assessment for the performance of multi-energy micro-grids. Meanwhile, the integration of source-charge-storage could impose a significant impact on the different aspects of the system, and hence it is not easy to determine the value of each evaluation index in deriving the final evaluation results. Due to the incomplete information of the selected evaluation indexes, the final comprehensive benefit evaluation results could be unrealistic and accurate, which may cause large economic losses in real-world implementations. In the aspect of benefit evaluation, most of the existing researches only focused on the benefit evaluation of single energy subsystem from the aspects of economy, energy conservation, and environmental protection, but failed to consider the technical characteristics of multi-energy systems. In other words, they failed to capture the complexity of the internal operation structure for multi-energy systems and the impact of uncertainties in external environment.

To fill in the above gap, in this study, we propose a new index system for the comprehensive performance evaluation of multi-energy microgrids. For this end, we follow the principles of “comprehensiveness, typicality, independence, and practicability” in the selection and design of evaluation indicators. Moreover, the technical characteristics of the multi-energy micro-grid system and renewable energy consumption requirements are especially considered in our proposed index system. The main advantages of the presented index system and its differences to the current engineering ones can be summarized as follows:

1. In the current studies, the issue of energy efficiency was seldom considered in the planning design of micro-grid. However, in reality, energy efficiency could be a critical factor when talking about the performance of a multi-energy micro-grid. This is because, in contrast to a conventional single energy-carrier-based system, the multi-energy micro-grid involves more energy categories. Therefore, to properly reflect the impact of heterogeneous energy integration on the operational efficiency of energy system, the energy efficiency issue is incorporated and considered in the proposed design of evaluation index system.
2. The multi-energy micro-grid is a comprehensive project with large investment and a long service period. Its economic benefits run through all the phases of project construction, operation, maintenance, and equipment decommissioning. Therefore, the design of evaluation indicator system must be based on the perspective of “life-cycle
assessment,” which is, however, barely addressed in the current studies. Compared with conventional evaluation approaches, the life-cycle-based indicators could reflect the impact of different processes on the system economic benefits and their superimposed effect over time. In practice, this could be helpful for the decision-makers to make truly optimal decisions for the system planning in the long run.

3. Since the multi-energy micro-grid system is a public infrastructure, the reliability of such system operation has a strong impact on the livelihood and wellbeing of its users. Therefore, to objectively quantify the potential capability of a multi-energy micro-grid to meet the energy demands of customers, the reliability indicators must be properly accounted for in the design of evaluation index system.

4. The development of multi-energy micro-grid could promote the exploitation of renewable energy and reduce the generation emission by leveraging the complementarity among various forms of energy carriers. Therefore, the issue of renewable energy utilization is another important aspect in the comprehensive evaluation of multi-energy micro-grid performance.

Based on the above considerations, a comprehensive evaluation index system for the performance of multi-energy micro-grid from the four dimensions: energy efficiency index, economic index, reliability index, and renewable energy utilization index, as shown in Table 2.

The corresponding descriptions of the above indicators are shown below.

| Attribute            | Indicator                                      | Definition                                                                                       | unit         |
|----------------------|------------------------------------------------|--------------------------------------------------------------------------------------------------|--------------|
| Energy efficiency    | Comprehensive energy efficiency                | The ratio of the output of cold, heat, and electricity in the system to the consumption of primary energy (including electricity from online shopping abroad) | %            |
|                      | Comprehensive energy-saving rate               | The ratio of energy consumption between the traditional energy system and the multi-energy micro-grid system | %            |
|                      | Exergic efficiency                             | The ability of a system to convert effective input energy into terminal usable energy             | %            |
| Economy              | Equivalent annual value of system investment  | The annual equivalent of system energy procurement cost and placement cost over the life of the project | Ten thousand yuan |
|                      | System operation and maintenance cost          | Used for the cost of repair and maintenance of the system equipment in normal operation           | Ten thousand yuan |
|                      | System procurement energy costs                | The total cost of electricity and natural gas purchased by users within the system area           | Ten thousand yuan |
|                      | Internal rate of return                        | The discount rate at which the net cash flows of an item over its lifetime add up to zero         | %            |
| Reliability          | Generalized expected energy not served (EENS)  | The undersupply ratio of heat, electricity, and cold energy demand in the system                  | MWh/year     |
|                      | Equivalent availability coefficient (EAF)      | The ratio of the available hours of the system unit minus the equivalent outage hours of the unit to the statistical period hours of the unit | %            |
| Renewable energy utilization | Renewable energy efficiency     | The ratio of distributed wind power/pv actual on-grid electricity in the region to available power generation | %            |
|                      | Share of renewable energy supply               | The ratio of renewable energy generation to total energy supply of the system                     | %            |
|                      | Carbon intensity targets                       | Mainly refers to amount of CO₂ emission                                                          | Ton          |

**Table 2** A system of indicators for comprehensive benefit evaluation of the multi-energy micro-grid
2.1 Indicators for energy consumption

1. Total energy utilization efficiency:

\[
\eta = \frac{aP_{\text{out}}^E + Q_{\text{out}}^H + Q_{\text{out}}^C}{bV_{\text{in}}^G + aP_{\text{in}}^E} \times 100\%
\]  

where \( \eta \) is total energy utilization efficiency; \( P_{\text{out}}^E \), \( Q_{\text{out}}^H \), and \( Q_{\text{out}}^C \) are the total output of electricity, heat, and cold quantity of the system, respectively; \( V_{\text{in}}^G \) and \( P_{\text{in}}^E \) are the total volume of natural gas acquired and total electricity purchased from the external network; \( a \) represents the conversion factor of kWh and KJ; \( b \) is the calorific value conversion coefficient for natural gas.

2. Comprehensive energy-saving rate:

\[
\beta = \frac{E_T - E_N}{E_T} \times 100\%
\]

where \( \beta \) is the comprehensive energy-saving rate of the system; in the case of the same energy output, \( E_T \) and \( E_N \) represent the energy consumption of the traditional energy system and the energy consumption of the multi-energy micro-grid system, respectively.

3. Exergic efficiency:

\[
\eta_{\text{ex}} = \frac{aP_{\text{out}}^E + A^H Q_{\text{out}}^H + A^C Q_{\text{out}}^C}{bV_{\text{in}}^G + aP_{\text{in}}^E} \times 100\%
\]

where \( \eta_{\text{ex}} \) is the exergic efficiency index of the system; \( A^H \) and \( A^C \) represent the Carnot cycle efficiency of heating quantity and cooling quantity, respectively; \( A^G \) is the energy quality coefficient of natural gas.

2.2 Indicators for economy

1. Annual value of system investment:

\[
C_1 = c_{\text{fix}}^{\text{chp}} + B_{\text{chp}}c_{\text{cap}}^{\text{chp}} + B_{\text{ch}}c_{\text{cap}}^{\text{ch}} + \beta_{\text{ch}}c_{\text{sq}}^{\text{ch}} + B_{\text{hp}}c_{\text{cap}}^{\text{hp}} + B_{\text{pv}}c_{\text{cap}}^{\text{pv}} + B_{\text{wt}}c_{\text{cap}}^{\text{wt}} + B_{\text{es}}c_{\text{cap}}^{\text{es}} + B_{\text{ts}}c_{\text{cap}}^{\text{ts}}
\]

\[
V_{\text{in}}^G = \beta_{\text{chp}}c_{\text{chp}}^{\text{chp}} + \beta_{\text{bo}}c_{\text{bo}}^{\text{bo}}
\]

\[
C_A = C_1 \left[ \frac{r(1+r)^T}{(1+r)^T - 1} \right]
\]

where \( C_1 \) is the total cost of investment in the system; \( c_{\text{fix}}^{\text{chp}} \) is the fixed investment cost of combined heat and power units (CHPs); \( c_{\text{chp}}^{\text{chp}}, c_{\text{ch}}^{\text{ch}}, c_{\text{hp}}^{\text{hp}}, c_{\text{pv}}^{\text{pv}}, c_{\text{es}}^{\text{es}}, c_{\text{ts}}^{\text{ts}}, c_{\text{sq}}^{\text{sq}} \) represent the construction cost of per unit capacity/area for CHPs, absorption refrigerators, heat pumps, photovoltaic modules, wind turbines, gas boilers, electro-chemical storage units, thermal storage units, and solar thermal equipment, respectively; \( \beta_{\text{ch}} \) and \( \beta_{\text{bo}} \) represent the consumption of natural gas in producing unit output by CHPs and gas boilers, respectively; \( B \) is the installed capacity of various types of energy units in a multi-energy micro-grid; \( Y_{\text{st}} \) represents the installed area of solar thermal equipment; \( C_A \) is the annual value of system investment; \( r \) represents the discount rate, where the actual interest rate of a bank’s long-term loan can be used; \( T \) represents the operating life of the system.

2. System operation and maintenance cost:

\[
C_O = \delta_{\text{chp}}P_{\text{chp}}^{\text{chp}} + \delta_{\text{ch}}P_{\text{ch}}^{\text{ch}} + \delta_{\text{bo}}P_{\text{bo}}^{\text{bo}} + \delta_{\text{hp}}P_{\text{hp}}^{\text{hp}} + \delta_{\text{pv}}P_{\text{pv}}^{\text{pv}} + \delta_{\text{wt}}P_{\text{wt}}^{\text{wt}} + \delta_{\text{es}}P_{\text{es}}^{\text{es}} + \delta_{\text{ts}}P_{\text{ts}}^{\text{ts}}
\]

where \( \delta \) is the operation and maintenance cost of unit capacity or area of various types of energy units in a multi-energy micro-grid; \( P_{\text{chp}}^{\text{chp}}, P_{\text{ch}}^{\text{ch}}, P_{\text{bo}}^{\text{bo}}, P_{\text{hp}}^{\text{hp}}, P_{\text{pv}}^{\text{pv}}, P_{\text{wt}}^{\text{wt}}, P_{\text{es}}^{\text{es}}, P_{\text{ts}}^{\text{ts}} \) represent the average annual power output of CHPs, distributed wind turbines, and photovoltaic modules, respectively; \( \bar{Q}^G \) and \( \bar{Q}^H \) represent the average annual cold and heat supply of absorption refrigerators and gas boilers, respectively; \( T_{\text{st}}, T_{\text{es}}, \) and \( T_{\text{hp}} \) represent the average annual working hours of electro-chemical storage units, heat storage tanks, and heat pumps, respectively; in this paper, the operation and maintenance cost of solar thermal equipment is deemed to be dependent only on its laying area.

3. Energy procurement cost:

\[
C_P = \bar{\lambda}^G V_{\text{in}}^G + \bar{\lambda}^E P_{\text{in}}^E
\]

where \( \bar{\lambda}^G \) and \( \bar{\lambda}^E \) represent the annual average natural gas price and electricity price, respectively.

4. Internal rate of return:

\[
F_{\text{NPV}} = \sum_{t=0}^{T} \left( C_{\text{in}} - C_{\text{out}}^{\text{t}} \right) = 0
\]

where \( i_{\text{IRR}} \) is the internal rate of return of system construction; \( C_{\text{in}} \) and \( C_{\text{out}} \) are the annual cash inflow and outflow in system construction and operation, respectively. If \( i_{\text{IRR}} \leq i_p \), it indicates that the construction of multi-energy micro-grid system project is feasible.

2.3 Indicators for reliability

1. Generalized EENS:

The safe and reliable operation of the multi-energy micro-grid system is the premise of the safe production of enterprises in the region and the convenience of residents. The access of distributed power supply has an impact on the reliability of the original multi-energy micro-grid, and the
significance of using the traditional index to guide the planning and decision-making of multi-energy micro-grid has limitations.\textsuperscript{32} In the reliability analysis of a traditional power system, expected energy not supplied (EENS) is an important evaluation index, which refers to the amount of power supply gap due to failures occurred in the system within a certain period.\textsuperscript{33} In the future, the multi-energy micro-grid needs to meet various user energy needs, such as cold, heat, and electricity, so its ability to meet different energy needs should be analyzed. This part uses generalized EENS to analyze the reliability of the multi-energy micro-grid, and the specific calculation is as follows:

$$\text{EENS} = \sum_{i=1}^{N} \left( \theta_E \text{EENS}_E^i + \theta_H \text{EENS}_H^i + \theta_C \text{EENS}_C^i \right)$$ \hspace{1cm} (10)

where $\text{EENS}$ represents the generalized EENS; $N$ represents the time horizon in the calculation; $\text{EENS}_E^i$, $\text{EENS}_H^i$, and $\text{EENS}_C^i$ represent the EENS for electricity, hot, and cold, respectively. Considering the varied effects of different energies’ EENS,\textsuperscript{34,35} three weights, $\theta_E$, $\theta_H$, and $\theta_C$, are used to reflect the effects on the system’s reliability in supplying these energies. In practice, these weights could be calculated as the normalized average loss from the interrupted supply of different types of energies.

2. Equivalent availability coefficient

$$\phi = \frac{T_a - T_d}{T_Y} \times 100\%$$ \hspace{1cm} (11)

where $T_a$ and $T_d$ refer to the annual available hours of the system and the equivalent outage hours of the system output reduction or maintenance, respectively; and $T_Y$ is the hours of the annual statistical period of the system.

Note that in this study, the calculation of system reliability is not only limited to electric power, but also involves other forms of energy sources, such as heat, gas, and cold. Thus, we could use these indicators to evaluate the capability of a micro-grid to supply different energy needs in a multi-energy environment. Moreover, several weighting coefficients have been introduced in the design of generalized EENS. In this way, the dependency of system reliability on the supply of different energy-carriers can be properly reflected in the assessment. Finally, as a multi-energy micro-grid could involve different energy carriers which could only be converted to each other through the energy conversion technologies (such as P2G and gas turbine), the reliability of these energy converters could be critical factor influencing the operational efficacy of the system. Such an issue has also been noticed and taken into account in our proposed framework by defining an indicator named “equivalent availability coefficient” to indicate the reliability of transformation relationship (coupling) in a multi-energy system. In view of the abovementioned features, the present work in this paper is fundamentally different to that of Muñoz-Delgado’s study in Ref. 32.

### 2.4 Indicators for consumption of renewables

1. Utilization efficiency of renewables:

$$\kappa = \frac{P^\text{pv} + P^\text{wt}}{T^\text{PV} B^\text{PV} + T^\text{WT} B^\text{WT}} \times 100\%$$ \hspace{1cm} (12)

where $\kappa$ represents the utilization efficiency of renewables in a multi-energy micro-grid; $T^\text{PV}$ and $T^\text{WT}$ represent the annual available hours of distributed photovoltaic modules and distributed wind power units, respectively.

2. Ratio of renewables in energy supply:

$$\gamma = \frac{a(P^\text{pv} + P^\text{wt})}{P^\text{out} + O^\text{H} + O^\text{C}} \times 100\%$$ \hspace{1cm} (13)

where $\gamma$ represents the ratio of renewables in the energy supply, which is calculated as the ratio between annual power output from renewables and the total energy supply of the system.

3. Generation emissions:

$$C^\text{em} = f^G V^G_{\text{in}} + f^E P^E_{\text{in}}$$ \hspace{1cm} (14)

where $C^\text{em}$ represents the amount of carbon emission of the system; $f^G$ and $f^E$ represent the carbon emissions per cubic meter of natural gas and the carbon emissions from generating per kWh of electricity purchased from the main network, respectively.

In summary, the comprehensive benefit evaluation index system of the multi-energy micro-grid is divided into four quasi-test layers and 12 evaluation indexes. The overall energy utilization rate, energy-saving rate, exergetic efficiency, renewable energy utilization efficiency, and proportion of renewable energy supply are the "efficiency" indicators. The equivalent annual value of system investment, system operation, and maintenance cost, off-system energy purchase cost, internal rate of return, generalized expected energy supply shortage, equivalent availability coefficient, and carbon emission intensity are "cost indicators."

### 3 A MEE EVALUATION APPROACH BASED ON COMBINED WEIGHTING METHOD

The basic concept of an MEE model is to represent a thing to be evaluated $N$ with an ordered triple $R$, that is, $R = <N$,
where $e, v$, are the matter element; $e = (c_1, c_2, c_3 \ldots c_n)$ is the characteristic index vector of $N_j$; $v = (v_1, v_2, v_3 \ldots v_n)$ is the quantity value of the corresponding characteristic index.

Assuming that the matter element $R$ has $m$ ratings to be evaluated, $R$ can be expressed in a matrix form as shown in formula (15):

$$
R = \begin{bmatrix}
R_1 \\
R_2 \\
\vdots \\
R_m
\end{bmatrix}
$$

According to the classical matter-element-extension model, the specific evaluation steps of the MEE evaluation model, assuming that the matter element $R$ has $m$ ratings to be evaluated, $R$ can be expressed in a matrix form as shown in formula (15):

$$
R = \begin{bmatrix}
R_1 \\
R_2 \\
\vdots \\
R_m
\end{bmatrix}
$$

3.1 | Determine the classical domain level

The classical domain level of matter element $R_j$ of each rating to be evaluated is shown in formula (16):

$$
R_j = (N_j, c, d) = 
\begin{bmatrix}
N_j \\
c_1 (v_{j1}, q_{j1}) \\
c_2 (v_{j2}, q_{j2}) \\
\vdots \\
c_n (v_{jn}, q_{jn})
\end{bmatrix}
$$

where $c_i$ represents the $i$th characteristic index vector of the rating $N_j$ to be evaluated; $i \leq n, j \leq m; d_j = (v_{ji}, q_{ji})$ represent the range of quantity value of index $c_i$, that is, the classical domain level of the matter element $R_j$ to be evaluated.

3.2 | Determine the joint domain level

$$
R_j = (p, c, d_{p_j}) = 
\begin{bmatrix}
p \\
c_1 (v_{p1}, q_{p1}) \\
c_2 (v_{p2}, q_{p2}) \\
\vdots \\
c_n (v_{pn}, q_{pn})
\end{bmatrix}
$$

where $p$ represents the complete set of the evaluation rating; $d_{p_j} = (v_{p1}, q_{p1})$ represents the range of quantity value of $p$ in relation to characteristic index vector $c_j$.

3.3 | Construction of model for matter-element to be evaluated

On the basis of the original data and the actual situation of the matter element $R$ to be evaluated in relation to the characteristic vector, the matter element can be expressed as in the following with the matter element model:

$$
R_0 = (p_0, c, d_0) = 
\begin{bmatrix}
p_0 \\
c_1 v_1 \\
c_2 v_2 \\
\vdots \\
c_n v_n
\end{bmatrix}
$$

where $R_0$ is the matter element to be evaluated; $p_0$ is the thing to be evaluated; $v_1, v_2, \ldots, v_n$ are the actual data of $p_0$ in relation to the characteristic index vector.

3.4 | Establishing the correlation function for evaluation and determining degree of correlation

On the basis of the correlation function in the matter element theory, the degree of correlation between each evaluation indicator and each rating to be evaluated is calculated as shown in formula (19):

$$
h_{ij}(v_i) = \begin{cases} 
\frac{\rho(v_i, d_{ji})}{\rho(v_i, d_{ip}) - \rho(v_i, d_{jp})}, & \rho(v_i, d_{ip}) \neq \rho(v_i, d_{jp}) \\
- \frac{\rho(v_i, d_{ip}) - \rho(v_i, d_{jp})}{d_{ij}}, & \rho(v_i, d_{ip}) = \rho(v_i, d_{jp})
\end{cases}, \quad i = 1, 2, \ldots, n; j = 1, 2, \ldots, m
$$

where $h_{ij}(v_i)$ is the correlation function value of the $i$th indicator in relation to the $j$th evaluation rating; $\rho(v_i, d_{ip})$ represents the distance between the $i$th indicator and its corresponding classical domain; $\rho(v_i, d_{jp})$ represents the distance between the $i$th indicator and its corresponding joint domain. $\rho(v_i, d_{ip})$ and $\rho(v_i, d_{jp})$ can be derived as follows:

$$
\rho(v_i, d_{pi}) = \sqrt{\frac{v_i - \frac{v_{p1} + q_{p1}}{2}}{2} - \frac{(q_{pi} - v_{pi})}{2}} \\
\rho(v_i, d_{pj}) = \sqrt{\frac{v_i - \frac{v_{p1} + q_{p1}}{2}}{2} - \frac{(q_{pi} - v_{pi})}{2}}
$$

3.5 | Assignment of weights

In this paper, the combined weighting method of the AHP-entropy weighting method is used to weight each index. The Analytic Hierarchy Process (AHP) is a hierarchy
weight decision making method, which decomposes elements related to decision-making according to goals, criteria, and schemes.\textsuperscript{37} In the process of forming the importance relation matrix, the subjective judgment of experts exists, and the weight obtained is more subjective. The entropy weight rule is based on the original evaluation data and gives weights to indexes from the perspective of information entropy. It mainly considers the degree of information of the original data of indexes, and the greater the entropy value is, the more important the information will be. Therefore, this paper adopts the improved entropy weight method to objectively give weights to indexes, and finally forms the final index weight by combining weights. This part mainly elaborates the entropy weight method and the combination weight process, specifically as follows:

\[
\begin{align*}
    b_{hi} &= \frac{v_{hi} - \overline{v}}{v_{\text{max}} - v_{\text{min}}} \\
    f_{hi} &= \frac{\sum_{h=1}^{L} b_{hi} + 1}{\sum_{h=1}^{L} b_{hi} + 1} \\
    H_i &= -(\sum_{h=1}^{L} f_{hi} \ln f_{hi}) / \ln L
\end{align*}
\]  \tag{21}

where \( h \) is the serial number of designs to be compared; \( i \) is the number of indicators; and \( L \) is the number of designs to be compared; \( \overline{v} \), \( v_{\text{max}} \), and \( v_{\text{min}} \) represent the mean, maximum, and minimum value of the same indicator under different designs, respectively; \( H_i \) is the entropy value variable for corresponding indicator \( c_i \). Thus, the weight of the corresponding indicator can be obtained as shown in formula (22):

\[
w_i^H = \frac{1 - H_i}{n - \sum_{i=1}^{n} H_i}
\]  \tag{22}

where \( w_i^H \) is the weight of the evaluation indicator \( c_i \) obtained by the entropy weighting method. The combined weight for indicator \( c_i \) can be obtained by calculating the weighted average of weights from the AHP and entropy weighting method, as shown in formula (23):

\[
w_i = H_i w_i^A + (1 - H_i) w_i^H
\]  \tag{23}

where \( w_i \), \( w_i^A \), and \( w_i^H \) represent the combined weight of indicator \( c_i \), the subjective weight obtained by the AHP method, and the objective weight obtained by the entropy weighting method, respectively. An indicator's entropy value used as weighting coefficient can help in obtaining a more objective and effective combined weight.

3.6 | Determining the final ranking from the evaluation

By weighting the correlation degrees of each evaluation index and different evaluation levels, the weighted correlation degree of the MTH to be evaluated can be expressed as

\[
h_j(R_0) = \sum_{i=1}^{n} w_i h_{ij}(v_i)
\]  \tag{24}

According to the maximum membership principle, the rank of the matter element \( R_0 \) to be evaluated can be obtained as follows:

\[
m_0 = j, \exists h_{m_0}(R_0) = \max(h_j(R_0)), \forall j \in m
\]  \tag{25}

where \( m_0 \) is the rank to which the matter element \( R_0 \) to be evaluated belongs. In addition, according to the MEE model, the variable characteristic value for the rank can be obtained, as shown in formula (26):

\[
\overline{h}_j(R_0) = \frac{h_j(R_0) - \min(h_j(R_0), \forall j)}{\max(h_j(R_0), \forall j) - \min(h_j(R_0), \forall j)}
\]  \tag{26}

\[
j^* = \frac{\sum_{j=1}^{m} j \overline{h}_j(R_0)}{\sum_{j=1}^{m} \overline{h}_j(R_0)}
\]  \tag{27}

where \( j^* \) is the variable characteristic value of the matter element to be evaluated, which is indicative of its tendency to drift to neighboring ranks and can be used to analyze its development trend.

4 | EXAMPLE ANALYSIS

In this paper, on the basis of the actual load data of a multi-energy micro-grid demonstration project from an existing micro-grid construction situation and planning scheme,\textsuperscript{38} a comparative evaluation of multi-energy micro-grid schemes under different planning schemes was carried out. The micro-grid pilot project has a total of eight load clusters, among which load clusters 1-5 are mainly residential user loads, load cluster 6-7 are small commercial loads, and load cluster 8 is mainly an industrial load. According to the existing planning objectives, the following multi-energy micro-grid planning schemes were formed, as shown in Table 3.

The above designs are mainly the derived results by considering the two planning objectives of construction cost and emissions indicator in the planning process. A multi-objective algorithm was implemented with the
constraint $\varepsilon$ to obtain the Pareto front. Therefore, in this paper, we selected four typical designs for comprehensive comparison. As they encompass different units, the multi-energy micro-grid demonstrates different characteristics in operation. Table 4 shows the setting of techno-economic parameters used in our case study, which are extracted from Ref. 39.

In this paper, it is assumed that the operational life of the multi-energy micro-grid is 20 years and the interest rate of long-term bank loans is 4.9%. The average price of externally purchased electricity is 0.5 Yuan/kWh, and the average price of natural gas is 2.63 Yuan/m³. Since the pilot project is located in southern China, for the generalized EENS calculated in this paper, the weights of $\theta_E$, $\theta_H$, and $\theta_C$ were assigned to be 0.7, 0.1, and 0.2, respectively. On the basis of the idea that a comprehensive evaluation of the multi-energy micro-grid should be put into perspective with indicators relevant to traditional micro-grids or distribution networks, this paper uses five ranks, namely, very poor, poor, normal, good, and very good, which are denoted as $K_1$, $K_2$, $K_3$, $K_4$, and $K_5$. Furthermore, on the basis of the original values of indicators for existing micro-grids and heating systems in the pilot area and indicators of other comparable multi-energy micro-grids, this paper determined the classical domain of each of the indicators as shown in Table 5.

The calculation of each indicator in the above scheme is based on the analysis and calculation of the system operation scenario results in the formation process of the actual planning scheme. In the calculation of expected power supply deficiency (EENS), the operation state of different types of equipment needs to be sampled using the Monte Carlo algorithm. The forced shutdown rate of all the equipment in this paper is 0.04. The load and renewable energy output scenarios and occurrence probability should be consistent with the system operation scenario in the planning scheme. In this paper, the specific operation scenarios are shown in Table 6.

### Assignment of weights

According to the weight determination method in 2.5, first of all, different index weights were obtained through the scores of 10 experts, and then the subjective weight was obtained. Secondly, according to the actual data of the four schemes, the indexes were standardized according

| Scheme | Details |
|--------|---------|
| I      | 3500 kW heat pump + 360 kW wind turbine + 200 kW CHP + 340 kWh electro-chemical storage |
| II     | 3200 kW heat pump + 500 kW absorption refrigerator + 360 kW wind turbine + 450 kW CHP |
| III    | 3200 kW heat pump + 500 kW gas boiler + 500 kW absorption refrigerator + 360 kW wind turbine + 400 kW CHP + 50 kWh thermal storage |
| IV     | 3200 kW heat pump + 200 kW gas boiler + 375 kW solar thermal + 500 kW absorption refrigerator + 360 kW wind turbine + 4000 kW PV + 500 kW CHP + 3200 kWh thermal storage + 500 kWh electro-chemical storage |

| Equipment | Fixed cost (Yuan) | Unit capacity acquiring cost (Yuan/kW) | Unit capacity operation and maintenance cost (Yuan/kW) |
|-----------|-------------------|--------------------------------------|------------------------------------------------------|
| Heat pump | -                 | 3000                                 | 0.1                                                  |
| Gas boiler| -                 | 1000                                 | 0.15                                                 |
| Solar thermal | -         | 300 Yuan/m²                          | 230 Yuan/m²                                          |
| Absorption refrigerator | -     | 4500                                 | 0.1                                                  |
| Distributed wind turbine | - | 7000                                 | 0.07                                                 |
| Distributed PV | - | 6000                                 | 0.005                                                |
| CHP       | 10 000            | 3500                                 | 0.15                                                 |
| Thermal storage | - | 500 Yuan/kWh                       | 0.1                                                  |
| Electro-chemical storage | - | 3000 Yuan/kWh                       | 0.05                                                 |
to the "cost-type indexes" and "efficiency-type indexes," and then the objective weight weights of the nine indexes were formed according to the entropy weight method. The weights of each index were combined with the entropy variable to obtain the weights of each index, as shown in Figure 1.

| Indicator                               | K₁       | K₂       | K₃       | K₄       | K₅       | Joint domain d_{πn} |
|-----------------------------------------|----------|----------|----------|----------|----------|---------------------|
| Total energy utilization efficiency     | [100,120) | [120,140) | [140,160) | [160,180) | [180,200) | [100,200]          |
| Comprehensive energy-saving rate        | [0,10)   | [10,20)  | [20,30)  | [30,40)  | [40,50]  | [0,50]             |
| Exergy efficiency                       | [20,40)  | [40,60)  | [60,80)  | [80,100) | [100,120) | [20,120]           |
| Annual value of system investment       | [3800,4500] | [3100,3800) | [2400,3100) | [1700,2400) | [1000,1700) | [1000,4500]        |
| System operation and maintenance cost   | [500,600] | [400,500) | [300,400) | [200,300) | [100,200) | [100,600]          |
| Energy procurement cost                 | [400,500) | [300,400) | [200,300) | [100,200) | [0,100)   | [0,500]            |
| Internal rate of return                 | [0,2)    | [2,4)    | [4,6)    | [6,8)    | [8,10)    | [0,10]             |
| Generalized EENS                        | [400,500) | [300,400) | [200,300) | [100,200) | [0,100)   | [0,500]            |
| Equivalent availability factor          | [90,92)  | [92,94)  | [94,96)  | [96,98)  | [98,100)  | [90,100]           |
| Utilization efficiency of renewables    | [50,60)  | [60,70)  | [70,80)  | [80,90)  | [90,100)  | [50,100]           |
| Ratio of renewables in energy supply    | [0,20)   | [20,40)  | [40,60)  | [60,80)  | [80,100)  | [0,100]            |
| Carbon intensity targets                | [400,500] | [300,400) | [200,300) | [100,200) | [0,100)   | [0,500]            |

**Table 6** Probabilities and parameters of typical scenarios expected

| Scenario                  | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---------------------------|------------|------------|------------|------------|------------|------------|
| Average power load of the system (kW) | 2105       | 2452       | 2987       | 1995       | 3067       | 2574       |
| Average heating load of the system (kW) | 4530       | 4985       | 5861       | 3796       | 3294       | 4090       |
| Average cooling load of the system (kW) | 1930       | 1531       | 973        | 1267       | 2680       | 2017       |
| Mean of wind speed (m/s)   | 7.9        | 5.1        | 6.3        | 6.9        | 4.2        | 7.1        |
| Mean radiation intensity (kW/m²) | 0.65       | 0.57       | 0.23       | 0.72       | 0.95       | 0.52       |
| Probability of the scenario | 0.15       | 0.09       | 0.16       | 0.03       | 0.03       | 0.05       |

| Scenario                  | Scenario 7 | Scenario 8 | Scenario 9 | Scenario 10 | Scenario 11 | Scenario 12 |
|---------------------------|------------|------------|------------|-------------|-------------|-------------|
| Average power load of the system (kW) | 3327       | 2687       | 2491       | 2636        | 2278        | 2852        |
| Average heating load of the system (kW) | 3089       | 4390       | 4219       | 4987        | 5313        | 3251        |
| Average cooling load of the system (kW) | 2988       | 1678       | 1985       | 2498        | 2628        | 1582        |
| Mean of wind speed (m/s)   | 5.3        | 9.2        | 8.1        | 8.7         | 7.3         | 6.9         |
| Mean radiation intensity (kW/m²) | 0.68       | 0.49       | 0.79       | 0.82        | 0.39        | 0.45        |
| Probability of the scenario | 0.06       | 0.05       | 0.07       | 0.15        | 0.09        | 0.07        |
It can be seen from the figure that the combined weight obtained by the improved entropy weight method is still close to the weighted result of AHP, indicating that the combined weight obtained is feasible and the final combined weight obtained is as follows:

$$w = [0.068 \ 0.060 \ 0.090 \ 0.157 \ 0.107 \ 0.102 \ 0.053 \ 0.069 \ 0.087 \ 0.057 \ 0.071 \ 0.079].$$

### 4.2 Evaluation results

On the basis of the weight of each index in 3.1 and the actual data of each index in each scheme, the above schemes were comprehensively evaluated. The correlation degree of each index in the different schemes is shown in Figures 2-5. The final evaluation results of each scheme are shown in Table 7.

According to the definition in formula (25), scheme 1 belongs to the $K_1$ level, scheme 2 belongs to the $K_2$ level, and schemes 3 and 4 both belong to the $K_4$ level. According to formula (27), we get that for scheme 3, $j^*_3 = 4.013$, and for Scheme 4, $j^*_4 = 3.776$. The above results indicate that scheme 3 is a better planning scheme than scheme 4.

Poor results of the evaluation, mainly due to the differences in the concerned system. The energy procurement cost and generalized expectations energy supply (EENS), renewable energy efficiency, and renewable energy supply compared to traditional independent planning run without too much of micro-network and network advantages, and renewable distributed power supply capacity is limited, mean that despite the electrical energy storage and heat pump's advantage in terms of renewable energy capacity, it was not considered to be a more attractive option than traditional systems. Plan 4, in terms of comprehensive efficiency of energy utilization, system energy procurement cost, generalized expectations energy supply (EENS), renewable energy utilization efficiency, the proportion of renewable energy supplies, and carbon intensity, which are $K_5$ level indicators, belongs to the "very good" level, but the greater investment in equipment makes the overall operational costs relatively high, leading to it being finally evaluated as a $K_4$ level. It also conforms to the law in which the marginal benefit of an investment gradually reduces. Take the EENS index as an example, although more flexible resources are allocated in plan 4, the EENS index is not significantly improved compared with plan 3.

Compared with them, the scheme of three better accomplishes the economic and technical index of the coordination, mainly due to the thermal energy storage access, which enables CHP to undergo "thermoelectric decoupling," have a larger
area of distributed renewable energy, the gas boiler, absorption chiller and heat pump are connected to give the system improved thermal/electric displacement ability. Furthermore, the system operation can be implemented to utilize complementary energy more efficiently. It also shows that much of our country’s current energy micro-network construction should focus more on existing micro-grid construction and modification, heating systems, and regulate the system coupling degree to full advantage, rather than blindly pursue systems with more flexible resources, which result in higher system construction costs and sub-optimal equipment utilization rate.

### 4.3 Comparative analysis with conventional evaluation method

In order to verify the superiority of the proposed evaluation method based on MEE, a comparative analysis is conducted in this section. For this end, a conventional method used for determining the weighting of evaluation indices in comprehensive evaluation studies, that is, Analytic Hierarchy Process (AHP) method is considered as reference case. This approach has been focused because it represents the most representative and commonly used comprehensive evaluation method in the industry.

In this test, the data setting remains the same as in previous analysis. The evaluation results derived based on different approaches are shown and compared in Table 8.

It can be seen that, in the traditional AHP weighted method, the planning scheme 1 is categorized into the K₁ level, while scheme 2 to K₄ level, and scheme 3 and 4 both fallen into K₅ level. Compared with the obtained results with MEE, there is a tendency of polarization in the AHP evaluation results, which indicates that the traditional evaluation methods have poor performance in terms of differentiation and accuracy. Specifically, on the one hand, from the fact that both scheme 3 and scheme 4 belong to K₅ level, it can be observed that since AHP weights the evaluation level constructed in a subjective manner, it is not capable of fully capturing the feature of evaluation objects, which makes the evaluation results obtained not satisfactorily accurate. On the other hand, from the fact that scheme 3 and 4 both fallen into K₅ level, it can be seen that the evaluation results from AHP are not adequate to reflect the differences between the advantages and disadvantages of different schemes when the featured characteristics between two schemes are less significant. In contrast, considering the same data and evaluation criteria, the improved MEE evaluation model can provide more scientific and reasonable results, which comprehensively reveals the

| Table 7 | Evaluation results for each candidate scheme |
| --- | --- |
| Scheme | K₁ | K₂ | K₃ | K₄ | K₅ |
| I | -0.0969 | -0.3182 | -0.4324 | -0.4344 | -0.3205 |
| II | -0.3340 | -0.1332 | -0.1533 | -0.1834 | -0.2381 |
| III | -0.5806 | -0.4790 | -0.3097 | 0.0522 | -0.0865 |
| IV | -0.4270 | -0.5348 | -0.4942 | -0.0291 | -0.3569 |

| Table 8 | Result comparison between the proposed MEE and conventional evaluation method |
| --- | --- |
| Method | Scheme | K₁ | K₂ | K₃ | K₄ | K₅ |
| AHP | Scheme 1 | -0.0781 | -0.3208 | -0.4469 | -0.4547 | -0.3343 |
| | Scheme 2 | -0.3266 | -0.1631 | -0.1441 | -0.1312 | -0.2698 |
| | Scheme 3 | -0.5800 | -0.4750 | -0.3000 | -0.0749 | 0.0474 |
| | Scheme 4 | -0.4138 | -0.5381 | -0.5046 | -0.3672 | -0.0228 |
| MEE | Scheme 1 | -0.0969 | -0.3182 | -0.4324 | -0.4344 | -0.3205 |
| | Scheme 2 | -0.3340 | -0.1332 | -0.1533 | -0.1834 | -0.2381 |
| | Scheme 3 | -0.5806 | -0.4790 | -0.3097 | -0.0522 | -0.0865 |
| | Scheme 4 | -0.4270 | -0.5348 | -0.4942 | -0.0291 | -0.3569 |
merits and demerits of each concerned scheme. Moreover, the proposed MEE method can give consideration to the discrimination and accuracy of evaluation results, and provide richer reference information for decision makers. In this sense, it can be concluded that the proposed MEE technique outweighs the conventional comprehensive evaluation method in real-world implementations.

5 DISCUSSION

In this paper, the comprehensive evaluation framework for the multi-energy micro-grid system based on the MEE technique is presented. To do so, a new evaluation index system for the performance of multi-energy microgrid is constructed, which covers the aspects including energy efficiency, economic-effectiveness, reliability of supply, and the renewable energy utilization of the system. The following conclusions can be drawn from this study:

1. This paper proposes a more scientific, comprehensive, and reasonable evaluation index system, especially in the evaluation process of the system reliability index. The generalized EENS index is introduced to make the reliability evaluation of the multi-energy micro-grid more objective and effective.

2. When investing in multi-energy micro-grid, from the point of view of evaluating a project, we should not blindly invest in new equipment and should consider the interaction between different system requirements and equipment. In this paper, the configuration of the proposed solution strategy, as a result of the lack of sufficient means of thermal/electric displacement, leads to a micro-network that has no advantage when compared with the traditional energy system.

3. The equipment configuration strategy should fully consider the investment economy. To achieve the commercialization of energy micro-grid, it is necessary to promote an integrated energy system for the implementation of landing. In this article, the results of plan three and four contrast evaluation means and demonstrate how more flexible configuration resources can improve the system of technical indicators; however, the larger required investment and gradually diminishing marginal benefit will ultimately affect the viability of the scheme.

4. By comparing with the traditional evaluation methods, the improved matter-element extension evaluation model can provide more scientific and reasonable evaluation results, with better discrimination and accuracy.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

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