Research on benefit evaluation method of integrated energy system project based on combination weight

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Abstract. The construction of integrated energy system contributes to the large-scale development of renewable energy and improves the flexibility and safety of social energy supply. However, the current integrated energy system project benefit evaluation index system is still not perfect, lacking the standard and can hardly be applied to the actual project evaluation. In view of these problems, this paper constructs a universally applicable integrated energy system project benefit evaluation index system named ‘3E1F’, evaluating benefits from four aspects which are energy efficiency, economic benefit, environment benefit and function benefit. The index weight is established by the combination of AHP-entropy weight method. The effectiveness and feasibility of the benefit evaluation index system and calculation method are verified by actual cases. Finally, combined with the actual cases and the main problems of the current integrated energy system project construction, this paper puts forward several optimization suggestions for improving the efficiency of the integrated energy system project.

1. Introduction

With the further adjustment of the national energy structure and the deepening of market-oriented reforms, the proportion of distributed clean energy in the national energy structure has increased year by year. As one of the most abundant and widely distributed renewable energy sources, distributed energy is an indispensable part of the integrated energy system and needs to be integrated and utilized. Therefore, Chinese President Xi Jinping proposed the concept of the development of the energy revolution, requiring the construction of a clean, low-carbon, safe and efficient modern energy system, which leads to rapid development of the integrated energy system. Since 2015, Chinese government has issued a number of policies to support the construction and development of integrated energy systems from new energy, micro-grid and multi-energy complementarity. A number of batches of multi-energy complementary integrated optimization demonstration projects, new energy micro-grid demonstration projects, and ‘Internet +’ smart energy demonstrations have emerged, accumulating experience in the integration and consumption of distributed energy, and promoting the research and development of integrated energy systems.

At present, researchers at home and abroad have carried out extensive and in-depth research on integrated energy systems, but most of them focus on the concepts, structures or models, etc. There are relatively few studies on the benefits of integrated energy system projects, and the economic, environmental and social benefits that the system can bring remain at the conceptual stage. For
example, Zhang Tao[1] and Dong Fugui[2] selected investment and operating costs, primary energy consumption and utilization, NOx and CO2 emissions as evaluation indicators from the economic, energy consumption, environment three perspectives. Du Ying[3] evaluated comprehensive alternative benefits of the wind, photovoltaic, biomass and other new energy. But this paper for alternative energy is only part of the new energy, not involved in other energy sources. It can be further improved.

Compared to the microscopic study of a particular or presumed regional energy system in China[4], foreign research on integrated energy system has focused mainly on the energy, economic and environmental fields[5]. Most of the benefits evaluation of integrated energy system in foreign countries follow the traditional evaluation index, that is, financial index, gas emission reduction index and other indicators, such as Biezma M V[6] used technical and economic evaluation methods to build a relatively complete evaluation index system of investment benefits, evaluated the investment benefit of CHP cogeneration system using electro-thermal coupling. The Index system is simple, clear and operable, but there are some limitations in its application.

From the existing research results, domestic and foreign research on the benefit evaluation index system of integrated energy system has been carried out, but there are some limitations. Comprehensive energy project benefit evaluation index system and its standards have not been fully established, and are difficult to be applied to practical evaluation. Based on this, this paper constructs the generally applicable ‘3E1F’ integrated energy system project benefit evaluation index system.

2. Integrated energy system overview

The concept of integrated energy systems has been emerging for a long time, but until now there is no uniform definition. Therefore, the integrated energy system studied in this paper means that in the process of planning, construction and operation, it is the physical carrier of energy internet to implement organic coordination and optimization for the generation, transmission and distribution, conversion, storage, consumption, transaction and other aspects [7-8]. Figure 1 shows the basic architecture.

3. Construction of comprehensive energy system benefit evaluation index system

On the basis of the ‘3E’ system composed of energy, economy and environment, this paper comprehensively considers the characteristics and functions of the integrated energy system project, and follows the principles of scientific, systematic, comprehensive, practical, operable, quantitative and qualitative combination of the index system. Table 1 shows the ‘3E1F’ comprehensive energy system project benefit evaluation index system constructed to carry out benefit evaluation. The ‘3E1F’ indicator system is made up of 4 secondary indicators consisting Energy Efficiency, Economic Benefit, Environment Benefit and Function Benefit and 19 third-level indicators.
Energy Efficiency mainly reflects the optimization of primary and renewable energy in integrated energy system, including the improvement of energy utilization rate, the change of energy conversion efficiency and so on. All indicators are benefit-oriented indicators.

Economic Benefit mainly reflects as an investment project, the integrated energy system can bring economic returns to investors after putting into operation. In addition to the investment payback period is the cost type index, others are the benefit type index.

Environment Benefit mainly reflects the impact of integrated energy system on the natural environment. The Emission reduction support benefit is the cost type index, the others are the benefit type indexes.

The Function Benefit mainly reflects the impact of integrated energy system on four aspects, which are power grids, users, regional development and industrial development. All of the thid-level indexes are benefit indexes.

Table 1. ‘3E1F’ integrated energy system project benefit evaluation index system.

| Primary indicators                  | Secondary indicators                  | Third-level indicators                                                                 |
|-------------------------------------|---------------------------------------|----------------------------------------------------------------------------------------|
| Benefits of integrated energy system project construction | Energy Efficiency B1                   | Energy conversion efficiency coefficient C1                                            |
|                                     |                                       | Renewable energy penetration rate C2                                                   |
|                                     |                                       | Increased rate of primary energy utilization C3                                        |
|                                     |                                       | Energy dissipation Rate C4                                                            |
|                                     | Economic Benefit B2                    | Net present value C5                                                                  |
|                                     |                                       | Internal rate of return C6                                                            |
|                                     |                                       | Investment payback period C7                                                          |
|                                     |                                       | Economic Value Added C8                                                               |
|                                     |                                       | Electrical yield C9                                                                  |
|                                     | Benefits of integrated energy system project construction A | Unit investment to increase the sale of electricity C10                               |
|                                     | Environment Benefit B3                 | Emission reduction support benefit C11                                               |
|                                     |                                       | Environmental impact of construction C12                                               |
|                                     |                                       | Operating Environment impact C13                                                     |
|                                     |                                       | Power grid Coverage capacity C14                                                      |
|                                     |                                       | Regional development Promotion capacity C15                                           |
|                                     | Function Benefit B4                    | Industrial development Promotion Capability C16                                       |
|                                     |                                       | User Service Capability C17                                                           |
|                                     |                                       | Valley Filling Capability C18                                                         |
|                                     |                                       | Safety and reliability of power supply C19                                             |

4. Construction of evaluation model based on combination weight

4.1. Indicator normalization processing method

Because of the difference between the dimensions and magnitudes of the integrated energy system project benefit evaluation, the data should be quantified and normalized. Different methods have different advantages and disadvantages, in order to solve the problem of non-public and numerical differences between the attributes, this paper choose the simplest calculation method to standardize indicators, as shown in formula (1). The $x_{ij}$ means the orginal value, the $b_{ij}$ means the normalized value.

$$b_{ij} = \begin{cases} \frac{x_{ij}}{\max x_y} & x_y \text{ is a benefit indicator} \\ \frac{\min x_y}{x_{ij}} & x_y \text{ is a cost indicator} \end{cases}$$ (1)
4.2. Methods for determining index combination weight

4.2.1. Weights determined by AHP. In order to fully reflect the opinions of the experts, effectively avoid the subjective bias of individual experts, this paper increases the responsibility of experts on the basis of traditional AHP. The main steps are as follows:

1. Figure 2 shows the evaluation system of expert weight constructed according to the different qualifications, authority and knowledge of experts, and the experts’ power $P_k(\text{k}=1,2,\ldots,m)$ is obtained by AHP method.

![Figure 2](Experts' power evaluation system)

2. Set up expert k to 2-2 comparison of the factors under the same attribute the relative importance matrix formed by the score is $A_k$, then the comprehensive judgment matrix composed of various expert opinions is $A^* = \sum_{k=1}^{m} P_k A_k$.

3. According to the principle of AHP method, the $A^*$ of the comprehensive judgment matrix is tested, the maximum eigenvalue and eigenvectors of the matrix are obtained, and the weight of the index $w_j^1$ is obtained by the consistency judgment.

4.2.2. Weight determined by entropy weight method. Entropy can measure the amount of effective information contained in known data, and then determine the weight of the indicator. When the index value gap is large, the entropy value is small. The steps to determine weights in the Entropy method are as follows:

1. Normalization of indicators. Transform all the indicators into relative data and build the matrix $X=[x_{ij}]_{y \times n}$, $n$ is the number of indicators, $y$ is the number of scenarios.

2. Standardize matrix $X$ and obtain $B=[b_{ij}]_{y \times n}$, according to the formula (1) to obtain the calculated value of each $b_{ij}$.

3. Calculate the entropy value of the indicator, as shown in the following formula.

$$H_j = -\frac{1}{\ln y} \left( \sum_{i=1}^{y} f_{ik} \ln f_{ik} \right), i = 1, 2, \ldots, y; j = 1, 2, \ldots, n$$

$$f_{ik} = \frac{b_{ij}}{\sum_{y} b_{ij}}$$  \hspace{1cm} (2)

4. Calculate weights $w_j^2$ by the following formula.

$$w_j^2 = \frac{1-H_j}{n \sum_{j=1}^{n} H_j}, j = 1, 2, \ldots, n$$  \hspace{1cm} (3)

4.2.3. Comprehensive weight calculation. After calculating the index weight values of AHP and entropy method respectively, combine the subjective empowerment and objective empowerment, and the comprehensive weight of the final index is shown in the following formula.

$$W_j = w_j^1 H_j + w_j^2 (1-H_j), \quad j = 1, 2, \ldots, n$$  \hspace{1cm} (4)

And $\sum_{j=1}^{n} W_j = 1$. In the formula, $w_j^1$ is the weight value determined by AHP, $w_j^2$ is the weight value determined by the entropy method, and $H_j$ is the entropy value of the evaluation index.
4.2.4. Comprehensive score calculation. After getting the comprehensive weight \( W_j \) of each indicator, the comprehensive score of each scheme can be achieved by formula (5), in which \( W_j \) is the comprehensive weight of the index and \( B \) is the standardized data matrix in the entropy weight method.

\[
v_{\text{value}} = W_j B, j = 1, 2, \cdots, n
\]

Combining the principle of maximum membership and the classification basis of literature [4], the five level benefit level membership function \( z_i \) of \([0,1]\) is constructed, as shown in formula (6)-(10), the score \( v_{\text{value}} \) is calculated, and the corresponding level of the maximum value is the benefit level grade of the scheme.

\[
z_1(v) = \begin{cases} 0, & v \leq 0.7 \\ v-0.7, & 0.7 < v < 0.9 \\ 0.9-0.7, & v \geq 0.9 \end{cases}
\]

\[
z_2(v) = \begin{cases} 0, & v \leq 0.5 \\ v-0.5, & 0.5 < v < 0.7 \\ 0.7-0.5, & v \geq 0.7 \end{cases}
\]

\[
z_3(v) = \begin{cases} 0, & v \leq 0.3 \\ v-0.3, & 0.3 < v < 0.5 \\ 0.7-0.5, & v \geq 0.7 \end{cases}
\]

\[
z_4(v) = \begin{cases} 0, & v \leq 0.1 \\ v-0.1, & 0.1 < v < 0.3 \\ 0.5-0.3, & v \geq 0.5 \end{cases}
\]

\[
z_5(v) = \begin{cases} 1, & v \leq 0.1 \\ 0.3-v, & 0.1 < v < 0.3 \\ 0, & v \geq 0.3 \end{cases}
\]

5. Case analysis

Based on practical research and statistical analysis, this paper selects five similar integrated energy system projects as research objects. The five integrated energy system projects are located in different regions, but the scale and the types of energy contained in the system are similar and comparable.

Integrated energy system project A is located in ‘a’ city where economic development is dominated by the secondary industry and supplemented by the tertiary industry. The city is rich in mine resources and water resources. The annual average sunshine hours is more than 2,400 hours. The city mainly develops photovoltaic power generation and garbage power generation. The existing renewable energy installed capacity of 197.36MW, accounting for 31.23% of the total installed power capacity.

Integrated energy system project B is located in a coastal city ‘b’. the total electricity consumption of the whole society is 70.9 billion kWꞏh. The annual average wind speed in the coastal area is above 9m/s , and the tidal energy reserves are 13.6 billion kWꞏh. This city has considerable wind and tidal resources and focuses on the development of offshore wind power and Tidal power generation, as well as small-scale Photovoltaic power generation and biomass power generation.

The city ‘c’, where integrated energy system project C located, has abundant wind resources, with an annual average wind speed of 8m/s. The city ‘c’ has a higher altitude and sufficient sunshine, and the annual sunshine hours are over 2,600 hours. The city mainly develops wind power and photovoltaic power generation.

The city ‘d’, where integrated energy system project D located, is similar to the city ‘c’, and has abundant wind energy reserves. The annual average wind speed is 7.5m/s, but the sunshine intensity in d city is relatively weak, while the water resources are abundant. The installed capacity of hydropower accounts for 28.53% of the total installed capacity of electric power. The development of renewable energy is mainly hydropower and wind power. The total installed capacity of the two accounts for 44% of the installed capacity of electric power. At the same time, the city develops photovoltaic power generation on a small scale.

Integrated energy system project E is located in the second-tier city ‘e’, where the total society electricity consumption is 16.838 billion kWꞏh, and the sunshine is sufficient: the annual sunshine
hours are over 2,500 hours. The proven natural gas reserves exceed 100 billion m$^3$, which means there’re abundant natural gas reserves. The photovoltaic power generation and natural gas power generation and heat generation are vigorously developed.

These five integrated energy system projects have multiple energy coupling access. The amount of distributed energy access has increased year by year, and the development of equipment and distribution networks has gradually improved, which is suitable as an example in this paper.

This paper invites 5 experts to score. According to the experts’ power shown in Figure 2, the final judgment weights of each expert’s powers and responsibilities are $P=[0.23, 0.28, 0.27, 0.11, 0.11]^T$. After obtained the final A-B comprehensive judgment matrix, $B_1$-$C$ comprehensive judgment matrix, $B_2$-$C$ comprehensive judgment matrix and $B_3$-$C$ comprehensive judgment matrix, the CR results of the these five matrices are (0.0038, 0.0029, 0.0023, 0.0050, 0.0025). The above results are all less than 0.1, which satisfies the consistency test. The above five matrices are weighted according to the AHP method and the results are shown in Table 2.

Quantifying the benefit evaluation indicators of the five integrated energy system projects and normalizing them according to the formula (1). After that, according to formulas (2)-(4), the entropy weight method weight and comprehensive weight can be calculated accordingly, as shown in Table 3, where $C_7$, $C_{12}$, and $C_{13}$ are cost-type indicators, and the rest are Benefit indicator.

| Indicator | AHP | Entropy weight method | Comprehensive weight | Indicator | AHP | Entropy weight method | Comprehensive weight |
|-----------|-----|-----------------------|---------------------|-----------|-----|-----------------------|---------------------|
| $C_1$     | 0.0714 | 0.0027 | 0.0713 | $C_{11}$ | 0.0739 | 0.0201 | 0.0732 |
| $C_2$     | 0.0561 | 0.0041 | 0.0560 | $C_{12}$ | 0.0794 | 0.3872 | 0.0750 |
| $C_3$     | 0.0466 | 0.0061 | 0.0464 | $C_{13}$ | 0.0932 | 0.3100 | 0.0715 |
| $C_4$     | 0.0401 | 0.0018 | 0.0401 | $C_{14}$ | 0.0366 | 0.0001 | 0.0366 |
| $C_5$     | 0.0394 | 0.0005 | 0.0394 | $C_{15}$ | 0.0425 | 0.0075 | 0.0423 |
| $C_6$     | 0.0394 | 0.0035 | 0.0393 | $C_{16}$ | 0.0448 | 0.0073 | 0.0446 |
| $C_7$     | 0.0322 | 0.2248 | 0.0610 | $C_{17}$ | 0.0507 | 0.0017 | 0.0506 |
| $C_8$     | 0.0478 | 0.0024 | 0.0477 | $C_{18}$ | 0.0451 | 0.0112 | 0.0448 |
| $C_9$     | 0.0563 | 0.0022 | 0.0562 | $C_{19}$ | 0.0451 | 0.0001 | 0.0451 |
| $C_{10}$  | 0.0591 | 0.0067 | 0.0589 |        |      |           |          |

According to the weighted calculation of formula (5), the benefit scores of the five integrated energy system projects are finally obtained, and the overall benefit level is B>D>C>E>A, as shown in Table 3.

| Project | Score | Total Score |
|---------|-------|-------------|
| A       | 0.1864 | 0.2087 | 0.0430 | 0.2226 | 0.6607 |
| B       | 0.2024 | 0.2297 | 0.1031 | 0.2621 | 0.7973 |
| C       | 0.1708 | 0.2164 | 0.0858 | 0.2467 | 0.7197 |
| D       | 0.1996 | 0.2452 | 0.0933 | 0.2507 | 0.7888 |
| E       | 0.1893 | 0.2292 | 0.0525 | 0.2263 | 0.6973 |

Substituting the above comprehensive score into the formulas (6)-(10), the membership function values of the benefit levels of each integrated energy system project can be obtained, as shown in Table 4. The efficiency level of each integrated energy system project is at a high level, in which A and E are at a high level in the initial stage, and the medium level is at a higher level in the late stage.
of the transition period; C is at a higher level in the middle stage and begins to gradually transition to a high level; B and D are in the middle and late stages of higher levels, and the high level to the high level is in the middle of the transition stage, which is about to reach the high level stage. The level of benefit of each integrated energy system project is basically consistent with the urban development of the region.

Combined with Tables 3 and 4, it can be seen that B contains coupling of multiple energy sources, and the traditional primary energy account is lower than the other 4 integrated energy systems, these lead to high energy efficiency. Besides, the offshore wind farm and the tidal power station do not occupy the cultivated land, flood the farmland, or need people to be relocated, and have less impact on the environment, so that B has the highest energy, environmental and functional benefit scores; However, the construction investment of offshore wind farms and tidal power stations is huge. Although the operating cost is low, it still has a certain impact on economic benefits. Therefore, the economic benefits of B are not as good as D.

A has the lowest overall score, mainly due to its large primary energy share. The type of power generation is still dominated by thermal power, and the environmental benefit score is low. E is similar to A, but its coupled natural gas energy utilization efficiency and conversion efficiency are higher than the garbage power generation, and the cost is lower. Therefore, its economic benefits are higher than A, and the overall score is slightly higher than A.

6. Conclusions
This paper sorts out the relevant policies of the state on integrated energy systems, introduces the related concepts, structural components and main features of integrated energy systems, and extracts indicators with universal applicability from the four aspects of energy, economy, environment and function, and proposes a comprehensive ‘3E1F’integrated energy system project benefit evaluation index system.

In view of the benefits of integrated energy system projects, this paper proposes three suggestions for improving the efficiency of integrated energy systems: First, it must make full use of location advantages and reasonably determine the type of integrated energy system; Second, it needs to improve energy and conversion efficiency through technological innovation to reduce production costs; Third, it needs to optimize energy allocation and structure, and improve energy planning and scheduling capabilities.

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