Synthetic evaluation of integrated energy system based on AHP-fuzzy comprehensive assessment method

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Abstract. Integrated energy system (IES) is an essential ingredient of energy reform. The construction of IES can promote the coupling utilization of multiple energy sources, and improve the reliability and flexibility of energy system. Based on amounts of literature study and experts' recommendations, 9 first-class indexes, 13 second-class indexes and 11 third-class indexes are confirmed to assess the integrated energy system from three dimensions of technology, economy, and environmental protection. Analytic Hierarchy Process (AHP) and fuzzy comprehensive assessment method are adopted to assess the overall quality of chosen integrated energy system. An industrial park is chosen to be an example and examine the evaluation condition of IES.

1 Introduction

Integrated energy system (IES) is an important part of energy internet, and it's not only the research hotspot in the field of energy, but also the development direction of energy restricting. The core of IES is carrying out energy conversion, utilization, and multi-energy complement [1-2]. U.S. Department of Energy had proposed a smart grid evaluation index system, which aimed to evaluate smart grid from six aspects [3]. The evaluation system can measure the reliability, security, and the interactive service for the user side of smart grid [4]. Europe also published smart grid earning evaluation index system to achieve the aim of improving grid earnings from nine fields and 21 key indexes [5].

In current literatures, methods of evaluation index always focus on power grid, and ignore the hot grid and cool gird [6-8]. Li et al. [9] built universal flow system models from the aspects of energy distribution, conversation, and storage. On this basis, the assessment system of IES from four dimensions of energy, devices, information, and system was come up. Luo et al. [10] studied the equivalent features of microgrid, and put forward the characteristics of intermittent power source, the islanding state of microgrid, and the benefits of microgrid. Zhang et al. [11] established an index evaluation model of park-level integrated energy system for microgrid from the aspects of economy, reliability, energy consumption and environmental protection.

Currently, the main methods of comprehensive evaluation method conclude principal component analysis (PCA) [12], AHP [13, 14], entropy weight method (EWM) [7, 15, 16], Data Envelope Approach (DEA) [17] and the method for order performance by similarity to ideal solution (TOPSIS) [15]. However, PCA and EWM always have errors when the evaluation indexes with small range of changes, and DEA is easily affected by extremes. Cavallaro et al. [15] used fuzzy Shannon entropy and fuzzy TOPSIS to assess five CHP technologies in terms of economy and efficiency. Ren et al. [13] chose various of evaluation indexes such as primary energy consumptions, investment costs, carbon emissions, and applied AHP to analyse the Japanese power supply system.

The AHP-Delphi method can combine the data and practical experience to a certain degree, and obtain more objective and reasonable evaluation indexes of IES. This method is used to determine the indexes and weight, and a park will be tested by fuzzy comprehensive assessment method.

2 Establishment of synthetic evaluation

Selection of evaluation index is both the foundation and key point of evaluation system of IES. Because the pros and cons of index always determine the quality of evaluation. Based on the construction concept of IES, this paper will expand the synthetic evaluation from three dimensions: technology, economy, and environment protection. Generally, IES is a multi-flow system, and it contains power flow, heating flow, cooling flow and so on. Third-class index aims at these questions to launch the discussion, and the synthetic assessment system of IES is illustrated in Figure 1.

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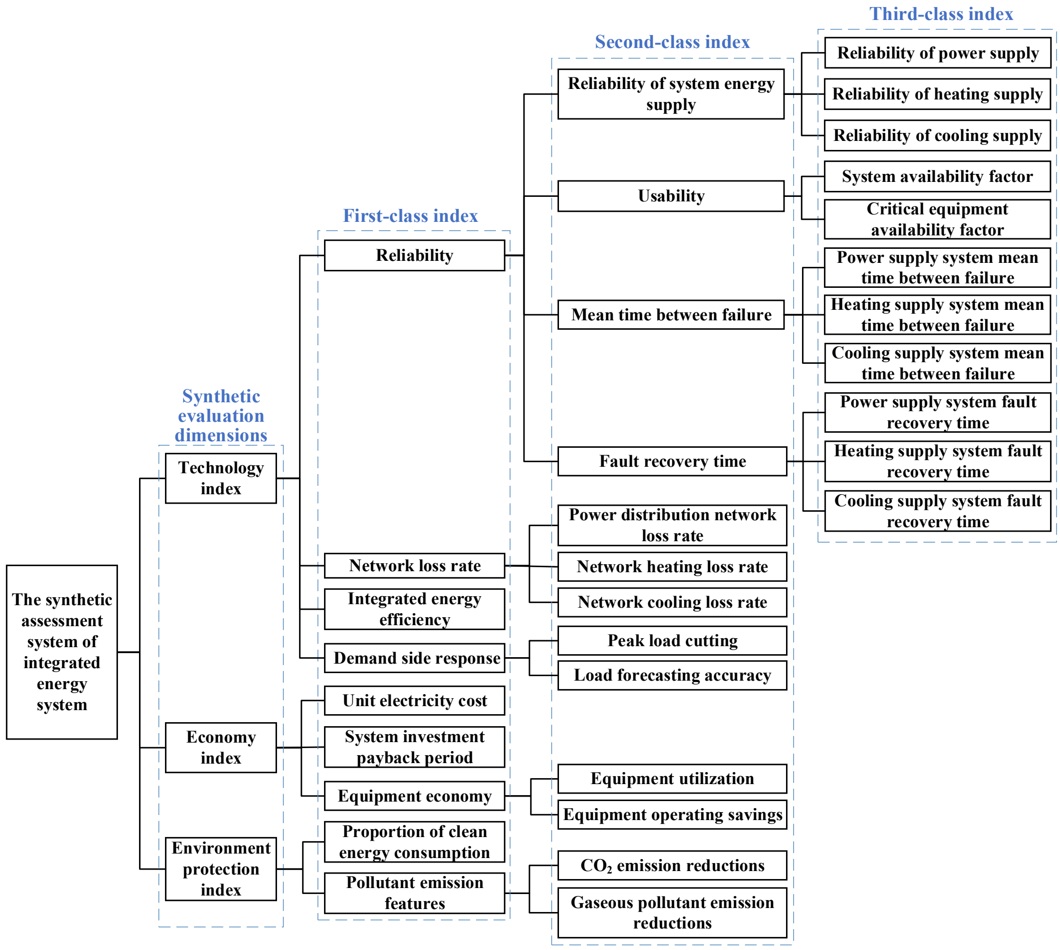

Figure 1. The synthetic assessment system of integrated energy system.

3 Establishment of weightiness and fuzzy discriminant vector

For IES, synthetic evaluation always used to indicate the advantages and disadvantages of the single index. AHP combines both qualitative analysis and quantitative analysis. Fuzzy comprehensive assessment method uses exact mathematics model to deal with indefinable and fuzzy things. Therefore, AHP - fuzzy comprehensive assessment method is used in this study. The flow diagram of synthetic evaluation is shown in Figure 2.

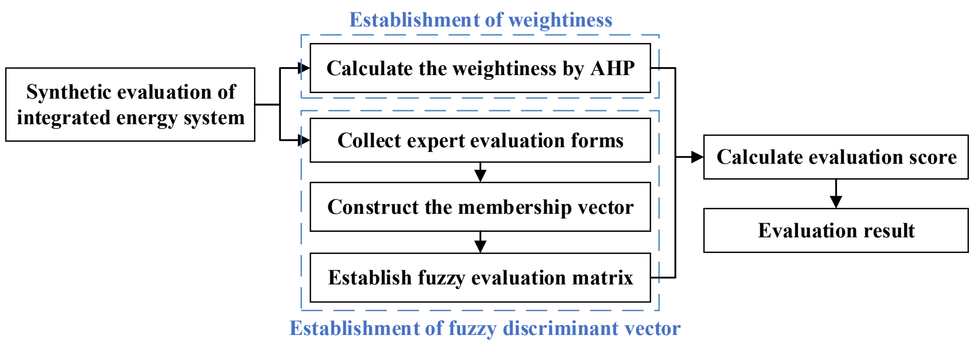

Figure 2. The flow diagram of synthetic evaluation

3.1 Establishment of weightiness

3.1.1 First-class index

Depending on Delphi method, importance degrees of each index are established, and the judgement matrix *C* of first-class index are illustrated in equation (1).

$$C=\begin{bmatrix}1 & 6 & 2 & 7 & 4 & 9 & 8 & 5 & 3\\ 1/6 & 1 & 1/5 & 2 & 1/3 & 4 & 3 & 1/2 & 1/4\\ 1/2 & 5 & 1 & 6 & 3 & 8 & 7 & 4 & 2\\ 1/7 & 1/2 & 1/6 & 1 & 1/4 & 3 & 2 & 1/3 & 1/5\\ 1/4 & 3 & 1/3 & 4 & 1 & 6 & 5 & 2 & 1/2\\ 1/9 & 1/4 & 1/8 & 1/3 & 1/6 & 1 & 1/2 & 1/5 & 1/7\\ 1/8 & 1/3 & 1/7 & 1/2 & 1/5 & 2 & 1 & 1/4 & 1/6\\ 1/5 & 2 & 1/4 & 3 & 1/2 & 5 & 4 & 1 & 1/3\\ 1/3 & 4 & 1/2 & 5 & 2 & 7 & 6 & 3 & 1\end{bmatrix} \quad (1)$$

Initial index weight of first-class index W, eigenvalue of maximum λ_{max} and coincidence indicator CI can be calculated by AHP.

$$W=\begin{bmatrix}0.2977 & 0.0492 & 0.2159 & 0.0340 & 0.1047 & 0.0173 & 0.0239 & 0.0718 & 0.1517\end{bmatrix}^T \quad (2)$$

After normalization,

$$W=\begin{bmatrix}0.3081 & 0.0509 & 0.2235 & 0.0352 & 0.1084 & 0.0179 & 0.0247 & 0.0743 & 0.1570\end{bmatrix}^T \quad (3)$$

Thus, $\lambda_{max}=9.4014, RI=1.45, CI=0.05$, CR=0.034<0.1, which meets consistency requirements.

3.1.2 Second-class index

In a similar way, judgement matrix, normalization matrix and initial index weight of second-class indexes can be calculated and the final weightiness of evaluation indexes are shown in Table 1.

Table 1. Formatting sections, subsections and subsubsections.

First-class index	*W*	Second-class index	*W*	W_z
Reliability	0.3081	Reliability of system energy supply	0.5076	0.1564
		Usability	0.3243	0.0999
		MTBF	0.0655	0.0202
		Fault recovery time	0.1026	0.0316
Network loss rate	0.0509	Power distribution network loss rate	0.7143	0.0363
		Network heating loss rate	0.1429	0.0073
		Network cooling loss rate	0.1429	0.0073
Integrated energy efficiency	0.2235	/	/	0.2235
Demand side response	0.0352	Peak load cutting	0.8333	0.0293
		Load forecasting accuracy	0.1667	0.0059
Unit electricity cost	0.1084	/	/	0.1084
System investment payback period	0.0179	/	/	0.0179
Equipment economy	0.0247	Equipment utilization	0.1429	0.0035
		Equipment operating savings	0.8571	0.0212
Pollutant emission features	0.0743	CO_2 emission reductions	0.6667	0.0495
		Gaseous pollutant emission reductions	0.3333	0.0248
Proportion of clean energy consumption	0.1570	/	/	0.1570

3.2 Establishment of fuzzy discriminant vector

3.2.1 Partition of factors set

Combined with the synthetic assessment system shown in Figure 1, index set *F* of first-class indexes is exhibited in equation (4).

$$\begin{aligned}F&=\{F_1,F_2,F_3,F_4,F_5,F_6,F_7,F_8,F_9\}\\&=\left\{\begin{array}{l}\text{re}liability; network\ loss\ rate; integrated\ energy\ efficiency; demand\ side\ response;\\ unit\ electricity\ cost; system\ investment\ \ payback\ \ period; equipment\ economy;\\ pollutant\ emission\ \ features; proportion\ of\ \ clean\ energy\ consumption\end{array}\right\}\end{aligned} \quad (4)$$

3.2.2 Calculated membership

Evaluation sets is shown in equation (5) and the score range is illustrated in Table 2.

$$V=\{v1,v2,v3,v4,v5\}=\{very\ good; good; just\ so\text{-}so; not\ bad; bad\} \quad (5)$$

Table 2. Score range and evaluation level

Score range	90-100	80-90	70-80	60-70	Below 60
Evaluation level	very good	good	just so-so	not bad	bad

An industrial park is chosen to be a calculation example. Based on expert evaluation, 5 pieces of data were collected to evaluate this example. After normalization, the memberships of each indicator are as shown in Table 3.

4 Calculation example

Table 3. The result of index membership

First-class index	**Second-class index**	**Membership (*Bi*, *i*=1, 2, … ,9)**
Reliability	Reliability of system energy supply	(0.4,0.4,0.2,0,0)
	Usability	(0.2,0.4,0.2,0.2,0)
	MTBF	(0.2,0.2,0.4,0.2,0)
	Fault recovery time	(0.2,0.2,0.4,0,0.2)
Network loss rate	Power distribution network loss rate	(0.2,0.2,0.6,0,0)
	Network heating loss rate	(0.2,0.4,0.4,0,0)
	Network cooling loss rate	(0.6,0.2,0.2,0,0)
Integrated energy efficiency	/	(0.6,0.2,0.2,0,0)
Demand side response	Peak load cutting	(0.6,0.4,0,0,0)
	Load forecasting accuracy	(0.2,0.2,0.4,0.2,0)
Unit electricity cost	/	(0.4,0.2,0.4,0,0)
System investment payback period	/	(0.2,0.2,0.6,0,0)
Equipment economy	Equipment utilization	(0.6,0.2,0.2,0,0)
	Equipment operating savings	(0.2,0.2,0.4,0.2,0)
Pollutant emission features	CO_2 emission reductions	(0.6,0.2,0.2,0,0)
	Gaseous pollutant emission reductions	(0.4,0.2,0.4,0,0)
Proportion of clean energy consumption	/	(0.2,0.2,0.4,0.2,0)

Take reliability as an example.

$$\widetilde{R_1} = \begin{bmatrix} 0.4 & 0.4 & 0.2 & 0 & 0 \\ 0.2 & 0.4 & 0.2 & 0.2 & 0 \\ 0.2 & 0.2 & 0.4 & 0.2 & 0 \\ 0.2 & 0.2 & 0.4 & 0 & 0.2 \end{bmatrix} \quad (6)$$

According to W_{21} = [0.5076 0.3243 0.0655 0.1026] ^{T},

$$\widetilde{B_1} = \widetilde{R_1} \circ W_{21}{}^T = \begin{bmatrix} 0.4 & 0.4 & 0.2 & 0.2 & 0.1026 \end{bmatrix} \quad (7)$$

where, ° is fuzzy matrix composition operator, the calculation method is as follows:

$$\widetilde{B} = \widetilde{A} \circ \widetilde{R} = (b_1, b_2, \cdots, b_m) \quad (8)$$

$$\mathrm{b}_j = \vee_{i=1}^{n} \left(a_i \wedge r_{ij} \right), j = 1, 2, \cdots, m. \quad (9)$$

After normalization, the fuzzy comprehensive evaluation vector of reliability:

$$\widetilde{B_1} = \begin{bmatrix} 0.3071 & 0.3071 & 0.1535 & 0.1535 & 0.0788 \end{bmatrix} \quad (10)$$

In a similar calculation way, the vectors of others first-class indexes can be calculated, and fuzzy comprehensive evaluation matrix is shown in equation (11).

$$\widetilde{R} = \left(\widetilde{B_1}, \widetilde{B_2}, \widetilde{B_3}, \widetilde{B_4}, \widetilde{B_5}, \widetilde{B_6}, \widetilde{B_7}, \widetilde{B_8}, \widetilde{B_9} \right)^T = \begin{bmatrix} 0.3071 & 0.3071 & 0.1535 & 0.1535 & 0.0788 \\ 0.2 & 0.2 & 0.6 & 0 & 0 \\ 0.6 & 0.2 & 0.2 & 0 & 0 \\ 0.45 & 0.3 & 0.125 & 0.125 & 0 \\ 0.4 & 0.2 & 0.4 & 0 & 0 \\ 0.2 & 0.2 & 0.6 & 0 & 0 \\ 0.2 & 0.2 & 0.4 & 0.2 & 0 \\ 0.5294 & 0.1765 & 0.2941 & 0 & 0 \\ 0.2 & 0.2 & 0.4 & 0.2 & 0 \end{bmatrix} \quad (11)$$

Thus, according to the combined weightiness in Table 1:

$$W = \begin{bmatrix} 0.3081 & 0.0509 & 0.2235 & 0.0352 & 0.1084 & 0.0179 & 0.0247 & 0.0743 & 0.1570 \end{bmatrix}^T \quad (12)$$

Total fuzzy comprehensive evaluation vector:

$$\widetilde{B} = \widetilde{R} \circ W^T = \begin{bmatrix} 0.3071 & 0.3071 & 0.2 & 0.1570 & 0.0788 \end{bmatrix} \tag{13}$$

After normalization,

$$B = \begin{bmatrix} 0.2925 & 0.2925 & 0.1905 & 0.1495 & 0.0750 \end{bmatrix} \tag{14}$$

Corresponding to

$$V = \begin{bmatrix} 100 & 90 & 80 & 70 & 60 \end{bmatrix} \tag{15}$$

Then,

$$S = V \cdot B^T = 85.78 \tag{16}$$

It means that the score of this industrial park is 85.78, and the evaluation level of this integrated energy system is "good".

5 Conclusion

The synthetic evaluation of IES is a very important work to monitor the operation status, and provide guidance for the future improvement and optimization. In this paper, a complete evaluation index system is established by AHP and Delphi method from three dimensions of technology, economy, and environmental protection. Also, an industrial park is selected to be a calculation example. After calculation based on the fuzzy comprehensive assessment method, evaluation score is obtained and corresponding evaluation level is good. The effectiveness and broad applicability of the synthetic assessment system are verified by the example.

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