A Review of Evaluation Method for Integrated Energy Systems

Yufan Zhao, Ruizhuo Song, Shijie Guo, and Zhengtao Wu

Abstract—**This article provides an overview and assessment of commonly used evaluation methods for integrated energy systems over the past decade, and discusses the characteristics and applicability of currently used evaluation methods. By summarizing and collating common evaluation methods and types of issues evaluated for integrated energy systems, recommendations are provided for the selection of evaluation methods, and advantages, disadvantages, and applicable issues of all the methods are clarified. In addition, a general process is proposed for the evaluation of integrated energy systems. Finally, the above research is summarized and an outlook on the future development direction is presented.**

Index Terms—**Integrated energy system, evaluation method, evaluation process, method selection**

I. Introduction

CHINA introduced the "3060" target in 2020, which aims to accelerate the overall decarbonization of the energy sector [1]. In this strategic context, integrated energy system (IES), which can satisfy multiple energy demands and efficiently utilize both conventional and renewable energy sources, has become a key part of the energy transition [2, 3].

With the continuous development of IES, the evaluation of various aspects of IES has become one of the indispensable links, and more and more researches are oriented to the evaluation methods of IES [4]. Reference [5] introduced an evaluation method for the location choice of photovoltaic power plant, which combined technique for order of preference by similarity to ideal solution (TOPSIS) and fuzzy analytic hierarchy process (AHP), and considered both subjective and objective factors to achieve the target. Reference [6] discussed how to apply multi-attribute decision making (MADM), and analyzed the theoretical basis and application value of MADM in renewable energy evaluation. Reference [7] constructed a complete evaluation system, which relied on the concept of the target IES. The system unfolded from three dimensions and divided 32 indicators into three levels. Meanwhile, entropy weight method (EWM) and AHP were used to calculate weights of indicators, and evaluation score of the IES was obtained by fuzzy comprehensive evaluation (FCE). Thus, accurate evaluation of the target IES was achieved. The evaluation system established by Ref. [8] divided the 41 performance evaluation indicators into four dimensions, gave clear definitions and calculation formulas for each indicator, and discussed the application scenarios of the evaluation methodology and the directions for future consideration. Reference [9] used the AHP-EWM method to calculate weights of indicators for actual IES project, and generated system-level performance evaluation scores through the FCE method. After analyzing the evaluation results and influencing factors, the article further suggested directions for energy system optimization.

All of the above studies have used certain methods to evaluate IES. Although there are currently a variety of evaluation methods available for IES, there are almost no articles on systematically sorting out and analyzing these evaluation methods. In addition, the current literature lacks discussion on the analysis and selection of various evaluation methods, and the general process for IES evaluation is not presented. This paper addresses the discussion of evaluation methods for IES. Section II compiles and analyses the evaluation methods for IES discussed in important journal articles in the past decade. Section III discusses the characteristics and application scenarios of commonly used evaluation methods, and proposes a general process for IES evaluation. Section IV summarizes the full text and provides an outlook on future.

II. Analysis of Evaluation Method for IES

A comprehensive evaluation allows decision makers o understand the comprehensive energy consumption situation and improve the weaker links of the IES based on the scores. The scores are derived from the actual operational data, which are processed and transformed into a comprehensive score through evaluation methods. Evaluation methods can usually be divided into three categories: single-indicator evaluation method, multi-indicator comprehensive evaluation method, and combined evaluation method [5]. Tables 1–3 summarizes the evaluation methods used in domestic and international literature over the past decade and the issues they addressed [10–34]. These methods provide a multi-faceted means of analysis for the development and optimization of IES, and are of great significance in improving the scientific validity and reliability of the evaluation results.

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Table 1 Evaluation methods used in the national and international literatures in last decades and the issues.

Year	Reference	Method	Issue
2014	[10]	1	(1)
	[11]	2	(2)
2015	[12]	3 and 4	(1)
	[13]	5 and 6	(2)
	[14]	7	(3)
2016	[15]	3 and 8	(4)
	[16]	9 and 10	(2)
2017	[17]	11 and 12	(5)
2018	[18]	5, 9, and 13	(2)
	[19]	5, 14, and 15	(6)
	[20]	15 and 16	(4)
2019	[21]	5, 17, and 18	(2)
2020	[22]	9, 19, and 20	(1)
	[23]	5, 9, 19, and 21	(2)
2021	[24]	5 and 9	(7)
	[25]	9, 19, and 22	(2)
	[26]	20	(3)
2022	[27]	9, 11, 17, 23, and 24	(2)
	[28]	3 and 13	(8)
2023	[29]	5 and 9	(2)
	[30]	5, 6, and 11	(2)
	[31]	9 and 19	(2)
2024	[32]	5, 9, 24, and 25	(8)
	[33]	24 and 25	(2)

A total of 24 articles were selected for analysis. According to Tables 1–3, it is known that the most popular methods include fuzzy mathematics method, EWM, AHP, statistical analysis method, and FCE, and the evaluation method formed by the combination of cloud models and other methods has only been widely used in China since 2019, while methods such as DEMATEL, GRA, and TOPSIS are mainly used as auxiliary methods that have to be used in conjunction with other evaluation methods. In most contemporary studies, combined evaluation methods are increasingly used in evaluations, where three or more techniques are generally selected for combination. As the evaluation of IES is more complex, it is hard to complete the whole process from the assignment of weights to the formation of scores by using single-indicator evaluation methods, and combined evaluation methods can fuse respective strengths of different methods, so that the evaluation results can be more precise.

Among the problems that IES evaluations aim to address, comprehensive evaluation is the most common type. When conducting a comprehensive evaluation of IES, it is often not limited to considering a single type of indicator, but rather combining social, technological, economic, and environmental perspectives. The score obtained from multi-faceted evaluation approach is generally more comprehensive and can reflect the overall condition of IES more precisely.

Table 2 Stadistics on type of method [34].

Number	Type of method
1	Hybrid multi-attribute group decision-making method based on dominance degree
2	Planning scheme evaluation method considering influence set
3	Fuzzy mathematics method
4	Mean-variance criterion
5	EWM
6	Expert evaluation method
7	Weighted method of multi-objective linear function
8	Elimination and choice translating reality (ELECTRE)
9	AHP
10	Interpretative structural modeling method (ISM)
11	Statistical analysis method
12	Mathematical calculation method
13	VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)
14	Analytic network process (ANP)
15	Target oriented decision making (TODIM)
16	Preference ranking organization method for enrichment evaluation (PROMETHEE)
17	Matter-element extension analysis method
18	Multilevel set-valued iterative method
19	FCE
20	Grey relation analysis (GRA)
21	Theory of evidence
22	Kendall’s correlation coefficient method
23	Criteria importance through inter-criteria correlation (CRITIC)
24	TOPSIS
25	Combined weighting method based on improved game theory

III. Selection of Evaluation Method for IES

It is known from Section II that some of the most popular methods include fuzzy mathematical method, EWM, AHP, statistical analysis method, and FCE. These most commonly used methods are described below and their applications to IES evaluation are illustrated.

The main application of fuzzy mathematical method in IES evaluation is processing fuzzy numbers and sets. By dealing with fuzzy sets and their affiliations, the challenges in dealing with uncertainty and non-quantitative information are overcome. For example, Ref. [35] classifies indicators into two categories, cost-oriented and benefit-oriented, with the

Table 3 Statistics on type of issue.

Number	Type of issue
(1)	Benefit evaluation of IES
(2)	Comprehensive evaluation of IES
(3)	Energy efficiency evaluation of IES
(4)	Location choice evaluation of IES
(5)	Reliability evaluation of IES
(6)	Investment evaluation of IES
(7)	Operation service evaluation of IES
(8)	Planning evaluation of IES

help of fuzzy set theory. Indicators are fuzzified using the affiliation function to calculate the comprehensive benefit optimization function. Then, AHP and anti-EWM are combined to calculate the integrated weights. Finally, renewable energy projects in a park in China were evaluated, the results accurately reflect the operation of the parks.

EWM is one of the most common objective assignment methods in IES evaluation and has been widely used in multi-criteria decision analysis. Due to its data-driven characteristics, the method can be calculated by computer software in high-quality data scenarios, enabling accurate analysis of data. The above characteristics indicate that EWM is particularly suitable for IES multi-criteria evaluation systems that rely on data-driven objective evaluation. However, if the data quality of the scenarios is poor, it means that inaccurate, incomplete data or the presence of extreme values may all lead to an unreasonable allocation of weights for EWM. In addition, if EWM is only used as a single evaluation method, its data-oriented nature makes it more difficult to evaluate subjective factors, including user preferences, policy requirements, and expert evaluation opinions. In actual IES evaluation, if subjective information is not taken into account, the results may not match the actual needs.

In most cases, the AHP is usually combined with the EWM. AHP is a subjective assignment method, where weights are calculated through decomposition and comparative judgement. Since the evaluation of IES needs to integrate both subjective and objective factors, the application of AHP can take into account the subjective factors and transform them into the form of quantitative scores for subsequent scoring. However, AHP is highly dependent on expert experience, when there are a large number of evaluation indicators, the computational difficulty and workload are significantly increased. Therefore, by combining AHP with EWM, the subjective and objective factors of IES can be better taken into account, thus improving the credibility of the evaluation results. Reference [36] first calculated subjective weights using AHP, then determined objective weights using EWM, and finally synthesized to obtain coupling weights. The method was applied in an IES in northern China, and evaluation results reflected the actual situation of the target IES.

Statistical analysis methods, like fuzzy mathematics, are not directly involved in the evaluation, but can be used to flexibly process data according to specific needs and reveal potential relationships between indicators during the evaluation process. Reference [37] used the grey TOPSIS method, which was used in the multi-indicator evaluation process to determine the difference value between the solutions and the positive and negative ideal values to provide support for weight calculation. Then, the least squares method was used to obtain the final score, and finally a comprehensive evaluation of an industrial park was carried out.

The FCE method is from fuzzy mathematical theory and can address the issue of indicators which are hard to quantify or ambiguous evaluation criteria. It can also be integrated with methods such as EWM, AHP, or others to deal with complex problems like ultra-fuzziness. Although FCE has significant advantages in dealing with subjective factors, its calculation process is relatively complex and the result is generally a fuzzy score or an interval, so it is poor in terms of the interpretability of how the indicators affect the system. In Ref. [7], the authors firstly calculated the objective factors in the evaluation system, while transforming the subjective factors into quantifiable values. Then, they used the AHP-EWM method to perform the normalization process and determined the weights of the factors. Finally, they calculated the scores using the FCE and provided a comprehensive evaluation of a typical IES. The evaluation results accurately reflect the actual operating conditions of the target IES.

In addition to the above mainstream methods, many other types of methods are also applied in the evaluation process. In Ref. [38], the author used the ISM to break down the problem of analyzing influencing factors in IES into logical relationships between influencing factors and matrix calculation problems. Based on indicator correlations, a connection matrix was established, and an accessibility matrix was calculated based on this matrix. The indicators were then stratified, and the AHP method was directly applied to establish a judgment matrix and calculate indicator weights. Through ISM, the influence relationships between evaluation indicators became clearer, more systematic, and more structured, and in conjunction with AHP, a relatively complete city-level energy system evaluation was achieved.

Based on the methods and cases mentioned above, the general process of evaluation of IES can be summarized as follows:

(1) Construct a reasonable evaluation system, which needs to clarify the evaluation objectives and select appropriate indicators around the objectives.

(2) Define the selected indicators, provide calculation formula for each quantitative indicator, and explicitly define the qualitative indicators.

(3) Select appropriate evaluation methods according to the evaluation system, select the indicator assignment method depending on the proportion of quantitative indicators to qualitative indicators first, and then select the auxiliary calculation method to prepare for the subsequent transformation of the weights.

(4) Determine the evaluation score of IES and display the results. First, use the selected indicator assignment method to get the weights of the indicators. Next, apply the selected auxiliary calculation method to define the evaluation set and the range of intervals, and calculate the subordination degree or other values of the indicators. Finally, apply the selected auxiliary calculation method, calculate the degree of subordination or other values, and aggregate these values to get the final evaluation results.

(5) Provide corresponding improvement suggestions. When selecting the method, the balance between subjectivity and objectivity should be considered in the selection of the assignment method. The auxiliary method should take into account the complexity and practicability of the calculation, so as to be practicable in the application. In addition, it is essential to ensure that methods selected are mutually

compatible and applicable to the actual application scenarios, thus ensuring the scientific rigor and accuracy of the evaluation results.

IV. SUMMARY AND OUTLOOK

Focusing on evaluation methods for IES, this paper compiles and summarizes the important literature on IES evaluation methods over the past decade. 25 commonly used methods and 8 types of evaluation questions involved in IES evaluation are collated. The more frequently used methods are analyzed and discussed in depth, and the general process of IES evaluation is clarified. IES evaluation usually adopts a combined evaluation method, which generally combines 3 to 4 methods and comprehensively takes into account energy efficiency, social impact, and other aspects, and focuses on calculating the weights of each indicator and obtaining the final score. Generally speaking, the evaluation process contains four steps: evaluation system construction, indicator definition, evaluation method selection, and calculation and display of evaluation scores, covering the complete steps from the confirmation of evaluation objectives to the proposal of improvement, which can serve as a reference for the evaluation of other IES in the future.

Among various methods of organization, AHP and EWM belong to the weighting method and are often used in weight distribution, statistical analysis methods are often used to process data in the evaluation process, fuzzy mathematics methods are often used to process indicators that are difficult to quantify, and FCE is similar, but can be directly combined with methods such as AHP to form intuitive evaluation results. In practical application, how to balance the calculated complexity and the evaluation comprehensiveness is often a major difficulty in the evaluation process due to the large number of available methods. In addition, among the existing evaluation methods, the full integration of artificial intelligence (AI) for evaluation has not yet appeared. With its powerful data processing capability, AI can realize the complete process of evaluation and provide improvement suggestions according to the actual situation. By applying fuzzy logic and multi-task learning models, AI can aggregate various types of indicators, analyze the correlation between indicators, and unify the assignment to achieve a more scientific weight distribution. At the same time, using expert system can reduce the subjectivity in selecting indicators and assigning weights. In addition, AI can automatically analyze the result and generate reports, which not only significantly improves the efficiency of the evaluation, but also enhances the precision of the evaluation. However, as of now, there are few studies on using AI and related methods in IES assessments. For example, Ref. [39] applied convolutional deep networks to reliability evaluations of distributed power distribution grids. Reference [40] combined machine learning techniques with Monte Carlo methods to achieve reliability assessment of a hybrid system combining renewable energy and hybrid vehicles based on transformers. Reference [41] used explainable deep learning models for performance assessment of photovoltaic grid-connected power generation systems to enhance system reliability. Reference [42] discussed comprehensive reliability assessment methods for power systems. Through comparative studies, it has been found that machine learning based methods significantly reduce computation time while maintaining assessment accuracy, playing an increasingly important role in improving both accuracy and computational performance. However, the aforementioned articles only address specific subsystems within IES, primarily focusing on feature extraction and enhancing computational efficiency.

With the full application of AI technology, the IES evaluation method will present higher intelligence and efficiency, helping the optimization and decision support of energy management. In the future, by constructing a systematic evaluation framework based on artificial intelligence, it is expected to further solve some difficulties and deficiencies existing in IES evaluation.

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