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Multi-Dimensional Evaluation of the Operational Benefits of Integrated Energy Systems in Zero-Carbon Parks Using Game Theory and Fuzzy Comprehensive Evaluation

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Abstract: In response to the global momentum toward carbon neutrality, the concept of "zero carbon" parks has gained significant attention in the energy and construction sectors. While existing research primarily focuses on optimizing standalone energy systems, a comprehensive methodological framework for evaluating the planning and management of integrated energy systems (IES) within zero-carbon parks remains underexplored. This study addresses this gap by examining the challenges inherent in the zero-carbon transformation of parks and proposing a multi-dimensional assessment index system tailored to IES. The evaluation framework encompasses five critical dimensions: environment, technology, economy, energy, and sustainability. To accurately determine the relative importance of these dimensions, the Analytic Hierarchy Process (AHP) and the Criteria Importance Through Intercriteria Correlation (CRITIC) method are employed for initial weight assignment, which is subsequently refined through game theory optimization. The fuzzy comprehensive evaluation method is then utilized to rigorously assess the benefits of IES across the planning, construction, and operational phases of zero-carbon parks. The findings highlight that the planning and operational stages are of greater significance than the construction phase. Specifically, the planning stage prioritizes environmental impact and technical advantages, while the operational phase emphasizes the equilibrium between economic benefits and ecological responsibilities. This research provides a scientific basis for the strategic planning and management of IES in zero-carbon parks, offering valuable insights for project managers and decision-makers in prioritizing resources across different project stages to achieve sustainable development. By addressing the current research gap, the study not only advances the understanding of IES in zero-carbon parks but also contributes practical guidance for achieving global carbon reduction goals.

Keywords: Integrated energy system (IES); Zero carbon park; Benefit evaluation; Game theory; Fuzzy comprehensive evaluation method

1 Introduction

Against the zero-carbon strategy and the "14th Five-Year" modern energy system planning, achieving the double carbon goal has become a vital driving force for energy transformation and social development. Facing this global challenge, the simplification of the traditional park energy system is no longer adapted to the requirements of low-carbon development [1]. As a consequence, it is of considerable value and significance to construct a comprehensive energy planning framework with zero carbon as the objective to encourage the decoupling of economic growth from carbon emissions in the park and enhance the zero carbon transformation of urban parks [2].

With financial support, capital has been directed to low-carbon and zero-carbon initiatives in international communities, especially in developed countries [3, 4]. The Chinese government has explicitly decided to support the "dual carbon" target in the "carbon peak action plan by 2030." It has recommended supporting 100 representative pilot cities and parks in terms of policy, capital, and technology to further the goal of reducing peak carbon dioxide emissions.

In China, constructing a 'zero carbon' park is a strong response to the purpose of 'double carbon'. Nevertheless, the park's 'zero-carbon' transformation is now confronted with challenges in many ways, such as technology, planning, and policy [5]. Existing industries and energy infrastructures are still highly dependent on traditional fossil fuels, which makes it hard to adapt to the transition to clean energy and low-carbon technologies. Furthermore, the park's 'zero carbon' transformation entails the overall design of each unit's growth, which necessitates extensive top-level design and scientific decision-making.

IES plays a pivotal role in accomplishing the objectives of safe energy usage, environmental protection, and zero-carbon by offering clean, efficient, and dependable energy supply and energy management services. Additionally, IES helps establish a "zero-carbon closed loop." On the other hand, most of the research now available focuses on the green and low-carbon renovation of structures as well as striking a balance between the park economy [6, 7], and emission reduction [8, 9]. Relatively little research has been done on the use of energy-efficient systems (IES) and their benefits in zero-carbon parks. These studies concentrate primarily on how IES can decrease carbon emissions and promote energy efficiency in parks. Furthermore, the research is mainly focused on optimizing a particular energy system; it does not evaluate the full advantages of IES, nor does it assess its applicability and benefits in different types of parks.

Therefore, the innovation of this paper is applying IES to the evaluation of the operational benefits of zero-carbon parks for the first time and making up for the excessive attention to optimizing a single energy system. Based on the game theory combination weighting-fuzzy comprehensive evaluation model, the IES evaluation method as well as the evaluation index system of environment, technology, economy, energy, and sustainability, which is established in this paper, will scientifically evaluate the operation benefits of the three stages of planning, construction, and operation of a zero-carbon park. Moreover, game theory is applied to integrate the objective weight of CRITIC and the subjective weight of the AHP to overcome the drawbacks of single weighting. To guarantee that the combination weighting in every phase is reasonable, a sensitivity analysis of the model is performed, strengthening the evaluation's accuracy and scientific rigor. This research will offer theoretical and practical recommendations for planning, constructing, and operating zero-carbon parks. It will also provide decision support for policymakers and park managers and encourage the establishment and growth of zero-carbon parks.

The rest of this paper is organized as follows: A literature review is done in the second Section to assess the state of research on zero-carbon parks and IES both domestically and internationally. The evaluation index system is built in the third Section using the following five criteria: environmental impact, technical benefit, economic benefit, energy benefit, and sustainability. The steps and methods of the evaluation model used in this paper are presented in the fourth part. In Section 5, IES is evaluated during the zero-carbon park's planning, construction, and operation stages. Sensitivity analysis serves to verify the model's accuracy. The summary and prospect are addressed in Section 6.

2 Literature Review

In the last few years, since worldwide climate change has become more severe and the energy crisis has loomed large, the imperative to foster an energy revolution and construct an energy framework that is clean, low-carbon, secure, and efficient has become paramount to meeting the goals of 'carbon peak and carbon neutrality' [10, 11]. As a crucial means of achieving carbon neutrality, the imperative to actualize a 'net-zero emissions' transformation within the park is both pressing and essential.

As the vanguard of sustainable urban development, zero-carbon parks incorporate sophisticated environmental strategies and leading-edge technologies, intending to reduce carbon emissions to a minimum or zero carbon emissions [12]. Its development goes through the stages of low carbon emission, near-zero emission, and net zero emission, and finally realizes the self-balance of carbon emission and absorption within the park. To accomplish this goal, the construction and management of zero-carbon parks should consider energy efficiency, renewable energy utilization, carbon capture and storage technologies, and sophisticated energy management systems [13]. At the same time, the development of zero-carbon parks also needs joint efforts in many aspects, such as policy support, technological innovation, capital investment, and public participation. These parks are pivotal in facilitating the shift to a low-carbon economy on a global scale and aligning with international environmental objectives exemplified by the Paris Agreement. Additionally, there are notable examples of such parks both domestically and internationally, as depicted in Table 1 [14, 15].

Internationally, the research and development of zero-carbon parks has made groundbreaking progress in various regions [16]. The obstacles associated with the development of zero-carbon industrial parks are examined and forecasted. North American researchers concentrate on improving energy efficiency and decreasing carbon emissions with digital technology while researching policies and incentives to support low-carbon industrial transformation [17]. Domestic research mainly emphasizes exploring the balance between emission reduction and the economic benefits of the park, as well as the green and low-carbon transformation of park buildings. Concerning policies, the Chinese government has issued China's National Program on Climate Change and China's Carbon Market Development Plan. The European Union has also set a goal of becoming carbon neutral by 2050 through the Green Deal. It has introduced policies such as the European Climate Act to encourage the creation of zero-carbon parks.

Table 1. Overview of typical zero-carbon park cases

Case	Domain	Main Content
London Beddington Zero Carbon Community [14]	Construction	The world's first zero-carbon community, with all community buildings adopting passive and integrated design concepts, realizing the transformation of buildings from "energy-consuming" to "energy-producing".
Oros Zero Carbon Industrial Park	Source of energy	The integrated wind-solar-storage clean energy system, employing a 'self-consume surplus, feed excess online' strategy, achieves a 100% clean energy supply.
Kalenburg Industrial Park, Denmark [15]	Ecology	The 'power generation-cogeneration-agriculture' system was devised to achieve the multifaceted use of energy and enhance the park's overall development efficiency.
Lin Orui Fu Zero Carbon Technology Park	Gas plant renovation	A gas station transformation, in terms of energy, terminal, operation, environment, and other aspects, fully realizes the industrial low-carbon, is the world's first zero-carbon park, but also become a milestone in the history of carbon neutrality in Germany.

To promote the development of zero-carbon parks, researchers at home and abroad have researched the optimal operation of IES to meet the energy efficiency and development needs of zero-carbon parks. It mainly focuses on three core areas: model construction, algorithm development, and mechanism design, to improve the accuracy of prediction models, the efficiency of optimization algorithms, and the flexibility of market mechanisms [18]. Regarding model construction, Irham et al. [19] proposed a multi-level optimization model based on model predictive control (MPC) to achieve multi-objective optimal energy management in IES. To improve equipment coordination ability and operation economy in IES [20], a multi-time scale optimal scheduling approach based on distributed model predictive control (DMPC) is suggested, which decreases costs while increasing economy and reliability. In terms of algorithm development [21], thinking about the complexity of multi-energy trading and the uncertainty of renewable energy output, an improved coyote optimization algorithm is proposed. Its usefulness in increasing income for operators, lowering energy expenditures, and improving energy usage economics has been demonstrated via case studies of industrial parks in northern China [22]. Aiming at the demand response and renewable energy uncertainty in IES, an interval optimal scheduling method based on soft actor-critic (SAC) deep reinforcement learning (DRL) is proposed, which improves the decision-making ability of IES optimal scheduling and effectively deals with the constraints of related equipment. With market mechanism design [23], a near-zero carbon IES (NZC-IES) optimization scheduling strategy is proposed. Through the establishment of a demand response and ladder carbon trading model, a new perspective is provided for the low-carbon operation of NZC-IES, and the case study results demonstrate the effectiveness of achieving waste-to-energy and low-carbon emissions while maintaining economic performance.

On this basis, IES has been widely used in many fields, such as industry, agriculture, and campus [24]. Aiming at the problem of relatively rough hydrogen energy storage modeling in traditional planning of IES in industrial parks, an IN-IES planning model was established to effectively improve the economic benefits of the system and reduce carbon pollution and power abandonment [25]. Aiming at the optimal scheduling model of multi-energy coupling agricultural IES, the low-carbon economic scheduling of agricultural IES is effectively optimized [26]. Aiming at the operation optimization of the IES of the school, the SIES technical and economic evaluation model based on the G1-anti-entropy weight TOPSIS method is proposed to effectively evaluate the IES of the school scientifically. This shows that the combination of IES and zero-carbon parks in in-depth research and optimization is an important direction for future research.

3 IES Evaluation Index

3.1 IES Structure

An IES is a platform for integrating multiple energy forms and technologies, with significant features such as source-grid-load-storage integration, multi-energy complementarity, and supply-demand coordination [27]. The central element of the system is the "source-network-load-storage" paradigm, which encompasses the full cycle of energy generation, conveyance, utilization, and conservation, ensuring a fluid interconnection of essential stages. Embedding the IES within the zero-carbon parks, offers the parks a clean, efficient, and dependable source of energy and energy management, while also making a notable contribution to the park's sustainability objectives, particularly in the realms of low-carbon energy consumption and ecological preservation [13]. There are different roles in the IES of a zero-carbon park.

"Source" refers to the point of origin of energy and relates to the generation and provision of clean energy, including solar, wind, hydro, and biomass, to reduce the use of fossil fuels and lower the carbon footprint of the zero-carbon park.

The "network" element of the system pertains to the infrastructure for energy conveyance and dissemination, encompassing a variety of interconnected networks, including electrical, thermal, gaseous, and hydrogen conduits. Engineered to augment energy efficiency and sophistication, these networks aim to refine the distribution of resources and uphold the consistency and dependability of the energy supply chain.

The "load" aspect signifies the demand side of energy usage, encompassing a range of sectors including industrial, commercial, and residential. By implementing demand-side management strategies and enhancing energy efficiency, the goal is to streamline energy utilization, maintain equilibrium in energy demand, and elevate overall energy efficiency.

"Storage" refers to energy storage facilities and technologies, such as battery energy storage, thermal energy storage, and water energy storage. Energy storage systems are critical to maintaining a balance between energy supply and demand, by buffering the intermittency of renewable energy, improving energy efficiency, and enhancing system stability.

The "source-net-charge-storage" model of the IES emphasizes the integration and collaborative optimization of the energy system. Through the effective management and technological innovation of these four links, the zero-carbon park can improve energy efficiency and promote the sustainable development of the environment.

3.2 Quantitative Model of Evaluation Index

The study follows the principles of science, operability, representativeness, and relevance as the basis for screening and identifying evaluation indicators. By analyzing the dynamic change of the operating parameters of the IES in the zero-carbon park and predicting future development demand, the paper aims to select the key system evaluation indicators and build a comprehensive energy system evaluation framework [28, 29]. The indicator selection process is shown in Figure 1.

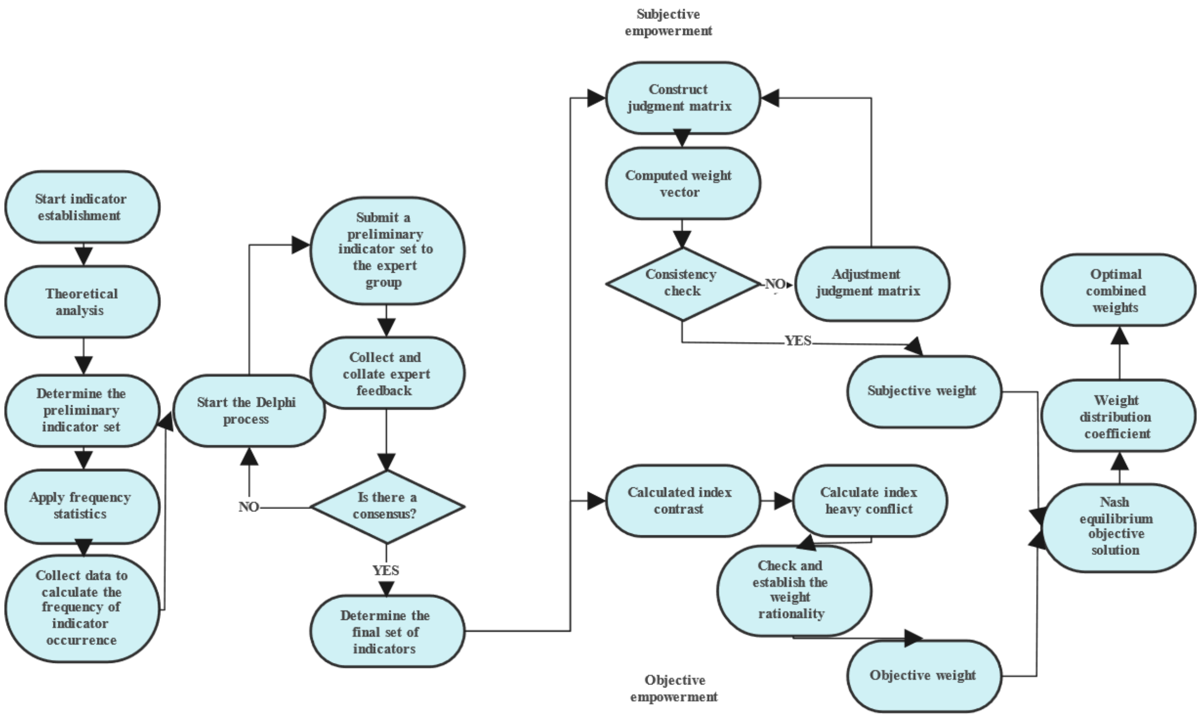

Figure 1. Indicator selection flow chart

Following the aforementioned principles, this study initially gathers pertinent indicators of the IES utilizing sources such as the Web of Science, CNKI, and government official websites [30, 31]. Subsequently, the collected indicators were preliminarily screened by combining theoretical analysis and frequency statistics to ensure the relevance and importance of the indicators. On this basis, the Delphi method was adopted to carry out two rounds of expert consultation, aiming to extract key indicators through expert consensus, and finally build a comprehensive evaluation index system of the IES low-carbon operation efficiency of zero-carbon parks, as shown in Figure 2.

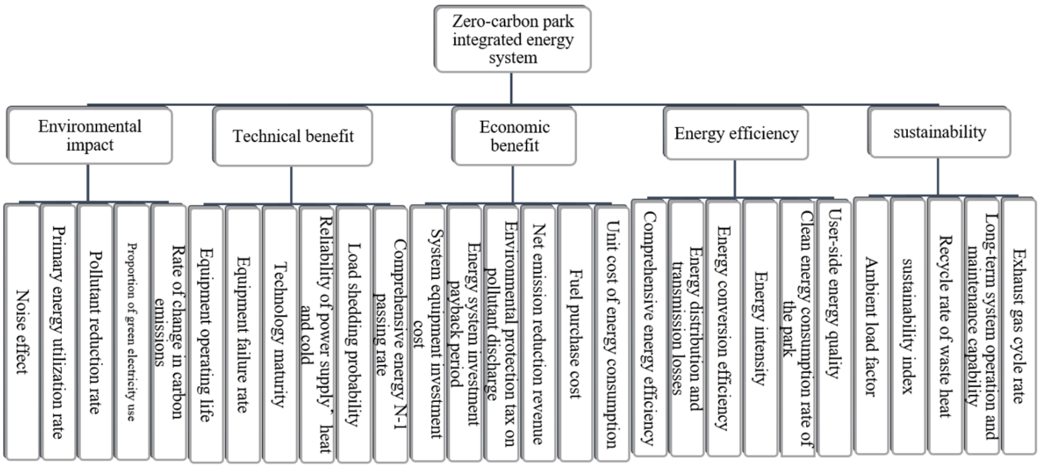

Figure 2. Index system of IES in zero-carbon park

3.2.1 Energy efficiency index

Energy efficiency is one of the core indicators used to measure the operating efficiency of IES in zero-carbon parks. This paper will show how IES can optimize energy use, reduce energy waste, and improve the overall efficiency of energy utilization by evaluating indicators such as energy conversion efficiency, energy intensity, and clean energy consumption rate in the park. Table 2 describes the specific indicators.

Table 2. Interpretation of energy efficiency indicators

Index Name	Meaning Interpretation	Calculation Formula
Energy conversion efficiency	In the process of converting one form of energy into another, the ratio of the actual output energy to the input energy [32].	$\eta = \frac{E_{\text{output}}}{E_{\text{input}}}$
Comprehensive energy utilization rate	The ratio of the total energy output of the system to the primary energy consumption [33].	$\lambda = \frac{\mathrm{W}}{\mathrm{Q}}$
Energy intensity	The comprehensive energy consumption per unit area, population, or output value of IES in the park [30].	qualitative
Clean energy consumption rate in the park	The percentage of renewable energy power generation to total load power consumption in a certain period [34].	$\beta = \frac{E_R}{E_L} \times 100\%$
Energy distribution and transmission losses	Energy loss in the process of energy transmission from the production site to the consumption end [29].	qualitative
User-side energy quality	Reflecting user-side energy quality, such as thermal sensory index, indoor air quality satisfaction, etc. [35].	qualitative

3.2.2 Technical benefit index

In terms of technical benefits, the innovative application of IES in zero-carbon parks is discussed to ensure that indicators can reflect the efficiency and reliability of energy systems. Indicators such as equipment operating life, load shedding probability, and mature technology are taken to show how IES brings significant advantages at the technical level to the park. The specific indicators are shown in Table 3.

3.2.3 Economic benefit index

The economic benefit is an important dimension in evaluating the operation of IES in Zero Carbon Park. This paper selects the system equipment investment cost, return on investment, and other indicators to explain the value and potential economic benefits of IES for the park at the financial level, see Table 4.

3.2.4 Environmental impact index

Environmental impact is an indispensable consideration in the construction of zero-carbon parks. In this part, this paper evaluates the positive impact of IES on the environment and its role in promoting the park's development through the primary energy utilization rate, pollutant discharge rate, and carbon emission change rate, see Table 5.

Table 3. Technical benefit index interpretation

Index Name	Meaning Interpretation	Calculation Formula
Equipment operating life	The period from when the equipment is used until its performance no longer meets the predetermined standards or reaches the established replacement cycle [36].	$L = \frac{T_{\text{fact}}}{T_{\text{initiate}}}$
Equipment failure rate	The average value of the failure duration of each type of energy equipment compared to the total duration of use in IES [37].	$F_N = \frac{\sum_{i=1}^{N} \frac{h_i}{S_i}}{N}$
Technology maturity	Assess the technology maturity of different technologies or components in the IES system [38].	qualitative
Reliability of power supply, heat, and cold	The ratio of the average failure time of the system to the total energy supply time [39].	$\delta_i = 1 - \frac{x_i}{N_i} \times 100\%$
Load shedding probability	To maintain the stability of the power grid, IES can actively implement the probability of load reduction or interruption [40].	qualitative
Comprehensive energy N-1 pass rate	The proportion of the total number of facilities meeting N-1 requirements to the total number of facilities [39].	$\eta_{pr} = \frac{N_N}{N_{al}}$

Table 4. Economic benefit index interpretation

Index Name	Meaning Interpretation	Calculation Formula
System equipment investment cost	The total cost of acquisition and installation of all necessary equipment in IES [39].	$I_{eq} = \frac{I \times (1+r)^n}{(1+r)^n - 1}$
Energy system investment payback period	After the project is operational, the economic benefits fully cover the time span required for the initial investment [30].	$0 = \sum_{a=0}^{T_{DPP}} (A_{\text{cin}}(a) - A_{\text{cout}}(t)) \cdot (1+i)^{-a}$ $0 = \sum_{a=0}^{T_{APP}} A_{\text{cin}}(a) - A_{\text{cout}}(a)$
Environmental protection tax on pollutant discharge	Environmental taxes for the production of pollutants [6].	$C = T_N m_N + T_C m_C + T_S m_S$
Net emission reduction revenue	Due to the economic benefits brought by emission reduction, the input costs paid to achieve emission reduction targets are deducted [36].	Income $= (\text{R}_{\text{Carbon rights}} + \text{R}_{\text{subsidy}} + \text{R}_{\text{economize}}) - (\text{C}_{\text{invest}} + \text{C}_{\text{Operation}} + \text{C}_{\text{chance}})$
Energy supply unit cost	The cost of each unit of energy consumption for the system to provide energy [30].	$C_u = \frac{C_p + C_t \times \eta + C_d + C_c}{E}$
Fuel purchase cost	The cost of various fuels purchased by the park.	None

3.2.5 Sustainability index

Finally, the potential for long-term application of IES in zero-carbon parks is explored from a sustainability perspective. The environmental load rate, long-term operation, and maintenance capability, and sustainability index of the system are selected to analyze how IES can provide long-term stable energy solutions for the park and support its sustainable development goals, see Table 6.

Table 5. Interpretation of environmental impact indicators

Index Name	Meaning Interpretation	Calculation Formula
Proportion of green electricity use	The share of electricity generated from renewable resources in total electricity consumption [22].	qualitative
Primary energy utilization rate	The ratio of total energy output to primary energy consumption [41].	$\eta = \frac{E_{c,y}\lambda_c + E_{H_1,y}\lambda_H + E_{e,y}\lambda_c}{\sum_i (W_i \lambda_i)}$
Pollutant reduction rate	The ratio of the emission of gas pollutants reduced by the use of clean energy in the system to the total emission of gas pollutants in the park [31].	$\Delta CE_0 = \sum Lf_i$
Rate of change in carbon emissions	The ratio of the CO_2 emissions reduced by the use of renewable energy in the system to the total CO_2 emissions of the park [31].	$CE_C = \frac{E_b}{\eta_T^P} CE_u + \frac{Q_h}{\eta_T^Q} CE_f$
Noise effect	The operation of multiple energy supply equipment may lead to an increase in environmental noise [42].	qualitative

Table 6. Sustainability indicators explained

Index Name	Meaning Interpretation	Calculation Formula
Ambient load factor	The proportion of non-renewable resource consumption and the sum of external social inputs to renewable resources.	$E_{LR} = \frac{N+F}{R}$
Sustainability index	Quantify the characteristics of systems such as energy efficiency, environmental impact, and organizational capacity [31].	$E_{SI} = E_{YR}/E_{LR}$
Recycle rate of waste heat	The ratio of recovered waste heat energy to total waste heat [22].	$\vartheta(\%) = \left(\frac{E_{\text{recycle}}}{E_{\text{Total}}}\right) \times 100$
Long-term system operation and maintenance capability	It reflects the reliability, maintenance cost, technology updating, and upgrading ability of the IES system in the long-running process, as well as the adaptability to external changes [43].	qualitative
Exhaust gas cycle rate	Indicators of waste recovery and reuse efficiency.	qualitative

4 Index Weight Calculation Method

4.1 AHP

The AHP is a decision support tool that enables decision-makers to synthesize qualitative and quantitative indicators and calculate the weight of each evaluation indicator through hierarchical processing and paired comparison of indicators. When assessing the operational advantages of a zero-carbon park's IES, AHP adeptly consolidates measurable and difficult-to-quantify indicators, offering a structured analytical approach to devising an all-encompassing assessment framework. The detailed computational procedures are outlined below.

(1) Utilizing the hierarchical structure depicted in Figure 1 for the IES framework of the Zero Carbon Park, the 1-to-9 scale is applied for pairwise comparison of indicators, leading to the formulation of the respective judgment matrix. The significance of each scale value is detailed in Table 7.

(2) Computed weight vector

The judgment matrix of each level is normalized, and the arithmetic mean value of each factor is used as the ranking weight of the factor of the level.

(3) Consistency test of the judgment matrix

The consistency index CI of the n-order matrix is calculated. The larger the value is, the more inconsistent the results of pairwise comparison of matrix elements are CI. The formula for calculating the CI value is as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

where, $\lambda_{\max}$ is the maximum eigenvalue of the matrix; n is the order of the matrix. The matrix consistency ratio is as follows:

Table 7. 1 - 9 scaling method

Scale Value	Implication
1	Factor U_a is equally important than U_b
3	Factor U_a is slightly more important than U_b
5	Factor U_a is significantly more important than U_b
7	Factor U_a is very much more important than U_b
9	Factor U_a is extremely more important than U_b
2, 4, 6, 8	Take the intermediate degree value of two adjacent judgment matrices
Remark	$a_{ij} = 1/a_{ji}; a_{ii} = 1$

$$CR = \frac{CI}{RI} \tag{2}$$

In the formula, RI is the average random consistency test index, and different matrix orders have different values. $\mathrm{CR} < 0.1$ is required to ensure the consistency of the judgment matrix; Otherwise, adjust the judgment matrix until the consistency test is met.

4.2 CRITIC Algorithm

As an objective weighting technology, the CRITIC algorithm can effectively deal with the comparison and conflict between multi-dimensional evaluation indexes of IES in zero-carbon parks, and then comprehensively determine the objective weight of each index. In addition, the algorithm also considers the variability and correlation of the indicators and makes full use of the intrinsic objective attributes of the data for scientific evaluation. The calculation steps are as follows:

Assuming that there are m evaluation objects and n evaluation indexes, the evaluation matrix can be expressed as:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{3}$$

Step 1: Dimensionless treatment of evaluation index. The aim is to eliminate the potential impact of the difference in the dimension and numerical range of the original data on the evaluation results. This process involves converting all indicators into dimensionless values and achieving dimensional unity through appropriate mathematical transformation to ensure that different indicators can be effectively compared consistently.

$$x'_{mm} = \frac{x_{mm} - \min(x_m)}{\max(x_m) - \min(x_m)} \tag{4}$$

$$x'_{mm} = \frac{\max(x_m) - x_{mm}}{\max(x_m) - \min(x_m)} \tag{5}$$

Step 2: Determine the index variability. The standard deviation is used to quantify the fluctuation of the index value. The larger standard deviation usually indicates a higher index fluctuation and information content. Therefore, the corresponding index should obtain a higher weight in the comprehensive evaluation.

$$\bar{x}_j = \frac{1}{n}\sum_{i=1}^{n} x_{ij} \tag{6}$$

$$S_j = \sqrt{\frac{\sum_{i=1}^{n}(x_{ij} - \bar{x}_j)^2}{n-1}} \tag{7}$$

where, S_j is the standard deviation of the j-th index.

Step 3: Determine the index conflict. By calculating the correlation coefficient, the relationship between the evaluation indexes can be quantified. Highly relevant indicators tend to show lower conflict, which reflects that they can provide more abundant information in the evaluation system, thus effectively reducing unnecessary repetition in the evaluation process. The calculation formula is as follows:

$$R_j = \sum_{i=1}^{p} (1 - r_{ij}) \tag{8}$$

where, r_{ij} is the correlation coefficient between evaluation indexes i and j.

Step 4: Calculate the objective weight:

$$C_j = S_j \sum_{i=1}^{p} (1 - r_{ij}) = S_j R_j \tag{9}$$

$$\beta_i = \frac{C_j}{\sum_{j=1}^{p} C_j} \tag{10}$$

where, C_j is the amount of information contained in the j-th evaluation index; β_j is the objective weight of the index.

4.3 Game Theory Combinatorial Weights

Game theory has many forms of evaluation models for the common planning and scheduling problems of IES, such as the game theory model, the non-cooperative game theory model, and the Stackelberg game theory model [44]. There are obvious limitations to applying subjective and objective weighting methods alone, and their combined use can significantly improve the effect. Therefore, this study adopts the game theory combination weighting method, combining the AHP and the CRITIC method to determine the index weight. This method takes NASH equilibrium as the coordination goal to ensure that in the scoring decisions of all experts, the scoring behavior of any single expert will not have an advantage over its decision weight, achieving a stable decision equilibrium. Through this method, we can minimize the sum of the deviations between the combined weights and the basic weights and then obtain more accurate combined weights.

The basic weight vector set ω_k is constructed. Assuming that G weight calculation methods are used, the n evaluation indexes in the index evaluation system are combined and weighted based on the game theory, and the corresponding weight vectors are obtained.

$$\omega_k = \omega_{k1}, \omega_{k2}, \ldots\ldots \omega_{kn} (k = 1, 2, \ldots, G), \tag{11}$$

Further, an arbitrary linear combination of weight sets of n weights is obtained:

$$W = \sum_{k=1}^{G} \alpha_k \omega_k^T \ (\alpha_k > 0, k = 1, 2, \ldots, G) \tag{12}$$

where, α_k is the weight coefficient.

By optimizing the weight coefficient, an optimal linear combination is constructed to minimize the deviation between the target weight vector W and each candidate weight vector ω_k. Construct the optimal linear combination.

$$W = \sum_{k=1}^{G} \alpha_k \omega_k^T \ (\alpha_k > 0, k = 1, 2, \ldots, G) \tag{13}$$

Using the differential characteristics of the matrix, the optimal first derivative condition can be obtained as follows:

$$\sum_{k=1}^{G} \alpha_k \cdot \omega_i \cdot \omega_k^T = \omega_i \cdot \omega_k^T \tag{14}$$

The corresponding system of linear equations is:

$$\begin{bmatrix} \omega_1 & \cdot & \omega_1^{\mathrm{T}} & \omega_1 & \cdot & \omega_2^{\mathrm{T}} & \cdots & \omega_1 & \cdot & \omega_G^{\mathrm{T}} \\ \omega_2 & \cdot & \omega_1^{\mathrm{T}} & \omega_2 & \cdot & \omega_2^{\mathrm{T}} & \cdots & \omega_2 & \cdot & \omega_G^{\mathrm{T}} \\ \vdots & . & \vdots & \vdots & . & \vdots & \ddots & \vdots & . & \vdots \\ \omega_{\mathrm{G}} & \cdot & \omega_1^{\mathrm{T}} & \omega_{\mathrm{G}} & \cdot & \omega_2^{\mathrm{T}} & \cdots & \omega_{\mathrm{G}} & \cdot & \omega_G^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_{\mathrm{G}} \end{bmatrix} = \begin{bmatrix} \omega_1 & \cdot & \omega_1^{\mathrm{T}} \\ \omega_2 & \cdot & \omega_1^{\mathrm{T}} \\ \vdots & . & \vdots \\ \omega_3 & \cdot & \omega_1^{\mathrm{T}} \end{bmatrix} \tag{15}$$

The optimal linear combination is $(a_1, a_2, \cdots, a_G)$ and normalized.

$$\alpha^* = \frac{\alpha_k}{\sum_{k=1}^{G} \alpha_k} \tag{16}$$

Solve for the final portfolio weights:

$$\omega = \sum_{k=1}^{G} \alpha^* \cdot \omega_k^T, k = 1, 2, \ldots, G \tag{17}$$

4.4 Fuzzy Comprehensive Evaluation

Considering the challenges of acquiring precise data and the presence of incomplete indices, the study employs a fuzzy comprehensive evaluation approach to assess the operational advantages of the IES within zero-carbon parks. Utilizing fuzzy mathematics, this approach adeptly addresses the inherent uncertainties within the system, proving particularly apt for evaluating complex systems [45]. By constructing a membership function to quantify the benefit of each evaluation index, and combining the index weight, a fuzzy synthesis algorithm was applied to synthesize the scores of each index, to obtain the overall operating benefit score of IES. Using the fuzzy comprehensive evaluation method, the main steps of IES system operation benefit evaluation are as follows:

Step 1: Construct a comprehensive factor set encompassing all pertinent factors, followed by the establishment of an evaluation set comprising the factors designated for assessment. By applying normalization techniques, the raw data is transformed into dimensionless numerical values. The specific evaluation criteria are delineated in Table 8.

Table 8. Index influence degree and rank set relationship

Level of Influence	Very large	Large	Moderate	Small	Very Small
Mark	5	4	3	2	1
Normalization	0.5	0.4	0.3	0.2	0.1

Step 2: Calculate the membership degree and construct the membership matrix R.

This paper uses the membership function in fuzzy logic to quantify each index. Specifically, the membership of each indicator is calculated based on the scores of experts in the relevant field, and the formula is as follows:

$$\mu_A(x) = \frac{1}{1 + (x - x_0)^2} \tag{18}$$

where, x is the score of respondents in different professional fields, and x_0 is the optimal score.

Step 3: The third step is to use the sum product operator in fuzzy logic to synthesize the fuzzy weight vector and fuzzy relation matrix, then calculate the comprehensive evaluation value F.

$$F = B^* V^T \tag{19}$$

5 Comprehensive IES Benefit Analysis of Zero Carbon Park

Located in North China, the park is rich in renewable resources and smart grid systems and is equipped with digital infrastructure, including wind turbines, photovoltaic panels, energy storage batteries, and other hardware facilities. The Park covers an area of about 0.267 square kilometers and is a typical "zero carbon" park. 80% of the energy demand in the park is directly supplied by wind power, photovoltaic panels, and energy storage systems, while the remaining 20% is optimized by the intelligent Internet of Things, which is balanced by selling electricity to the grid when there is excess power production. In addition, the park also realizes the traceability, analysis, and visualization of carbon emission and energy consumption indicators, and conducts real-time monitoring, early warning, and optimized closed-loop control through a unified data management platform. This study aims to assess the importance of each evaluation indicator in the three stages of planning, construction, and operation of this park. By calculating the weight of each indicator and combining the combination assignment method, this study will use a fuzzy comprehensive evaluation model to quantify the operational benefits of IES in the zero-carbon park.

5.1 Combinatorial Weighting is Determined

5.1.1 Subjective weight determination of AHP

In our practical research, we established a panel of 15 experts, including energy system planners, economists, architects and urban planners, renewable energy technology specialists, and operations management professionals. Using the LIKERT 5-point scale method, experts scored and assigned independently. Based on the evaluation results of each expert, we construct the judgment matrix A of the first-level index to the target layer and calculate the weight. Then, the corresponding judgment matrix is also constructed for the secondary indicators, and their weights are obtained. In the end, by multiplying step by step, we get the combined weight of each secondary indicator at the target level.

$$A = \begin{bmatrix} 1 & 2 & 4 & 3 & 1 \\ 1/2 & 1 & 2 & 1/3 & 1/2 \\ 1/4 & 1/2 & 1 & 1/4 & 1/3 \\ 1/3 & 3 & 4 & 1 & 1/2 \\ 1 & 2 & 3 & 2 & 1 \end{bmatrix}$$

Through subjective calculation weight and consistency test, it is concluded that the subjective weight of the first-level index is ω = (0.3557, 0.1027, 0.0513, 0.1911, 0.2991), $\lambda_{\max}$=5.2565, CI = 0.0573 $<$ 0.1, which passes the consistency test. The subjective weight and consistency test results of the secondary indicators are shown in Table 9.

Table 9. Design phase subjective weight calculation

Index Name	Judgment Matrix	Maximum Characteristic Root	Consistency Check	ω
Environmental impact	$\begin{bmatrix} 1 & 2 & 2 & 1 & 2 \\ 1/2 & 1 & 3 & 1/2 & 4 \\ 1/2 & 1/3 & 1 & 1/3 & 2 \\ 1 & 2 & 3 & 1 & 4 \\ 1/2 & 1/4 & 1/2 & 1/4 & 1 \end{bmatrix}$	5.2288	0.0511	0.2738 0.2143 0.0940 0.3604 0.0576
Technical benefit	$\begin{bmatrix} 1 & 2 & 1 & 1 & 3 & 1/2 \\ 1/2 & 1 & 2 & 1/2 & 3 & 1/3 \\ 1 & 1/2 & 1 & 1 & 3 & 1 \\ 1 & 2 & 1 & 1 & 2 & 2 \\ 1/3 & 1/3 & 1/3 & 1/2 & 1 & 1/5 \\ 2 & 3 & 1 & 1/2 & 5 & 1 \end{bmatrix}$	6.3470	0.551	0.2093 0.1125 0.2961 0.0719 0.0427 0.2675
Economic benefit	$\begin{bmatrix} 1 & 2 & 1 & 1 & 3 & 1/2 \\ 1/2 & 1 & 2 & 1/2 & 3 & 1/3 \\ 1 & 1/2 & 1 & 1 & 3 & 1 \\ 1 & 2 & 1 & 1 & 2 & 2 \\ 1/3 & 1/3 & 1/3 & 1/2 & 1 & 1/5 \\ 2 & 3 & 1 & 1/2 & 5 & 1 \end{bmatrix}$	6.4942	0.0784	0.1838 0.1174 0.1546 0.2349 0.0345 0.2749
Energy efficiency	$\begin{bmatrix} 1 & 4 & 1 & 4 & 2 & 2 \\ 1/4 & 1 & 1/2 & 2 & 1 & 1/2 \\ 1 & 2 & 1 & 3 & 2 & 3 \\ 1/4 & 1/2 & 1/3 & 1 & 1/3 & 1/3 \\ 1/2 & 1 & 1/2 & 3 & 1 & 1/3 \\ 1/2 & 2 & 1/3 & 3 & 3 & 1 \end{bmatrix}$	6.2916	0.0463	0.3468 0.0729 0.3003 0.0591 0.1193 0.1788
Sustainability	$\begin{bmatrix} 1 & 3 & 1 & 2 & 1 \\ 1/3 & 1 & 1/2 & 2 & 1/2 \\ 1 & 2 & 1 & 1/2 & 2 \\ 1/2 & 1 & 2 & 1 & 2 \\ 1 & 2 & 1/2 & 1/2 & 1 \end{bmatrix}$	5.2785	0.0622	0.4119 0.0866 0.1732 0.2059 0.1224

5.1.2 Objective weight determination of CRITIC

In this study, the CRITIC method has been deployed to ascertain the intrinsic weights of the various components within the IES of a zero-carbon park. The experts invited by the previous AHP, based on a standardized quantitative table, which covers the two dimensions of competitiveness and conflict of indicators, score the indicators. To ensure the comprehensiveness and consistency of expert opinions, the collected data were subjected to two rounds of questionnaire surveys, screened and standardized, and sensitivity analyses of different expert opinions were conducted to ensure the robustness of the results. The weights of each secondary indicator on the target layer were then determined through the formula, as shown in Table 10.

Table 10. Objective weight calculation in the planning stage

Primary Index	Weight	Secondary Index	Weight
Environmental impact	0.3160	Noise effect	0.01329
		Primary energy utilization rate	0.03648
		Pollutant reduction rate	0.01329
		Proportion of green electricity use	0.01329
		Rate of change in carbon emissions	0.04933
Technical benefit	0.1619	Equipment operating life	0.03859
		Equipment failure rate	0.05718
		Technology maturity	0.04131
		Reliability of power supply, heat, and cold	0.02720
		Load shedding probability	0.01321
		Comprehensive energy N-1 passing rate	0.03164
Economic benefit	0.2305	System equipment investment cost	0.05123
		Energy system investment payback period	0.01329
		Environmental protection tax on pollutant discharge	0.06699
		Net emission reduction revenue	0.03875
		Fuel purchase cost	0.01329
		Unit cost of energy consumption	0.05306
Energy efficiency	0.1102	Comprehensive energy efficiency	0.02647
		Energy distribution and transmission losses	0.01567
		Energy conversion efficiency	0.02835
		Energy intensity	0.01354
		The clean energy consumption rate of the park	0.01368
		User-side energy quality	0.02531
Sustainability	0.1815	Ambient load factor	0.08427
		Sustainability index	0.02881
		Recycle rate of waste heat	0.07334
		Long-term system operation and maintenance capability	0.09143
		Exhaust gas cycle rate	0.02770

5.1.3 Determination of combinatorial weights in game theory

Based on the theory of game theory, the subjective weight and objective weight in Table 8 and Table 9 are determined by the formula to determine the weight of each level index to the target layer, and then the correction coefficient of the first level index and the second level index is obtained by the linear equation formula (12-16). They are $(a_{11}, a_{21}) = (0.70950, 0.29050)$, $(a_{12}, a_{22}) = (0.69708, 0.30292)$, and then the final optimal combination weight is obtained from Eq. (17). The results are shown in Table 11.

It can be seen from the weight distribution maps of the first-level and second-level indicators that there is a certain deviation in the weights obtained by the AHP and the CRITIC method, especially the two aspects of economic benefit indicators and sustainability indicators. The subjective weight values of the energy conversion coefficient (0.0974) and the green power use ratio (0.1282) are about 7 times and 10 times the objective weight, respectively. The objective weight of the system equipment investment cost and operation and maintenance cost index is 5 times and 8 times larger than the subjective weight.

From the comparison of the weights of the three algorithms in Figure 3 and Figure 4, it can be seen that the combined weight algorithm combines subjective and objective weights, and the results obtained are similar to the results of the other two independent methods, thus verifying their credibility. In addition, the weight distribution of the algorithm on technical benefits and sustainability indicators is higher than that of traditional objective algorithms, which better meet the high standards of economic and technical safety in contemporary energy development. Therefore, the proposed comprehensive weight method based on game theory has significant advantages in rationality and accuracy.

Table 11. Combinatorial weight calculation based on game theory

Index Name	First-Order Index Weight $\omega_{\text{group }1} = \mathbf{a}_{11} \times \omega_{11} + \mathbf{a}_{21} \times \omega_{21}$	Secondary Index Weight $\omega_{\text{group }2} = \mathbf{a}_{12} \times \omega_{12} + \mathbf{a}_{22} \times \omega_{22}$
Environmental impact (A1)	0.3442	0.0388
		0.0485
		0.0194
		0.0481
		0.0406
Technical benefit (A2)	0.1199	0.0334
		0.0434
		0.0380
		0.0212
		0.0105
		0.0303
Economic benefit (A3)	0.1034	0.0386
		0.0111
		0.0491
		0.0307
		0.0098
		0.0413
Energy efficiency (A4)	0.1676	0.0310
		0.0277
		0.0371
		0.0129
		0.0164
		0.0280
Sustainability (A5)	0.2650	0.0961
		0.0279
		0.0668
		0.0824
		0.0304

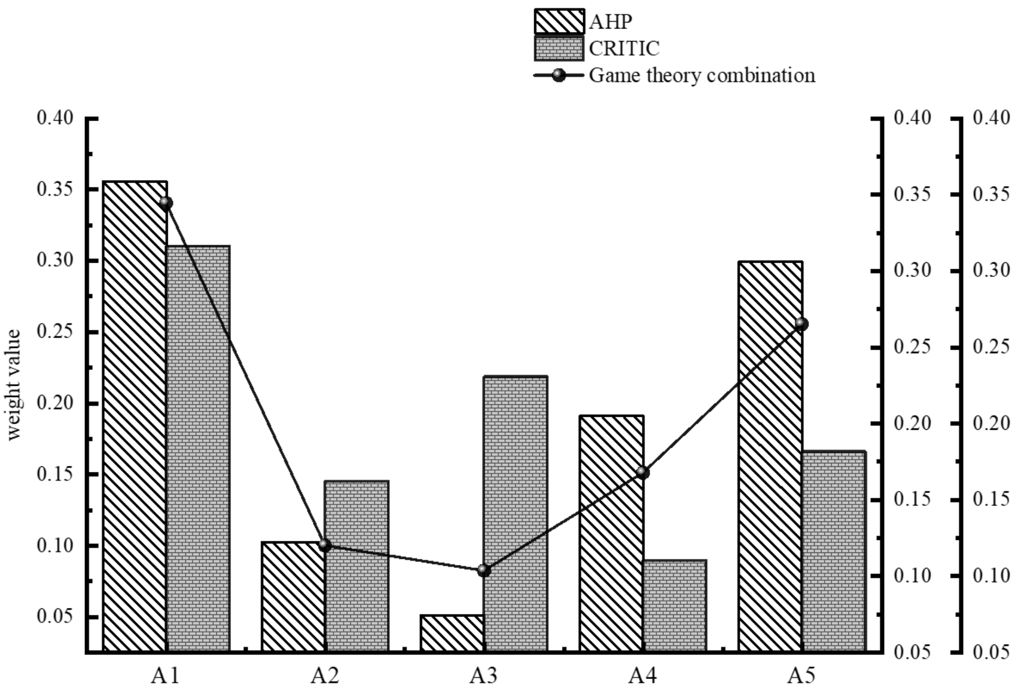

Figure 3. Comparison of first-level index weights

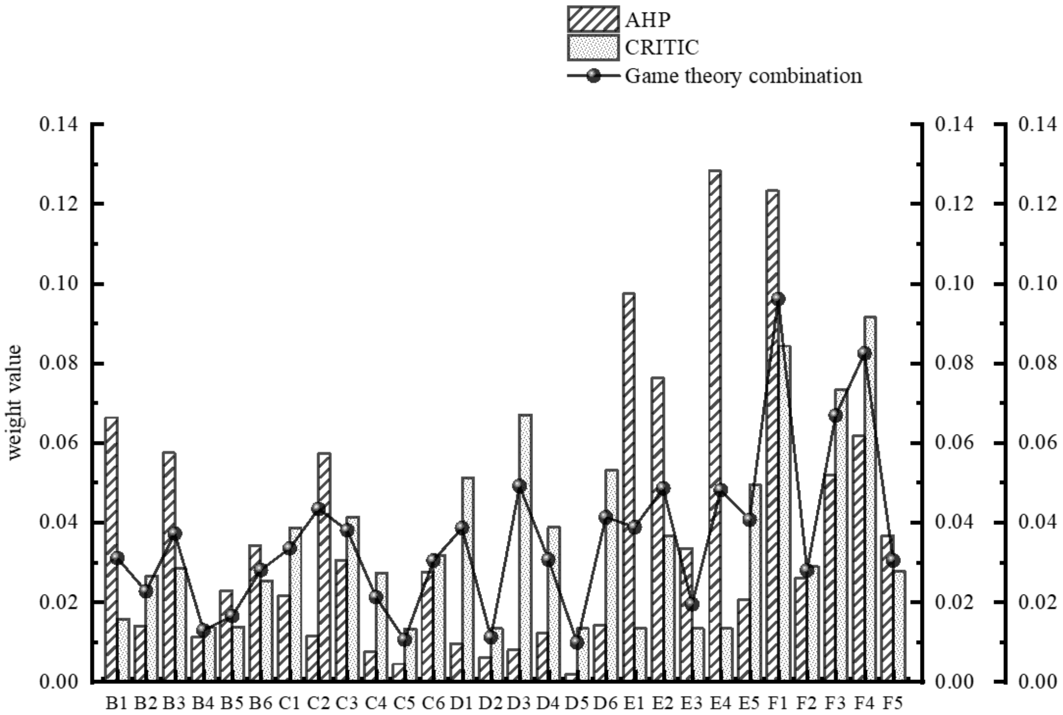

Figure 4. Comparison of second-level index weights

5.2 Analysis and Research of Fuzzy Comprehensive Evaluation

The fuzzy comprehensive evaluation method is used to evaluate the benefit of IES operations in zero-carbon parks. The scores of each index are obtained from relevant people in different fields and questionnaires, and calculated and normalized according to the membership function. A total of 130 questionnaires were distributed, of which 118 were valid, with a recovery rate of 91%. The data in the questionnaire are analyzed and sorted to obtain the fuzzy relation matrix and the normalized fuzzy comprehensive evaluation vector, as shown in Table 12.

According to the table data and the importance level $V = \{5, 4, 3, 2, 1\}$ = {very large, large, moderate, small, very small}, the comprehensive evaluation value of IES in the planning stage of zero carbon park operation benefit is calculated.

$$F_P = B \times V^T = \omega_{\text{first grade indexes}} \times (Y_1, Y_2, Y_3, Y_4, Y_5) \times (5, 4, 3, 2, 1)^T = 3.5375$$

The above is the process of solving for the operational benefits of IES in the zero-carbon park in the planning stage. Similarly, the composite scores for each indicator in the construction and operation phases are obtained, and the results are shown in Table 13 and Table 14.

5.3 Evaluation and Analysis of IES Zero Carbon Park Operation Benefit

5.3.1 Evaluation and analysis

This study conducted a comprehensive benefit assessment of the three key phases of the IES zero-carbon park's planning, construction, and operation. The results show that the planning and operation phases are crucial in achieving the park's low-carbon operation goals.

(1) Impact analysis of first-level indicators

In the first-level indicator impact analysis, by comparing the data in Figure 5 and Figure 6, we found that the environmental impact and technical benefit scores in the planning stage were the highest, which were 4.3898 and 4.3220, respectively. It is worth noting that the weighted value of environmental impact (1.5109) is significantly higher than the weighted value of technical safety benefits (0.5182). This difference indicates that environmental factors have a higher priority in decision-making at the planning stage. The score of economic benefit was the lowest (3.4068), but the weighted value (0.3522) was not the lowest in the construction stage, the weighted value of environmental impact is still the largest, but it is slightly lower than that in the design stage, and the economic benefit score (4.1441) score becomes the highest, which is significantly higher than that in the planning stage. In the operation stage, the sustainability score (4.2881) and the weighted value (1.1703) are the highest. The energy efficiency (4.2203) score is higher than the economic benefit (3.8559), but the weighted value is 0.1268 (24%) smaller.

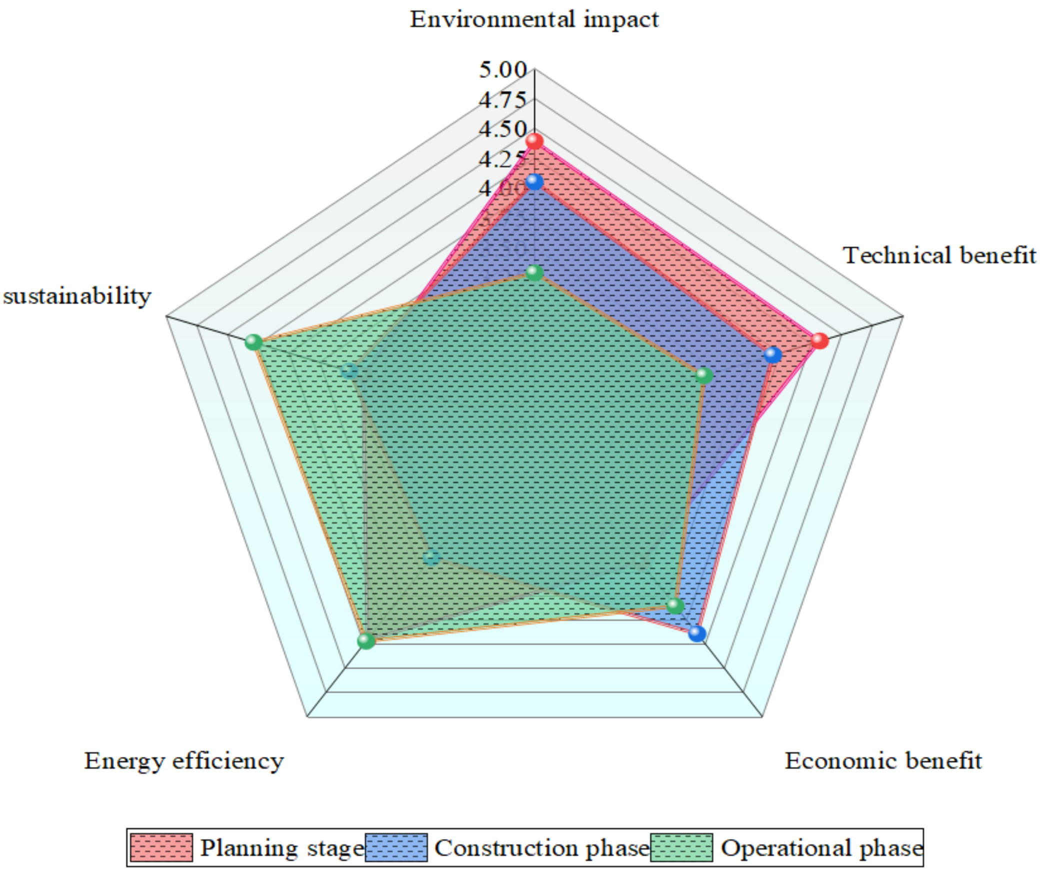

Figure 5. The score value of each stage of the first-level index

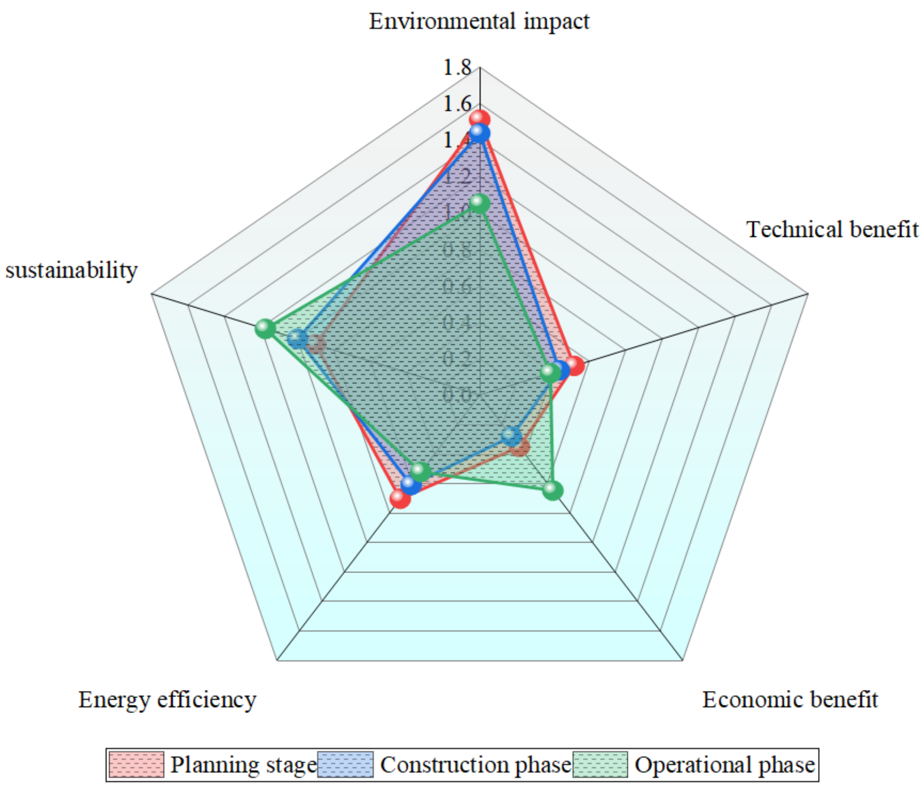

Figure 6. The weighted value of each stage of the first-level index

Table 12. Fuzzy matrix and fuzzy comprehensive evaluation vector calculation

Index Name	Fuzzy Matrix R/ Fuzzy Comprehensive Evaluation Vector Y
Environmental impact (A1)	$R_1 = \begin{bmatrix} 0.2034 & 0.3814 & 0.2542 & 0.0763 & 0.0000 \\ 0.1780 & 0.3559 & 0.1949 & 0.1780 & 0.0932 \\ 0.5339 & 0.2542 & 0.1525 & 0.0593 & 0.0000 \\ 0.5932 & 0.2966 & 0.0508 & 0.0424 & 0.0169 \\ 0.7034 & 0.1864 & 0.0847 & 0.0254 & 0.0000 \end{bmatrix}$ $Y_1 = \begin{pmatrix} 0.4371 & 0.3062 & 0.1466 & 0.0823 & 0.0278 \end{pmatrix}$
Technical benefit (A2)	$R_2 = \begin{bmatrix} 0.3220 & 0.2203 & 0.2119 & 0.1864 & 0.0593 \\ 0.0763 & 0.1356 & 0.3559 & 0.2527 & 0.1695 \\ 0.2881 & 0.1949 & 0.2542 & 0.2288 & 0.0339 \\ 0.1102 & 0.1356 & 0.3983 & 0.2373 & 0.1186 \\ 0.1271 & 0.0763 & 0.5000 & 0.1864 & 0.1102 \\ 0.2712 & 0.1610 & 0.3559 & 0.1780 & 0.0339 \end{bmatrix}$ $Y_2 = \begin{pmatrix} 0.2088 & 01652 & 0.3205 & 0.2189 & 0.0866 \end{pmatrix}$
Economic benefit (A3)	$R_3 = \begin{bmatrix} 0.0763 & 0.2203 & 0.2542 & 0.4153 & 0.0339 \\ 0.1949 & 0.2797 & 0.3644 & 0.0678 & 0.0932 \\ 0.1525 & 0.2203 & 0.2881 & 0.1949 & 0.1441 \\ 0.2219 & 0.1864 & 0.4068 & 0.1695 & 0.0254 \\ 0.1017 & 0.1186 & 0.5085 & 0.1610 & 0.1102 \\ 0.2881 & 0.1102 & 0.3983 & 0.1525 & 0.0508 \end{bmatrix}$ $Y_3 = \begin{pmatrix} 0.1772 & 0.1875 & 0.3429 & 0.2183 & 0.0741 \end{pmatrix}$
Energy efficiency (A4)	$R_4 = \begin{bmatrix} 0.3390 & 0.2712 & 0.2797 & 0.1102 & 0.0000 \\ 0.0763 & 0.1441 & 0.3051 & 0.2712 & 0.2034 \\ 0.2712 & 0.4153 & 0.2373 & 0.0508 & 0.0254 \\ 0.0763 & 0.1271 & 0.3475 & 0.2881 & 0.1610 \\ 0.3220 & 0.2203 & 0.2034 & 0.2458 & 0.0085 \\ 0.1271 & 0.2034 & 0.3220 & 0.2373 & 0.1102 \end{bmatrix}$ $Y_4 = \begin{pmatrix} 0.2170 & 0.2569 & 0.2784 & 0.1745 & 0.0732 \end{pmatrix}$
Sustainability (A5)	$R_5 = \begin{bmatrix} 0.4746 & 0.2542 & 0.1780 & 0.0847 & 0.0085 \\ 0.2627 & 0.2034 & 0.2881 & 0.1441 & 0.1017 \\ 0.2966 & 0.3305 & 0.1441 & 0.1610 & 0.0593 \\ 0.2458 & 0.1780 & 0.2966 & 0.2373 & 0.0424 \\ 0.5085 & 0.1949 & 0.2203 & 0.0678 & 0.0085 \end{bmatrix}$ $Y_5 = \begin{pmatrix} 0.3579 & 0.2402 & 0.2175 & 0.1470 & 0.0375 \end{pmatrix}$

(2) Influence analysis of secondary index analysis

It can be seen from Figure 7 and Figure 8 that the comprehensive energy utilization rate and technology maturity maintain a high level in all stages. The score (3.7881) and weighted value (0.0524) of energy intensity in the operation stage were significantly higher than those in the planning and construction stage. The weighted value of the clean energy consumption rate (0.0665) and user-side energy quality (0.0851) in the park is the highest in the three stages of the operation stage. The weighted value of the investment cost of system equipment is the highest in the planning stage (0.1115), while the weighted value of the return on investment of the energy system is the highest in the operation stage (0.1575). The three indicators of pollutant emissions, green power use ratio, and carbon emission change rate have significantly improved in the operation stage. The weighted value of pollutant emission environmental protection tax is the highest in the construction stage (0.1816), while the weighted value of long-term operation and maintenance capacity of the system in the operation stage (0.3805) is much higher than that in the design and construction stage.

(3) Comprehensive evaluation and analysis

Multi-stage consideration: The key to the successful realization of a zero-carbon park is a comprehensive consideration of the planning, construction, and operation stages. This includes in-depth analysis and extensive assessment of multi-dimensional factors such as environmental impact, technological application, economic efficiency, energy efficiency, and sustainability. Throughout the life cycle of the park, environmental impact and energy efficiency, such as the integrated energy utilization rate and the park's clean energy consumption rate, are always high-priority considerations, especially during the planning and operational stages.

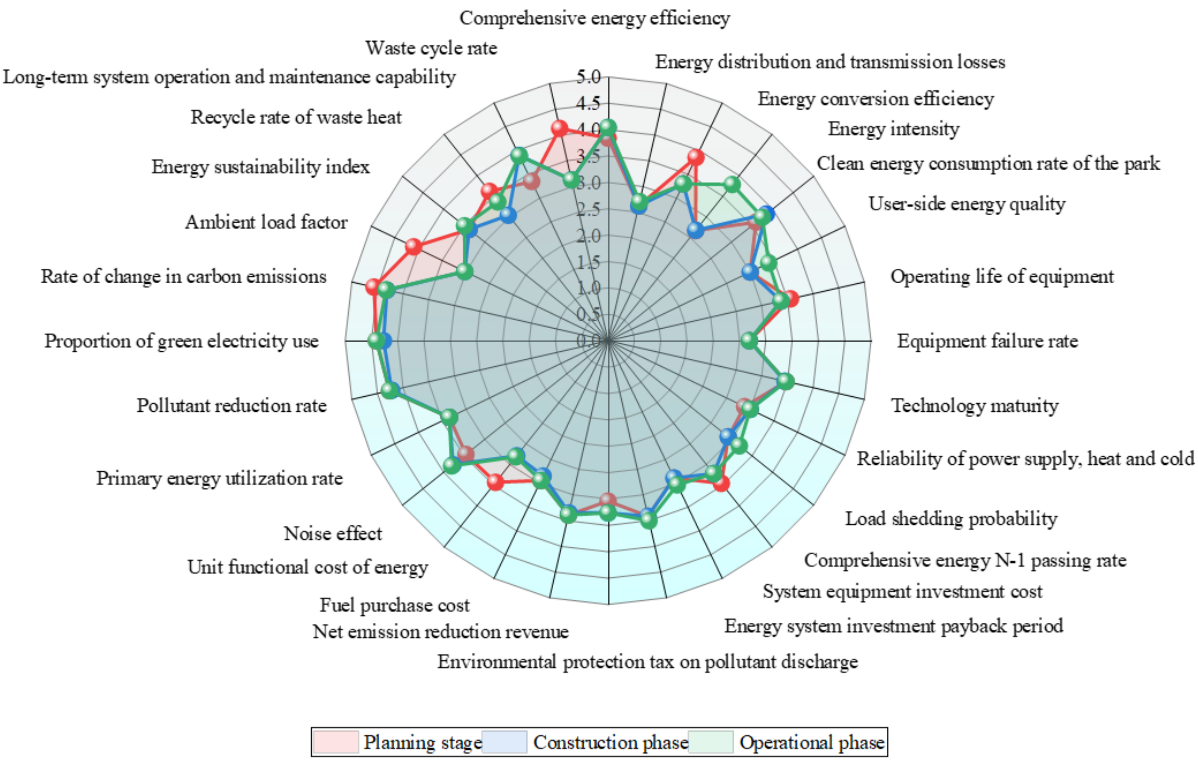

Figure 7. Scores of secondary indicators at each stage

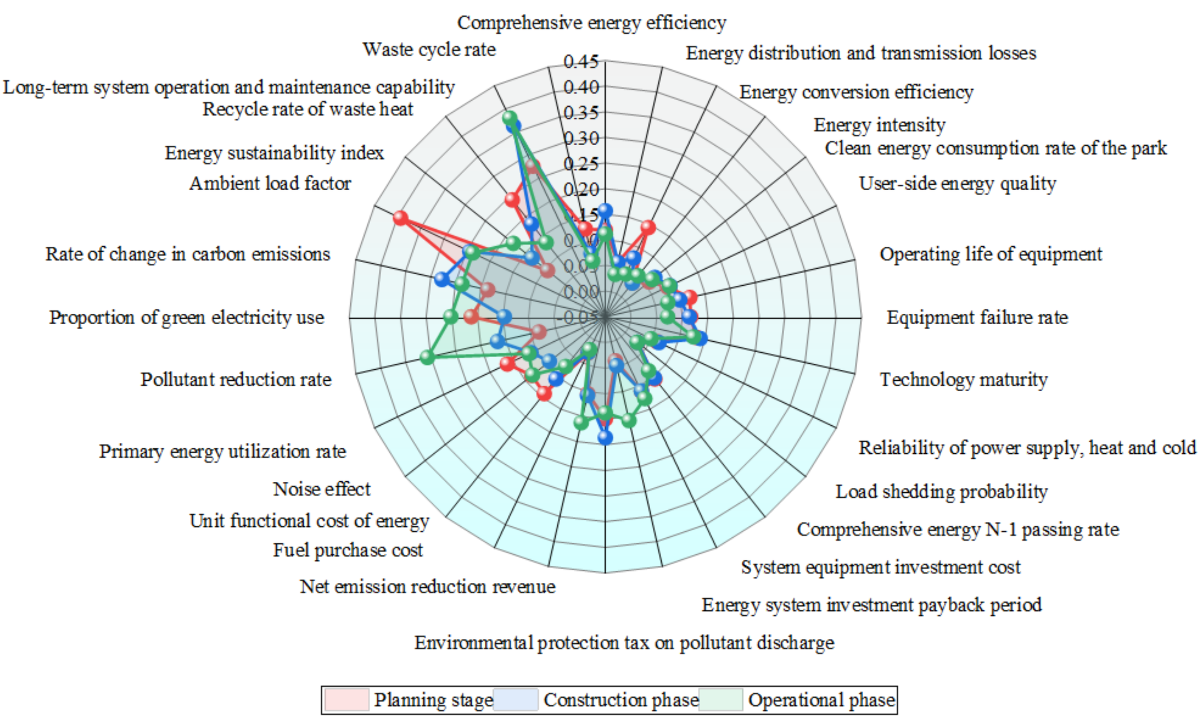

Figure 8. The weighted value of each stage of the secondary index

Energy efficiency should be a long-term concern: Energy efficiency and environmental benefits are ongoing concerns throughout the life cycle of the park, especially in the design and operation phases, key metrics such as energy intensity, energy conversion efficiency, and energy unit function cost.

Technical safety and economic return: Technology maturity and equipment operating life always get high scores and significant weights in the evaluation of the operation stage, which can be seen that technical benefits and economic benefits play a crucial role in the long-term operation of the park.

Table 13. Comprehensive score of influencing factors of first-level indicators in each stage

Index Name	Planning Stage (3.5375)		
	Comprehensive Valuation	Weight	Weighted Value
Environmental impact (A1)	4.3898	0.3442	1.5109
Technical benefit (A2)	4.3220	0.1199	0.5182
Economic benefit (A3)	3.4068	0.1034	0.3522
Energy efficiency (A4)	4.2034	0.1676	0.7044
Sustainability (A5)	3.3983	0.2650	0.9004
Index Name	**Construction Phase (3.4377)**		
	Comprehensive Valuation	**Weight**	**Weighted Value**
Environmental impact (A1)	4.0508	0.3548	1.4374
Technical benefit (A2)	3.9407	0.1109	0.4371
Economic benefit (A3)	4.1441	0.0681	0.2820
Energy efficiency (A4)	3.3559	0.1816	0.6096
Sustainability (A5)	3.5085	0.2845	0.9983
Index Name	**Operational Phase (3.5052)**		
	Comprehensive Valuation	**Weight**	**Weighted Value**
Environmental impact (A1)	3.2881	0.3196	1.0509
Technical benefit (A2)	3.3810	0.1146	0.3874
Economic benefit (A3)	3.8559	0.1682	0.6485
Energy efficiency (A4)	4.2203	0.1236	0.5217
Sustainability (A5)	4.2881	0.2740	1.1750

Table 14. Comprehensive score of influencing factors of secondary indexes in each stage

Index Name	Planning Stage		
	Comprehensive Valuation	Weight	Weighted Value
Noise effect (B1)	3.4576	0.0388	0.1341
Primary energy utilization rate (B2)	3.3475	0.0485	0.1624
Pollutant reduction rate (B3)	4.2627	0.0194	0.0827
Proportion of green electricity use (B4)	4.4068	0.0481	0.2120
Rate of change in carbon emissions (B5)	4.5678	0.0406	0.1854
Operating life of equipment (C1)	3.5593	0.0334	0.1189
Equipment failure rate (C2)	2.6864	0.0434	0.1165
Technology maturity (C3)	3.4746	0.0380	0.1321
Reliability of power supply, heat, and cold (C4)	2.8814	0.0212	0.0611
Load shedding probability (C5)	2.9237	0.0105	0.0308
Comprehensive energy N-1 passing rate (C6)	3.4576	0.0304	0.1050
System equipment investment cost (D1)	2.8898	0.0386	0.1115
Energy system investment payback period (D2)	3.4153	0.0111	0.0379
Environmental protection tax on pollutant discharge (D3)	3.0424	0.0491	0.1494
Net emission reduction revenue (D4)	3.3898	0.0307	0.1039
Fuel purchase cost (D5)	2.9407	0.0098	0.0288
Unit functional cost of energy (D6)	3.4322	0.0413	0.1416
Comprehensive energy efficiency (E1)	3.8390	0.0310	0.1190
Energy distribution and transmission losses (E2)	2.6186	0.0227	0.0594
Energy conversion efficiency (E3)	3.8559	0.0371	0.1432
Energy intensity (E4)	2.6695	0.0129	0.0343
Clean energy consumption rate of the park (E5)	3.6017	0.0164	0.0592
User-side energy quality (E6)	3.0000	0.0280	0.0840
Ambient load factor (F1)	4.1017	0.0961	0.3940
Energy sustainability index (F2)	3.3814	0.0279	0.0944
Recycle rate of waste heat (F3)	3.6186	0.0668	0.2418
Long-term system operation and maintenance capability (F4)	3.3475	0.0824	0.2758
Waste cycle rate (F5)	4.1271	0.0304	0.1255

Index Name	Construction Phase		
	Comprehensive Valuation	Weight	Weighted Value
Noise effect (B1)	3.7712	0.0238	0.0898
Primary energy utilization rate (B2)	3.3475	0.0332	0.1111
Pollutant reduction rate (B3)	4.2203	0.0393	0.1658
Proportion of green electricity use (B4)	4.2712	0.0345	0.1473
Rate of change in carbon emissions (B5)	4.3136	0.0643	0.2775
Operating life of equipment (C1)	3.3729	0.0293	0.0988
Equipment failure rate (C2)	2.6864	0.0424	0.1139
Technology maturity (C3)	3.4492	0.0405	0.1397
Reliability of power supply, heat, and cold (C4)	3.0000	0.0220	0.0659
Load shedding probability (C5)	2.9237	0.0102	0.0299
Comprehensive energy N-1 passing rate (C6)	3.2203	0.0319	0.1027
System equipment investment cost (D1)	2.8898	0.0383	0.1107
Energy system investment payback period (D2)	3.4153	0.0141	0.0480
Environmental protection tax on pollutant discharge (D3)	3.2627	0.0570	0.1861
Net emission reduction revenue (D4)	3.3475	0.0321	0.1075
Fuel purchase cost (D5)	2.8475	0.0095	0.0271
Unit functional cost of energy (D6)	2.7881	0.0377	0.1050
Comprehensive energy efficiency (E1)	4.0424	0.0388	0.1567
Energy distribution and transmission losses (E2)	2.6186	0.0223	0.0585
Energy conversion efficiency (E3)	3.2966	0.0234	0.0773
Energy intensity (E4)	2.6780	0.0128	0.0342
Clean energy consumption rate of the park (E5)	3.8475	0.0190	0.0732
User-side energy quality (E6)	3.0000	0.0300	0.0899
Ambient load factor (F1)	3.0254	0.0805	0.2437
Energy sustainability index (F2)	3.3814	0.0394	0.1333
Recycle rate of waste heat (F3)	3.0424	0.0595	0.1810
Long-term system operation and maintenance capability (F4)	3.8983	0.0931	0.3630
Waste cycle rate (F5)	3.1271	0.0245	0.0765
Index Name	**Operational Phase**		
	Comprehensive Valuation	**Weight**	**Weighted Value**
Noise effect (B1)	3.8051	0.0346	0.1316
Primary energy utilization rate (B2)	3.3475	0.0346	0.1159
Pollutant reduction rate (B3)	4.2627	0.0719	0.3064
Proportion of green electricity use (B4)	4.4068	0.0571	0.2516
Rate of change in carbon emissions (B5)	4.3305	0.0547	0.2371
Operating life of equipment (C1)	3.3729	0.0222	0.0749
Equipment failure rate (C2)	2.6864	0.0265	0.0713
Technology maturity (C3)	3.4746	0.0364	0.1264
Reliability of power supply, heat, and cold (C4)	3.0000	0.0163	0.0488
Load shedding probability (C5)	3.1949	0.0093	0.0296
Comprehensive energy N-1 passing rate (C6)	3.2203	0.0264	0.0851
System equipment investment cost (D1)	3.0339	0.0419	0.1272
Energy system investment payback period (D2)	3.5000	0.0450	0.1575
Environmental protection tax on pollutant discharge (D3)	3.2627	0.0422	0.1376
Net emission reduction revenue (D4)	3.3898	0.0478	0.1621
Fuel purchase cost (D5)	2.9407	0.0072	0.0211
Unit functional cost of energy (D6)	2.8136	0.0264	0.0743
Comprehensive energy efficiency (E1)	4.0424	0.0275	0.1112
Energy distribution and transmission losses (E2)	2.7034	0.0129	0.0348
Energy conversion efficiency (E3)	3.2966	0.0128	0.0421
Energy intensity (E4)	3.7881	0.0138	0.0524
Clean energy consumption rate of the park (E5)	3.7542	0.0177	0.0665
User-side energy quality (E6)	3.3898	0.0263	0.0890
Ambient load factor (F1)	3.0254	0.0784	0.2372
Energy sustainability index (F2)	3.4915	0.0515	0.1799
Recycle rate of waste heat (F3)	3.3644	0.0402	0.1352
Long-term system operation and maintenance capability (F4)	3.8898	0.0978	0.3805
Waste cycle rate (F5)	3.1271	0.0196	0.0614

5.3.2 Sensitivity analysis

To verify the influence degree of each main factor on the benefit, so that decision-makers can carry out targeted management, this section has carried out the sensitivity analysis. This paper uses game theory to obtain accurate combination weights, with Nash equilibrium as the goal. However, in practice, due to subjective and objective factors, the decision-making attitude of experts cannot be completely rational. Therefore, this paper changes the combination weights under the five first-level indicators in the operation stage by ± 10%, ± 20%, and ± 30%, respectively, to simulate the deviation from reality and analyze the impact of these changes on the results. The process uses the percentage formula:

$$w_{ij}^{*} = \frac{w_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} w_{ij}} \tag{20}$$

Ensure that the sum of weights is 1, where i is a first-level indicator and j is a second-level indicator. The results are shown in Table 15 and Figure 9.

Table 15. Benefit scores after changes in tier 1 indicators during the operational phase

	−30%	−20%	−10%	+10%	+20%	+30%
Environmental Impact	3.5117	3.5146	3.5172	3.5220	3.5242	3.5263
Technical Benefit	3.5315	3.5274	3.5235	3.5160	3.5124	3.5088
Economic Benefit	3.5344	3.5312	3.5244	3.5151	3.5107	3.5064
Energy Efficiency	3.4961	3.5024	3.5129	3.5271	3.5344	3.5416
Sustainability	3.5248	3.5213	3.5230	3.5199	3.5167	3.5154

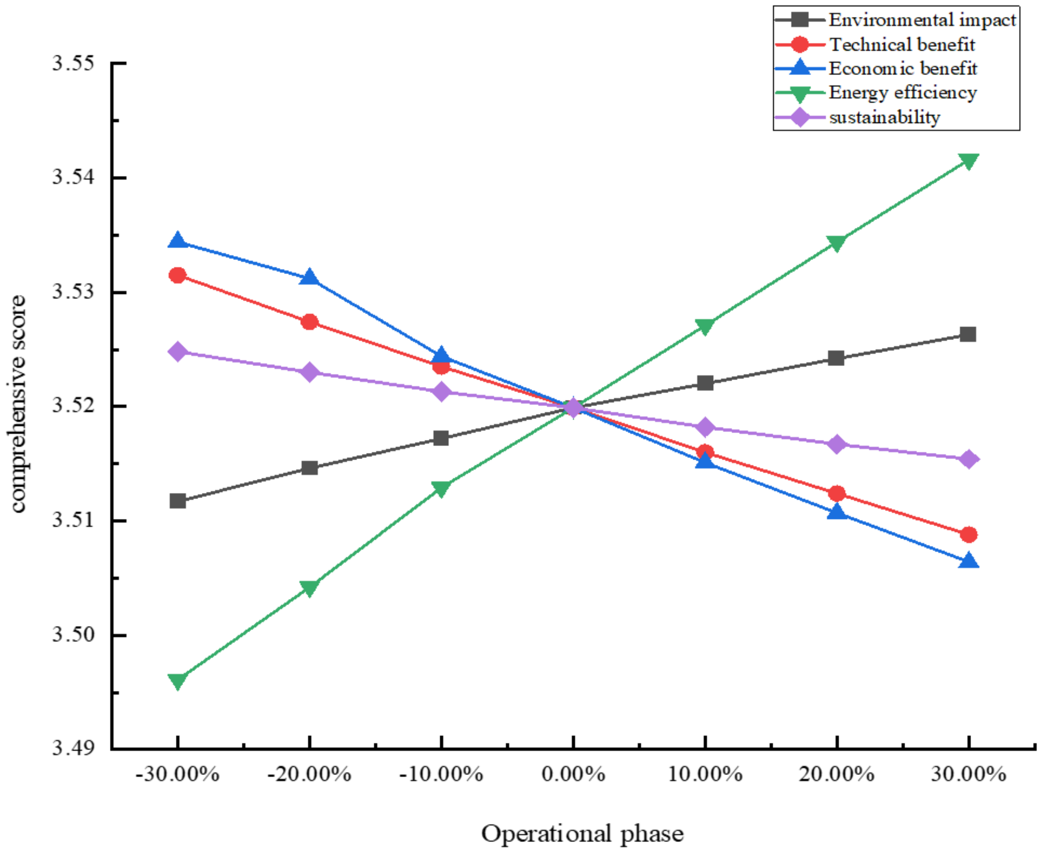

Figure 9. Sensitivity analysis chart of comprehensive scoring system

Figure 9 shows the changes of the comprehensive benefit caused by the change of different weights in the range of [-30%, +30%]. Among them, the reduction and increase of environmental weight have almost the same impact on comprehensive benefits. Technology exhibits greater sensitivity to lower weights, whereas energy and economic factors are more responsive to higher weights. Specifically, the energy index score demonstrates an ascending trend in line with the change percentage, increasing from 3.4961 at -30% change to 3.5416 at 30%. This suggests that the energy index is particularly sensitive to substantial weight variations. In contrast, sustainability scores remain relatively consistent, fluctuating minimally from 3.5248 at -10% to 3.5154 at 30%, indicating higher stability within a moderate range of weight changes. However, sustainability may exhibit sensitivity to more extreme weight adjustments. These findings underscore the importance of prioritizing energy efficiency within the benefit evaluation framework for zero-carbon park operations while placing a relatively lower emphasis on environmental impact. Decision-makers are thus advised to focus on enhancing energy efficiency, leveraging renewable energy sources, advancing energy technologies, and reducing energy intensity. They should implement effective energy strategies, optimize operational mechanisms, and minimize energy wastage. Notably, the operational efficiency of the IES during the zero-carbon park's operational phase remains consistently stable, indicating a lack of significant variability and thereby affirming the reliability of the study's outcomes.

6 Conclusion

Based on the combination weighting-fuzzy comprehensive evaluation (GRA-FCE) model of game theory, this study evaluates the benefits of IES in the three stages of planning, construction, and operation of zero-carbon parks. Using the weighted values in the model, the attention to key indicators at different stages is deeply revealed, and a clear quantitative standard is provided for the evaluation process through its scoring mechanism. It also provides a comprehensive analytical framework for the benefit evaluation of IES in zero-carbon parks. Based on this model, the following are key conclusions:

(1) First of all, we utilized the expert survey approach to develop an IES assessment indicator system for zero-carbon parks, which included five first-level indicators for environmental effect, technical benefits, economic benefits, energy benefits, and sustainability, as well as 28 second-level indicators. The system's structure is versatile and widely adaptable.

(2) Secondly, game theory is used to optimize the combination of subjective weights of the hierarchical method and objective weights of CRITIC. It avoids the limitation of a single weight and greatly improves the rationality of the combination of subjective and objective weights, making the evaluation more scientific and accurate.

(3) Finally, based on the questionnaire and the combination weight data, the sensitivity analysis of the combination weight is carried out to verify the reliability of the model, and the importance degree and influence level of each index are obtained by the fuzzy comprehensive evaluation method. Combined with the case to verify the feasibility of the evaluation model, the evaluation result of the low-carbon benefit of zero-carbon park construction is obtained. Based on the evaluation results, project managers and decision-makers are helped to identify priorities at different stages and allocate resources rationally to achieve the goal of a zero-carbon park.

Facing a large number of domestic parks and the diversity of types, the IES is confronted with many challenges in the process of helping the park achieve the goal of 'zero carbon', such as the difficulty of technology integration, the balance between energy storage and supply and demand, and the difficulty of operation and management. For this reason, in future development, against the different regions and energy carrier characteristics of the park, it is necessary to further study the research and evaluation model of IES to meet the requirements of the optimal design and operation planning of the zero-carbon park at all stages of construction. An intelligent energy system is processing that integrates multiple technologies and optimizes the IES to a greater extent by introducing diversified modeling and simulation of the Internet and digital twin technology to help the park achieve the goal of 'zero carbon'.

The evaluation system utilized in this study has not been able to fully capture the complexity of the actual situation. During the sustainable development process of zero-carbon parks, this indicator system should be continuously improved in future studies. To effectively address the challenges, future development should focus on formulating comprehensive top-level planning and deeply integrating the concept of carbon neutrality into every stage of park development. Furthermore, due to the lack of a unified standard system for constructing zero-carbon parks, it is a priority to study and construct a comprehensive evaluation system covering multiple dimensions such as technology, market, policy, and environment for in-depth risk assessment and management. Government departments should further complete the operational mechanism of the carbon trading market and utilize market incentives to promote enterprises in the park to achieve carbon emission reduction.

In summary, this study suggests that project managers should integrate the zero-carbon concept into all aspects of planning, construction, and operation. They should also formulate effective strategies according to the characteristics of each stage to enhance the overall benefits of zero-carbon parks. Additionally, the construction of zero-carbon parks not only offers a wide range of IES application scenarios but also serves as a testing ground for system innovation and progress. Looking ahead, the development of IES requires multi-dimensional joint efforts, including technological innovation, policy support, capital investment, talent training, community participation, and international cooperation. Through these comprehensive efforts, IES is expected to become a major driver in achieving the goal of zero-carbon parks and playing a central role in global sustainable development processes.

Author Contributions

Methodology, T.Q.S. and L.S.; data curation, T.Q.S. and L.S.; investigation, T.Q.S. and L.S.; writing – original draft, T.Q.S. and L.S.; writing – review & editing, T.Q.S. and L.S.; funding acquisition (support), T.Q.S.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] G. Siciliano, L. Wallbott, F. Urban, A. N. Dang, and M. Lederer, "Low-carbon energy, sustainable development, and justice: Towards a just energy transition for the society and the environment," *Sust. Dev.*, vol. 29, no. 6, pp. 1049–1061, 2021. https://doi.org/10.1002/sd.2193

[2] F. Si, E. Du, N. Zhang, Y. Wang, and Y. Han, "China's urban energy system transition towards carbon neutrality: Challenges and experience of Beijing and Suzhou," *Renew. Sust. Energy. Rev.*, vol. 183, p. 113468, 2023. https://doi.org/10.1016/j.rser.2023.113468

[3] S. Hu, P. Zhang, and T. Wei, "Financial measures to reduce carbon emissions in Britain, Japan and The United States: A SWOT analysis," *Int. J. Environ. Res. Public. Health.*, vol. 19, no. 17, p. 10771, 2022. https://doi.org/10.3390/ijerph191710771

[4] G. Ulpiani, E. Rebolledo, N. Vetters, P. Florio, and P. Bertoldi, "Funding and financing the zero emissions journey: Urban visions from the 100 Climate-Neutral and Smart Cities Mission," *Hum. Soc. Sci. Commun.*, vol. 10, no. 1, pp. 1–14, 2023. https://doi.org/10.1057/s41599-023-02055-5

[5] H. Ranasinghe, "Carbon net-zero by 2050: Benefits, challenges and way forward," *J. Trop. For. Environ.*, vol. 12, no. 1, p. 6107, 2022. https://doi.org/10.31357/jtfe.v12i01.6107

[6] A. Urbina, "Sustainability of photovoltaic technologies in future net-zero emissions scenarios," *Prog. Photovolt. Res. Appl.*, vol. 31, no. 12, pp. 1255–1269, 2023. https://doi.org/10.1002/pip.3642

[7] P. W. Newton and B. C. Rogers, "Transforming built environments: Towards carbon neutral and blue-green cities," *Sust.*, vol. 12, no. 11, p. 4745, 2020. https://doi.org/10.3390/su12114745

[8] A. Miglioli, N. Aste, C. Del Pero, and F. Leonforte, "Photovoltaic-thermal solar-assisted heat pump systems for building applications: Integration and design methods," *Energy Build. Environ.*, vol. 4, no. 1, pp. 39–56, 2023. https://doi.org/10.1016/j.enbenv.2021.07.002

[9] G. Di Ruocco, L. P. Iglesias, B. Blandón, and R. Melella, "Low-carbon tourism—technical, economic and management project of a greenway, for enhancing inner areas of the Cilento National Park, Italy," *Sust.*, vol. 12, no. 23, p. 10012, 2020. https://doi.org/10.3390/su122310012

[10] S. Evro, B. A. Oni, and O. S. Tomomewo, "Carbon neutrality and hydrogen energy systems," *Int. J. Hydrog. Energy*, vol. 78, pp. 1449–1467, 2024. https://doi.org/10.1016/j.ijhydene.2024.06.407

[11] B. Modu, M. P. Abdullah, A. L. Bukar, and M. F. Hamza, "A systematic review of hybrid renewable energy systems with hydrogen storage: Sizing, optimization, and energy management strategy," *Int. J. Hydrog. Energy*, vol. 48, no. 97, pp. 38 354–38 373, 2023. https://doi.org/10.1016/j.ijhydene.2023.06.126

[12] S. Evro, B. A. Oni, and O. S. Tomomewo, "Global strategies for a low-carbon future: Lessons from the US, China, and EU's pursuit of carbon neutrality," *J. Clean. Prod.*, vol. 461, p. 142635, 2024. https://doi.org/10.1016/j.jclepro.2024.142635

[13] B. K. Sovacool, M. Iskandarova, and F. W. Geels, ""Bigger than government": Exploring the social construction and contestation of net-zero industrial megaprojects in England," *Technol. Forecast. Soc. Change*, vol. 188, p. 122332, 2023. https://doi.org/10.1016/j.techfore.2023.122332

[14] T. Chance, "Towards sustainable residential communities; the Beddington Zero Energy Development (BedZED) and beyond," *Environ. Urbaniz.*, vol. 21, no. 2, pp. 527–544, 2009. https://doi.org/10.1177/0956247809339007

[15] X. He and B. Li, "A study on the influence of green industrial policy on urban green development: Based on the empirical data of ecological industrial park pilot construction," *Sustain.*, vol. 15, no. 13, p. 10065, 2023. https://doi.org/10.3390/su151310065

[16] C. Liu and R. Côté, "A framework for integrating ecosystem services into China's circular economy: The case of eco-industrial parks," *Sustain.*, vol. 9, no. 9, p. 1510, 2017. https://doi.org/10.3390/su9091510

[17] H. Yu and H. Liu, "Impact of digitization on carbon productivity: An empirical analysis of 136 countries," *Sci. Rep.*, vol. 14, no. 1, p. 5094, 2024. https://doi.org/10.1038/s41598-024-55848-2

[18] D. Song, W. Meng, M. Dong, J. Yang, J. Wang, X. Chen, and L. Huang, "A critical survey of integrated energy system: Summaries, methodologies and analysis," *Energy Convers. Manag.*, vol. 266, p. 115863, 2022.

[19] A. Irham, M. F. Roslan, K. P. Jern, M. A. Hannan, and T. I. Mahlia, "Hydrogen energy storage integrated grid: A bibliometric analysis for sustainable energy production," *Int. J. Hydrog. Energy.*, vol. 63, pp. 1044–1087, 2024. https://doi.org/10.1016/j.ijhydene.2024.03.235

[20] K. Hu, B. Wang, S. Cao, W. Li, and L. Wang, "A novel model predictive control strategy for multi-time scale optimal scheduling of integrated energy system," *Energy Rep.*, vol. 8, pp. 7420–7433, 2022. https://doi.org/10.1016/j.egyr.2022.05.184

[21] J. Li, Y. Wang, Y. Zheng, C. Liu, X. Xu, and R. Chen, "Optimization operation of the park-level integrated energy system based on the improved coyote optimization algorithm," *Int. Transact. Electr. Energy Syst.*, vol. 2022, no. 1, p. 6204918, 2022. https://doi.org/10.1155/2022/6204918

[22] Y. Dong, H. Zhang, C. Wang, and X. Zhou, "Soft actor-critic DRL algorithm for interval optimal dispatch of integrated energy systems with uncertainty in demand response and renewable energy," *Eng. Appl. Artif. Intell.*, vol. 127, p. 107230, 2024. https://doi.org/10.1016/j.engappai.2023.107230

[23] W. Zheng, Z. Xu, Z. Shao, J. Li, K. Lei, and J. Li, "Optimal dispatch of nearly-zero carbon integrated energy system considering waste incineration plant-carbon capture system and market mechanisms," *Int. J. Hydrog. Energy*, vol. 48, no. 69, pp. 27 013–27 031, 2023. https://doi.org/10.1016/j.ijhydene.2023.03.305

[24] J. Lin and R. Cai, "Optimal planning for industrial park-integrated energy system with hydrogen energy industry chain," *Int. J. Hydrog. Energy*, vol. 48, no. 50, pp. 19 046–19 059, 2023. https://doi.org/10.1016/j.ijhydene.2023.01.371

[25] L. Gao, F. Fei, Y. Jia, P. Wen, X. Zhao, H. Shao, T. Feng, and L. Huo, "Optimal dispatching of integrated agricultural energy system considering ladder-type carbon trading mechanism and demand response," *Int. J. Electr. Power Energy Syst.*, vol. 156, p. 109693, 2024. httpsdoi.org/10.1016/j.ijepes.2023.109693

[26] Q. Zhao, C. Yu, J. Liu, Y. Zhu, L. Yang, H. Zhao, H. Wang, and S. Gao, "The techno-economic evaluation of school integrated energy system based on G1-anti-entropy weight-TOPSIS method," *IOP Conf. Series. Earth Environ. Sci.*, vol. 675, no. 1, p. 012157, 2021. https://doi.org/10.1088/1755-1315/675/1/012157

[27] M. Shi, J. C. Vasquez, J. M. Guerrero, and Y. Huang, "Smart communities-design of integrated energy packages considering incentive integrated demand response and optimization of coupled electricity-gas-cooling-heat and hydrogen systems," *Int. J. Hydrog Energy*, vol. 48, no. 80, pp. 31 063–31 077, 2023. https://doi.org/10.1016/j.ijhydene.2023.04.272

[28] L. Fan, X. Zhong, J. Chen, Y. Tu, and J. Jiang, "Comprehensive energy system evaluation method of low-carbon park based on improved entropy weight," *J. Phys. Conf. Ser.*, vol. 2418, no. 1, p. 012025, 2023. https://doi.org/10.1088/1742-6596/2418/1/012025

[29] K. S. Alam, A. D. Kaif, S. K. Das *et al.*, "Towards net zero: A technological review on the potential of space-based solar power and wireless power transmission," *Heliyon*, vol. 10, no. 9, p. e29996, 2024. https://doi.org/10.1016/j.heliyon.2024.e29996

[30] Y. Haddad, E. G. De Bonneval, M. Afy-Shararah, J. Carter, J. Artingstall, and K. Salonitis, "Energy flexibility in aerospace manufacturing: The case of low carbon intensity production," *J. Manuf. Syst.*, vol. 74, pp. 812–825, 2024. https://doi.org/10.1016/j.jmsy.2024.05.004

[31] Y. Wang, L. Shi, M. Song, M. Jia, and B. Li, "Evaluating the energy-exergy-economy-environment performance of the biomass-photovoltaic-hydrogen integrated energy system based on hybrid multi-criterion decision-making model," *Renew. Energy*, vol. 224, p. 120220, 2024. https://doi.org/10.1016/j.renene.2024.120220

[32] S. Mohammed, F. Eljack, S. Al-Sobhi, and M. K. Kazi, "A systematic review: The role of emerging carbon capture and conversion technologies for energy transition to clean hydrogen," *J. Clean. Prod.*, vol. 447, p. 141506, 2024. https://doi.org/10.1016/j.jclepro.2024.141506

[33] L. N. K. Weerasinghe, A. Darko, A. P. Chan, K. B. Blay, and D. J. Edwards, "Measures, benefits, and challenges to retrofitting existing buildings to net zero carbon: A comprehensive review," *J. Build. Eng.*, vol. 94, p. 109998, 2024. https://doi.org/10.1016/j.jobe.2024.109998

[34] K. Obaideen, M. N. AlMallahi, A. H. Alami, M. Ramadan, M. A. Abdelkareem, N. Shehata, and A. G. Olabi, "On the contribution of solar energy to sustainable developments goals: Case study on Mohammed bin Rashid Al Maktoum Solar Park," *Int. J. Thermofluids*, vol. 12, p. 100123, 2021. https://doi.org/10.1016/j.ijft.2021.100123

[35] S. Chatterjee, V. Stavrakas, G. Oreggioni, D. Süsser, I. Staffell, J. Lilliestam, G. Molnar, A. Flamos, and D. Ürge Vorsatz, "Existing tools, user needs and required model adjustments for energy demand modelling of a carbon-

neutral europe," *Energy Res. Social Sci.*, vol. 90, p. 102662, 2022. https://doi.org/10.1016/j.erss.2022.102662

[36] H. Yousefi, R. Habibifar, A. Farhadi, and S. M. Hosseini, "Integrated energy, cost, and environmental life cycle analysis of electricity generation and supply in Tehran, Iran," *Sustain. Citi. Soc.*, vol. 97, p. 104748, 2023. https://doi.org/10.1016/j.scs.2023.104748

[37] S. Adams, F. Atsu, E. M. Klobodu, and L. Richmond, "Electricity transmission, distribution losses and economic growth in South Africa," *Heliyon*, vol. 6, no. 11, p. e05564, 2020. https://doi.org/10.1016/j.heliyon.2020.e05564

[38] T. Motloung, H. Quak, N. Anand, and R. van Duin, "The zero-emission city logistics maturity model–What do inner city SMEs know about planned zero-emission zones," *Trans. Res. Proc.*, vol. 79, pp. 194–201, 2024. https://doi.org/10.1016/j.trpro.2024.03.027

[39] A. Younesi, Z. Wang, and P. Siano, "Enhancing the resilience of zero-carbon energy communities: Leveraging network reconfiguration and effective load carrying capability quantification," *J. Clean. Produc.*, vol. 434, p. 139794, 2024. https://doi.org/10.1016/j.jclepro.2023.139794

[40] J. Park, W. Yang, S. Jung, H. Lee, J. Hong, Y. Lee, and S. Kim, "Assessment of energy self-sufficiency of a smart farm through integrated modeling of air-source heat pumps and solar power generation," *Appl. Energy*, vol. 367, p. 123398, 2024. https://doi.org/10.1016/j.apenergy.2024.123398

[41] S. Sreenath, A. M. Azmi, and Z. A. M. Ismail, "Feasibility of solar hybrid energy system at a conservation park: Technical, economic, environmental analysis," *Energy Rep.*, vol. 9, pp. 711–719, 2023. https://doi.org/10.1016/j.egyr.2022.11.065

[42] S. H. B. Motlagh, S. A. Hosseini, and O. Pons-Valladares, "Integrated value model for sustainability assessment of residential solar energy systems towards minimizing urban air pollution in Tehran," *Solar. Energy*, vol. 249, pp. 40–66, 2023. https://doi.org/10.1016/j.solener.2022.10.047

[43] T. M. Alabi, E. I. Aghimien, F. D. Agbajor, Z. Yang, L. Lu, A. R. Adeoye, and B. Gopaluni, "A review on the integrated optimization techniques and machine learning approaches for modeling, prediction, and decision making on integrated energy systems," *Renew. Energy*, vol. 194, pp. 822–849, 2022. https://doi.org/10.1016/j.renene.2022.05.123

[44] M. K. Kazi and M. F. Hasan, "Optimal and secure peer-to-peer carbon emission trading: A game theory informed framework on blockchain," *Compu. Chemi. Eng.*, vol. 180, p. 108478, 2024. https://doi.org/10.1016/j.compchemeng.2023.108478

[45] I. Kaya, M. Çolak, and F. Terzi, "A comprehensive review of fuzzy multi criteria decision making methodologies for energy policy making," *Energy Strate. Rev.*, vol. 24, pp. 207–228, 2019. https://doi.org/10.1016/j.esr.2019.03.003