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Original scientific paper

Comprehensive Evaluation of Port Self-Sufficient Energy Systems Based on the G1-CRITIC-Cloud Model

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Abstract: With the in-depth advancement of the dual-carbon strategy, the planning and construction of self-sufficient energy systems of ports, as key nodes for the integration of transportation and energy, have become a key research area. To address the problems of fuzziness and randomness in the comprehensive evaluation of port self-sufficient energy systems, this study proposes a comprehensive evaluation method on the basis of order relation analysis (G1)-criteria importance through intercriteria correlation (CRITIC) combined weighting, and a cloud model. First, an evaluation system with 15 secondary indicators was constructed from five dimensions: economic feasibility, environmental effect, energy efficiency, self-sufficiency, and reliability. Second, the subjective and objective weights were determined by the G1 ordinal relation analysis method and the CRITIC method, respectively. Third, cloud model theory was introduced, the fuzziness and randomness of evaluation levels were characterized by three numerical characteristics (expectation, entropy, and hyperentropy), and standard and comprehensive evaluation clouds were generated. Finally, with Shanghai Port in China as the research object, an empirical analysis was conducted. Results show that the equipment utilization rate, system disaster resistance, and net present value are the core indicators that affect the evaluation results and have weights of 0.0927, 0.0910, and 0.0894, respectively. The expectation values of each secondary indicator are distributed between 75 and 87. The score of carbon emission reduction is the highest, whereas that of equipment failure rate is the lowest. The expectation value of the comprehensive evaluation cloud is 80.938, which corresponds to the good level and indicates that the overall planning scheme of Shanghai Port's self-sufficient energy system is safe, and the risk is within an acceptable range. The study verifies the applicability and effectiveness of the G1-CRITIC-cloud model method in the evaluation of port self-sufficient energy systems. This method can provide methodological support for the green transformation and scientific decision-making of port energy systems.

Keywords: comprehensive evaluation; cloud model; G1-CRITIC combined weighting; indicator weight; port self-sufficient energy system

1 INTRODUCTION

Against the backdrop of global efforts to address climate change, China has explicitly proposed the strategic goals of carbon peaking and carbon neutrality, charting a course for green, low-carbon transformation across various industries. Ports, serving as critical hubs for global trade and vital nodes within the integrated transportation system, have elicited growing concern because of its energy consumption and carbon emissions [1]. Statistics indicate that port operations, including shore power supply, loading/unloading machinery, and horizontal transport, consume substantial fossil fuel, making their carbon emissions an important component of the transportation sector [2]. Port areas typically possess abundant clean energy resources, such as wind and solar power, granting them inherent advantages in developing self-sufficient energy systems [3]. In recent years, ports worldwide have been exploring pathways for energy transition; for instance, the Port of Duisburg in Germany has established a CO_2-neutral self-sufficient energy system that integrates hydrogen fuel cells, photovoltaic power generation, and smart energy storage technologies, providing a replicable model for large logistics hubs [4]. China's Tianjin Port has achieved a total installed wind power capacity of 68 MW, generating 150 million kWh annually, and Ningbo-Zhoushan Port has planned a port-vessel multi-energy integration system that is based primarily on wind energy with complementary energy sources [5]. However, the current application of clean energy in ports still faces challenges, such as singular models, low penetration rates, and technical bottlenecks in multi-energy grid integration, urgently necessitating a fundamental transformation of the port energy structure from a systemic perspective [6]. In this context, the concept of port self-sufficient energy systems has emerged; this concept integrates various energy forms, such as wind, solar, hydrogen, and storage, supported by intelligent energy management platforms to achieve self-sufficiency and green, low-carbon operation of port energy consumption.

The planning and construction of a port's self-sufficient energy system constitute a complex system engineering task that involves comprehensive considerations across multiple dimensions, such as energy configuration, technology selection, economic assessment, and environmental influence. Existing research has focused on system architecture design or optimal dispatch strategies, and a systematic evaluation framework and methodological support for scientifically assessing the merits of different planning schemes remain lacking. As a crucial tool for scheme comparison and decision optimization, comprehensive evaluation hinges on the construction of an indicator system and the rational determination of indicator weights. Given that the evaluation of port self-sufficient energy systems involves multiple objectives, including economic viability, environmental friendliness, energy efficiency, self-sufficiency capability, and operational reliability, and that complex interrelationships may exist among indicators, neither purely subjective nor purely objective weighting methods can adequately balance expert judgment with the statistical characteristics of the data. Therefore, this study proposes a combined evaluation method that is based on the order relation analysis (G1)-criteria importance through intercriteria correlation (CRITIC)-cloud model. The G1 method can reflect experts' subjective judgment of indicator importance, avoiding the consistency check issues of the analytic hierarchy process; the CRITIC method, an objective weighting approach on the basis of interindicator correlation, can reveal information regarding data volatility and conflict for objective weighting. The combined weights derived from the two methods respect domain knowledge while reflecting data patterns. On this basis, cloud model theory is introduced to characterize the fuzziness and randomness of evaluation grades through three numerical characteristics, namely, expectation, entropy, and hyperentropy, thereby organically integrating qualitative evaluation with quantitative representation. This study constructs an evaluation indicator system from five dimensions, namely, economy, environment, energy efficiency, self-sufficiency, and reliability, and conducts an empirical study by using a typical port self-sufficient energy planning scheme as the object. The aim is to provide a scientific evaluation tool and decision-making reference for the green transformation of port energy systems.

2 LITERATURE REVIEW

In recent years, with the in-depth advancement of the carbon peaking and carbon neutrality strategy, the integrated development of transportation and energy has become a focal point for academia and industries. As a crucial carrier for this integration, self-sufficient energy systems have been extensively explored in many scenarios, such as highways, railways, and ports. Related research primarily revolves around system architecture design, optimal configuration, evaluation methods, key technologies, and other dimensions, accumulating a rich body of work.

At the level of system architecture and planning design, scholars have proposed differentiated self-sufficient energy system schemes for various transportation scenarios. Lu et al. constructed a railway self-sufficient energy system architecture on the basis of multistate clean energy, providing a top-level design reference for energy self-sufficiency in railway contexts [7]. Gardashov et al. focused on highway service areas in arid desert regions [8]; they researched the planning and design of green energy self-sufficient systems and explored energy facility design, planning technologies [9], and construction techniques for integrated energy storage systems [10] under energy self-sufficient conditions, thus forming a complete technical chain from planning to construction. Pourbehzadi et al. systematically reviewed key issues in the planning of highway self-sufficient energy systems and clarified research directions in this field [11]. Guo et al. [12] extended their research scope to the port scenario and proposed a multiscenario planning method for port self-sufficient new energy systems that considers the optimal coupling of transportation demand and energy load, thus offering a new perspective toward port energy system planning.

With regard to optimal configuration and dispatch operation, scholars have employed various optimization methods to enhance system performance. Wang et al. studied the optimal configuration of self-sufficient energy systems for typical highway scenarios [13]. He et al. examined the optimal configuration problem of highway traffic-based self-sufficient energy multimicrogrid systems [14]. Zhang et al. considered different operation modes to optimize the architecture configuration of transportation self-sufficient energy systems [15]. At the dispatch operation level, Huang et al. studied the optimal dispatch method for green power self-sufficient systems in remote areas of China [16]. Jung et al. focused on the emergency resource optimal dispatch problem for highway self-sufficient energy systems under extreme weather conditions [17]. Chen et al. introduced the Aquila Optimizer algorithm to explore optimal control methods for transportation self-sufficient energy systems [18]. Li et al. analyzed typical scenarios and key issues in the integrated development of transportation and energy from a macro perspective and proposed development recommendations [19]. Meanwhile, Srivastava et al. [20] and Farhadi et al. [21] investigated highway and railway self-sufficient energy systems from the perspectives of microgrid operation control and complex network models, respectively. Zavadskas et al. focused on the coordinated control of hybrid AC/DC microgrids in highway self-sufficient energy systems [22].

In the area of evaluation methods and indicator system construction, the research findings are abundant. Pannala et al. innovatively introduced the k-medoids clustering algorithm into the evaluation of highway self-sufficient energy systems, thereby optimizing the evaluation methodology [23]. Zhang et al. constructed a highway energy evaluation system on the basis of an improved Delphi-entropy weight method [24] and studied comprehensive energy efficiency evaluation methods for systems [25]. Nakada et al. explored data- and model-driven state estimation methods for transportation self-sufficient energy systems in highway service areas [26]. Shi et al. systematically studied the optimal dispatch of highway traffic self-sufficient energy systems in their dissertation [27]. Guo et al. focused on the compatibility between intelligent facilities and new energy vehicles and conducted research on the evaluation and optimization of the compatibility between highway development levels and self-sufficient energy systems [28]. Meanwhile, Adeel et al. extended their research scenario to road-water intermodal transport and explored the optimal configuration method for green road-water intermodal self-sufficient systems [29].

Recent research has further shifted towards the decarbonization of port hubs. For instance, Wang et al. explored the optimization of multi-energy microgrids for zero-carbon ports, emphasizing the role of hydrogen storage in buffering renewable fluctuations [30]. Similarly, Jin et al. developed a lifecycle sustainability assessment framework specifically for green port infrastructure, which provides a more granular view of environmental impacts than earlier models [31]. These studies highlight a trend towards integrating high-fidelity operational data with multi-objective decision-making, yet a gap remains in effectively bridging qualitative expert judgment with stochastic cloud model characteristics in port-specific contexts.

Extant research indicates that studies on self-sufficient energy systems have formed a multidimensional and multi-scenario research frameworks. In terms of evaluation methods, the trend has shifted from single methods, such as the entropy weight method and the Delphi method, to combined weighting and intelligent clustering. With regard to research subjects, the focus has gradually expanded from highways to complex scenarios, such as railways, ports, and road-water intermodal transport. For the port scenario, preliminary evaluation frameworks have been established, but the systematic nature of indicator systems and the applicability of evaluation methods still have room for improvement. On this basis, this study adopts a method that combines G1-CRITIC combined weighting and the cloud model to conduct a comprehensive evaluation of port self-sufficient energy systems. This method organically combines the G1 order relation analysis method and the CRITIC objective weighting method to determine indicator weights from the two dimensions of subjective expert judgment and objective data patterns, respectively, thereby obtaining comprehensive weights that balance the advantages of both. Subsequently, cloud model theory is introduced, and its three numerical characteristics (i.e., expectation, entropy, and hyperentropy) are used to effectively characterize the fuzziness and randomness in the evaluation process, thereby transforming qualitative evaluation into quantitative results. This technical approach aims to provide a scientific, rigorous, reliable evaluation tool for multidimensional performance assessment of port self-sufficient energy systems.

3 METHODOLOGY

3.1 Combined Weighting Model

This study adopts the G1-CRITIC combined weighting method to rank the importance of evaluation indicators, thus ensuring the objectivity and rationality of the comprehensive evaluation of theport's self-sufficient energy system.

3.1.1 G1 Model

The G1 method has a simple structure, clear logic, and no requirement for a consistency test, making it suitable for multi-index subjective weighting scenarios. The specific implementation steps of the G1 method are as follows.

Before weight ranking, a consistency test must be conducted, and experts' opinions need to be processed to reduce subjective bias. First, the deviation-degree test method is used to examine the difference between raw score x_k (given by the *k*-th expert for an indicator) and the mean score, as shown in Eq. (1).

$$d_k = \frac{|x_k - \bar{x}|}{\bar{x}} \tag{1}$$

where x_k is the *k*-th expert for an indicator, $\bar{x}$ is the arithmetic mean of scores from all experts for the indicator, k is the expert index ($k = 1, 2, \ldots, m$), and m is the total number of experts.

If d_k exceeds a preset threshold (e.g., 20%), the expert is prompted to re-evaluate. Meanwhile, the coefficient of variation (CV) is calculated as

$$CV = \frac{\sigma}{\bar{x}} \tag{2}$$

where σ represents the standard deviation of scores from all experts for the indicator.

An excessively large *CV* (e.g., > 0.25) indicates substantial divergence of experts' opinions. Next, through opinion screening, scores that deviate considerably or are unreasonable are removed or revised. If the overall dispersion remains large, a coordination mechanism (e.g., expert discussion or rescoring) can be activated until a consistent judgment is reached. These steps effectively mitigate the effect of individual experts' subjective biases on the results, ensuring the scientificity and robustness of the subsequent weight calculations.

(1) Assume that *n* evaluation indicators are present and ranked by experts' judgment of importance (from the highest to the lowest), that is, $X_1, X_2, \ldots, X_n$. Their corresponding weights are $W_1, W_2, \ldots, W_n$.

(2) Define the adjacent ratio as follows:

$$\alpha_i = \frac{W_{i+1}}{W_i}, \ (i = 1, 2, \ldots, n-1, 0 < \alpha_i < 1) \tag{3}$$

where α_i is the ratio of the weight of X_{i+1} (W_{i+1}) to the weight of X_i (W_i).

(3) With the last-term weight being set as $W_n = 1$, sequentially calculate the nonnormalized weights of the remaining indicators as follows:

$$W_i = \frac{W_{i+1}}{\alpha_i}, \ (i = n-1, n-2, \ldots, 1) \tag{4}$$

(4) Obtain nonnormalized weight sequence $W_1, W_2, \ldots, W_n$. After normalization, derive final subjective weight W_i^* as follows:

$$W_i^* = \frac{W_i}{\sum_{j=1}^{n} W_j}, (i = 1, 2, \ldots, n) \tag{5}$$

where W_i^* is the final normalized subjective weight of the *i*-th indicator X_i, W_i is the nonnormalized weight of the *i*-th indicator, and $\sum_{j=1}^{n} W_j$ is the sum of the nonnormalized weights of all n indicators ($1 \le j \le n$).

3.1.2 CRITIC Model

The CRITIC method is employed to calculate the weights of the primary indicators and determine the final weight of each indicator. It is a technique for weight determination that comprehensively considers the contrast intensity and conflict between indicators. Specifically, it measures intraindicator variation via standard deviation and reflects interindicator correlation by using the correlation coefficient. A large standard deviation implies large differences in the values of evaluation objects under the same indicator (large weight); a large correlation coefficient implies minimal conflict between indicators (small weight). The calculation steps for weight determination via the CRITIC method are discussed below.

For the comprehensive evaluation of port self-sufficient energy systems, indicators often exhibit correlations. In this study, the CRITIC method is adopted to calculate objective weights. Assume that *m* evaluation schemes are available, and each scheme has *n* indicators.

Evaluation matrix X is used to describe the evaluation data, and its expression is given by

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{6}$$

(1) Indicator Directionalization

During the identification of risk assessment indicators, negative indicators (e.g., quality of prefabricated components, where a large value indicates low risk) and positive indicators (where a large value indicates high risk) may exist. The co-occurrence of the two types of indicators complicates calculations. Thus, indicator directionalization (to ensure that all indicators have the same trend) is necessary for easy computation, and the conversion formula is as follows:

$$x'_{ij} = \frac{1}{\lambda + \max\left|X_i\right| + x_{ij}} \tag{7}$$

where: x_{ij} - original value of the j-th indicator for the i-th scheme, x'_{ij} - value of the j-th indicator after directionalization, $\max\left|X_i\right|$ - maximum absolute value of the j-th indicator, λ - coordination coefficient (typically set to 0.1).

After this processing, forward-directed evaluation matrix X' is obtained.

(2) Indicator Standardization

Given the different meanings and units of indicators in X', each indicator's values must be converted to a uniform scale. The standardization formula is

$$x''_{ij} = \frac{x'_{ij} - \min(x'_{ij})}{\max(x'_{ij}) - \min(x'_{ij})} \tag{8}$$

where x''_{ij} denotes the standardized value of the j-th indicator for the i-th scheme.

(3) Calculation of Objective Indicator Weights

From standardized matrix X'', the standard deviation (σ_i) of each indicator and the correlation coefficient (ρ_{ij}) between indicators can be derived; their calculation formulas are given in Eqs. (9) and (10), respectively.

$$\sigma_i = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(x_j^n - \overline{x}_i^n\right)^2}, i = 1, 2, ..., n \tag{9}$$

$$\rho_{ij} = \operatorname{cov}(X_i^n, X_j^n)/(\sigma_i \sigma_j), \ i = 1, 2, ..., n \tag{10}$$

where: x''_i - mean value of the j-th indicator, $\operatorname{cov}(X_i^n, X_j^n)$ - covariance between the i-th and j-th indicators.

The information content, G_i, of each indicator (a key factor for weight determination) is calculated as

$$G_i = \sigma_i \sum_{j=1}^{n}(1 - \rho_{ij}), \ i = 1, 2, ..., n \tag{11}$$

A large G_i indicates high relative importance and abundant information contained in the i-th indicator. Then, the objective weight (β_i) of the i-th indicator is computed as

$$\beta_i = \frac{G_i}{\sum_{j=1}^{n} G_j} \tag{12}$$

3.1.3 Determination of Combined Weights

To balance subjective cognition and objective data characteristics, this study adopts the product method to fuse the G1 and CRITIC weights and determine the final combined weights. This method can effectively integrate weight information from different sources and avoid weight imbalance. The calculation of combined weights via the product method is as follows:

$$W_j^{(c)} = \frac{W_j^{(s)} \cdot W_j^{(o)}}{\sum_{j=1}^{n}\left(W_j^{(s)} \cdot W_j^{(o)}\right)}, \ j = 1, 2, ..., n \tag{13}$$

where: $W_j^{(s)}$ - subjective weight of the j-th secondary indicator, $W_j^{(o)}$ - objective weight of the j-th secondary indicator, $W_j^{(c)}$ - combined weight, n - total number of indicators.

This method regards subjective and objective weights as two independent probability distributions from different sources, takes their product as the possibility of joint occurrence, and performs normalization (via Eq. (14)) to ensure that the sum of all combined weights equals 1.

$$\sum_{j=1}^{n} W_j^{(c)} = 1, W_j^{(c)} \geq 0 \tag{14}$$

The product operation is performed for all indicators to obtain $W_j^{(s)}$ and $W_j^{(o)}$, and all product values are normalized to derive the final combined weight $W_j^{(c)}$. In this study, the G1 method is employed to obtain the subjective weights of 15 secondary indicators, and the CRITIC method is used to derive their objective weights. The two weight sets are fused via the product method, yielding a comprehensive and robust combined weight result.

3.2 Cloud Model

The cloud model is an artificial intelligence theory for resolving uncertain problems, and it can effectively realize two-way conversion between qualitative concepts and quantitative descriptions. In comprehensive evaluation, the cloud model characterizes the fuzziness and randomness of evaluation levels through three numerical characteristics: expectation (*Ex*), entropy (*En*), and hyperentropy (*He*). *Ex* is the typical sample value that best represents the qualitative concept. *En* comprehensively reflects the uncertainty and fuzziness of the concept, revealing the discrete degree of the index value. *He* measures the uncertainty of entropy (i.e., the thickness of the cloud), reflecting the randomness of the evaluation process. This method can overcome the rigid either-or division defect of traditional evaluation methods in index grading and is particularly suitable for complex systems, such as port self-sufficient energy systems that involve multisource heterogeneous data and have fuzzy evaluation boundaries. In this study, first, the comprehensive weights of each index are determined by the G1-CRITIC combined weighting method. Second, the index values of the scheme to be evaluated are converted into cloud parameters through the forward cloud generator, and standard clouds of each evaluation level and the comprehensive cloud of the scheme to be evaluated are generated. Finally, the final evaluation level of the port self-sufficient energy system is determined by calculating the similarity or closeness between the comprehensive cloud and the standard cloud to systematically characterize its comprehensive performance in multiple dimensions, such as economy, environmental protection, and autonomy.

The calculation of the cloud model is mainly divided into five steps.

(1) Calculate the three characteristic parameters of the standard cloud of each index level (expectation *Ex*, entropy *En*, and hyperentropy *He*) through the equation

$$\begin{cases} Ex = (U_{\min} + U_{\max}) / 2 \\ En = (U_{\max} - U_{\min}) / 6 \\ He = 0.1En \end{cases} \tag{15}$$

where $U_{\max}$ and $U_{\min}$ are the maximum and minimum values of the standard for different levels of the index, respectively.

(2) Generate n random numbers $En_n \sim N(En, He^2)$ and k random numbers $x'_k \sim N(Ex, En_n^2)$. Calculate the standard cloud membership degree of x'_k as follows:

$$\mu_k(x'_k) = \exp\left[-\frac{(x'_k - Ex)^2}{2En^2}\right] \tag{16}$$

(3) Let (x'_k, μ_k) represent one cloud drop. Repeat Step (2) until 1,500 cloud drops are generated. With Eqs. (17) and (18), calculate the cloud-related membership degree $\mu_v(x_i)$ between measured value x_i and each level v.

$$\mu_k(x_i) = \exp\left[-\frac{(x_i - Ex)^2}{2{En_n}^2}\right] \tag{17}$$

$$\mu_v(x_i) = \sum_{k=1}^{3000} \mu_k(x_i) \tag{18}$$

(4) Determine the comprehensive membership degree $D_v(T)$ of object T under different risk levels v in accordance with the equation

$$D_v(T) = \sum_{i=1}^{n} \mu_v(x_i) v_i, i = 1, 2, ..., n \tag{19}$$

where v_i represents the standardized weight of the i-th index.

(5) Judge the safety risk level on the basis of the maximum membership degree principle. Calculate the numerical characteristic values of the normal cloud model for each evaluation index through the MATLAB program. Generate the evaluation index cloud map by using the cloud generation algorithm and the standard normal cloud model. In accordance with the grading of the lithium battery energy storage station safety risk evaluation index system, adopt the $3E_n$ rule-based cloud-determined calculation rule (Fig. 1).

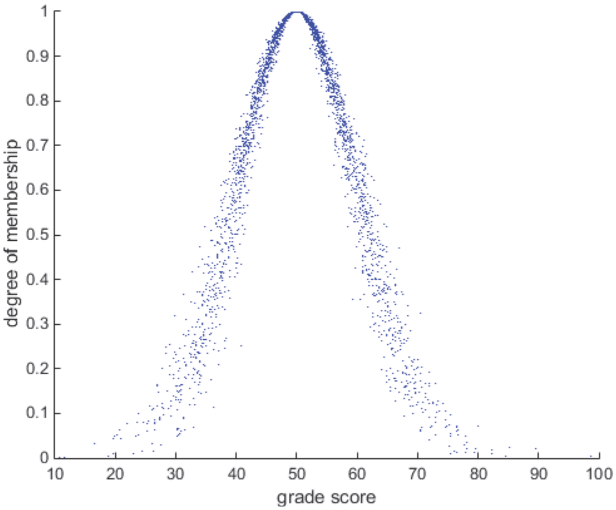

Figure 1 Standard cloud model

3.3 Construction of the Evaluation Index System

This study adheres to the principles of systematicness, scientificity, comparability, and operability. Following a series of steps (clarifying the evaluation objective, conducting a literature review, formulating key evaluation dimensions, screening and classifying indicators, and evaluating/updating indicators), we select evaluation indicators from five dimensions (i.e., economy, environment, energy efficiency, autonomy, and reliability). Each dimension contains multiple secondary indicators, jointly forming a hierarchical comprehensive evaluation index system for the port self-sufficient energy system planning scheme (Tab. 1).

To comprehensively assess the feasibility and performance of port self-sufficient energy system planning schemes, this study establishes an evaluation framework from five core dimensions, each with distinct evaluation foci and indicator systems.

(1) Economic Feasibility

Economic feasibility is the primary criterion for measuring whether a port self-sufficient energy system planning scheme has investment value and financial sustainability. This dimension reflects the project's capital recovery speed and risk level through the payback period, measures the total economic benefits generated by the project throughout its life cycle from an absolute-value perspective by using the net present value, and reflects the profitability of the capital occupied by the project from a relative-efficiency perspective through the internal rate of return. The combination of the three indicators enables a comprehensive evaluation of the economic rationality and capital attractiveness of energy system construction.

Table 1 Evaluation index system

Target Layer	Criterion Layer	Indicator Layer	Symbol	Indicator Meaning/Explanation
Comprehensive Evaluation Index System for Port Self-sufficient energy system Planning Scheme	Economic Feasibility (B1)	Payback Period	B11	Evaluate the project's capital recovery ability, reflecting the number of years to recoup the initial investment via operating income.
		Net Present Value	B12	Consider the time value of capital to measure the absolute economic benefit of the project over the entire planning period.
		Internal Rate of Return	B13	Reflect the project's inherent investment return rate, measuring capital utilization efficiency.
	Environmental Effect (B2)	Carbon Emission Reduction	B21	Amount of CO_2 emissions reduced by the system compared with traditional energy models; a core environmental indicator.
		Pollutant Emission Reduction	B22	Evaluate the reduction effect on air pollutants (e.g., SO_x and NO_x).
		Proportion of Clean Energy	B23	Proportion of renewable energy generation in the total electricity consumption, reflecting the cleanliness of the energy structure.
	Energy Efficiency (B3)	Energy Utilization Rate	B31	Proportion of input energy converted into effectively utilized energy, reflecting the technical level of the system's energy conversion and utilization.
		Renewable Energy Penetration Rate	B32	Ratio of renewable energy installed capacity to the maximum load, characterizing the access depth of renewable energy.
		Equipment Utilization Rate	B33	Reflect the operation efficiency and idle status of key power generation equipment (e.g., photovoltaics and wind turbines).
	Energy Self-Sufficiency (B4)	Energy Self-Sufficiency Rate	B41	Proportion of the system's self-generated power meeting the port's total energy consumption demand; a core indicator of autonomy.
		Peak Load Self-Sufficiency Rate	B42	Degree of self-sufficiency during peak electricity demand, testing the system's peak-shaving capability.
	Reliability (B5)	Power Supply Reliability	B51	Evaluate the system's continuous power supply capability, which is typically measured by the annual power outage duration or frequency.
		Energy Supply Stability	B52	For intermittent power sources (e.g., wind and photovoltaic), evaluate the effect of their output fluctuations on the port power grid's stability.
		Equipment Failure Rate	B53	Reflect the health status of key equipment in the system and the maintenance level.
		System Disaster Resistance & Recovery Ability	B54	Ability to maintain basic operation and recover rapidly under extreme weather or external disturbances.

(2) Environmental Effect

The environmental effect criterion focuses on the contribution of the port self-sufficient energy system to green, low-carbon development and is the core dimension for evaluating the system's ecological benefits. This indicator layer directly quantifies the reduction effect of the system on greenhouse and harmful gases, such as SO_x and NO_x, after replacing traditional fossil energy through carbon emission reduction and pollutant emission reduction. It also measures the optimization degree of the energy structure via the proportion of clean energy to comprehensively reflect the system's support capability for the port to achieve dual-carbon goals and green transformation.

(3) Energy Efficiency

The energy efficiency criterion is mainly used to evaluate the technical level and operation efficiency of the port self-sufficient energy system in terms of energy conversion, transmission, and utilization. The energy utilization rate focuses on the overall efficiency of the system from the input of primary energy to effective terminal utilization. The renewable energy penetration rate reflects the access depth of intermittent power sources, such as wind and photovoltaic, in the system. The equipment utilization rate evaluates the matching degree between the actual operating load and the rated capacity of key assets, such as photovoltaic and wind turbines. This criterion helps identify potential points for improving the energy efficiency of the system.

(4) Energy Self-Sufficiency

Energy self-sufficiency is the core criterion embodying the autonomous characteristics of the port energy system, and it aims to measure the system's ability to independently meet the port's energy demand. The energy self-sufficiency rate evaluates the proportion of the system's own power generation covering the port's annual total energy consumption from the perspective of total quantity and is the basic characterization of autonomy. The peak load self-sufficiency rate examines the system's ability to cope with load shocks by relying on its own power supply during peak electricity consumption periods from a dynamic perspective; such an ability is directly related to the reliability of the system's independent operation without the main power grid.

(5) Reliability

The reliability criterion is important for ensuring the continuity and safety of port production operations and mainly evaluates the stable operation ability of an energy system under complex working conditions. Specifically, power supply reliability reflects the quality of the system's continuous power supply by statistically analyzing the power outage time and frequency. Energy supply stability evaluates the disturbance effect of the fluctuating output of new energy on the frequency and voltage of the port power grid. The equipment failure rate reflects the operation health status of key facilities, and system disaster resistance and recovery capability considers the survival toughness and rapid recovery ability of the system when it encounters extreme weather or external effects.

4 RESULTS ANALYSIS

This study adopts Shanghai Port, a representative port along China's coast, as the research object and systematically conducts a comprehensive evaluation and analysis of the port's self-sufficiency energy system planning scheme. Through a quantitative evaluation and horizontal comparison of Shanghai Port in terms of key indicators, such as energy self-sufficiency rate, proportion of clean energy, power supply reliability, and economic feasibility, this work aims to reveal the development characteristics and optimization paths of the port's self-sufficiency energy system under different location conditions and operation scales and provide a scientific basis and decision-making reference for promoting the transformation of China's port energy structure, thereby improving the level of energy self-sufficiency and comprehensive competitiveness.

4.1 Data Sources

The original data are mainly from China Statistical Yearbook, Statistical Communiqué on National Economic and Social Development, China Port Statistical Yearbook, and Shanghai Municipal Bureau of Statistics. The original data of the involved indicators are from the corresponding year's China City Statistical Yearbook, EPS data platform, Wind database, National Basic Geographic Information Center, and Columbia University's Center for Social and Economic Data and Applications. With regard to the indicators involving price changes, they are all deflated by index with 2003 as the base period. The specific data utilized in this study are primarily sourced from the statistical yearbooks and databases corresponding to the year 2024, which ensures the timeliness and reflects the latest operational status of the port energy systems.

4.2 Determination of the Weights of Indicators at all Levels

The comprehensive evaluation of Shanghai Port's self-sufficiency energy system planning scheme should be conducted from five aspects: economic feasibility, environmental effect, energy efficiency, self-sufficiency, and reliability. The port's self-sufficiency energy system planning scheme should also be determined. In accordance with the cloud model on the basis of the G1-CRITIC combined weighting method established above, this study uses the G1-CRITIC method to determine the weights of each indicator and obtains the weight values of each third-level indicator through calculation. The specific results are shown in Tab. 2.

Table 2 Calculation results of the G1-CRITIC combination method

Criteria Level	Indicator Level	Symbol	G1 Weight	CRITIC Weight	Combined Weight
Economic Feasibility (B1)	Payback Period of Investment	B11	0.0653	0.0751	0.0749
	Net Present Value	B12	0.0557	0.1051	0.0894
	Internal Rate of Return	B13	0.0800	0.0501	0.0612
Environmental Effect (B2)	Reduction in Carbon Emissions	B21	0.0536	0.0789	0.0646
	Reduction in Pollutant Emissions	B22	0.0493	0.0581	0.0437
	Proportion of Clean Energy	B23	0.0797	0.0468	0.0570
Energy Efficiency (B3)	Energy Utilization Rate	B31	0.0404	0.0484	0.0299
	Penetration Rate of Renewable Energy	B32	0.0713	0.0695	0.0756
	Equipment Utilization Rate	B33	0.0856	0.0709	0.0927
Self-Sufficiency (B4)	Energy Self-Sufficiency Rate	B41	0.0576	0.0724	0.0637
	Peak Load Self-Sufficiency Rate	B42	0.0547	0.0690	0.0576
Reliability (B5)	Power Supply Reliability	B51	0.0872	0.0488	0.0650
	Stability of Energy Supply	B52	0.0525	0.0753	0.0603
	Equipment Failure Rate	B53	0.0916	0.0524	0.0732
	System's Disaster Resistance Capability	B54	0.0653	0.0751	0.0749

4.3 Determination of the Weights of Indicators at all Levels

The comprehensive evaluation grades of Shanghai Port's self-sufficient energy system are divided into five levels, as shown in Tab. 3, on the basis of the actual situation of the self-sufficient energy system at the port and by referring to relevant comprehensive evaluation studies on self-sufficient energy systems.

Table 3 Evaluation grade set

Valuation Grade	Grade Interval
Poor	[0, 30)
Bad	[30, 60)
Average	[60, 75)
Good	[75, 85)
Excellent	[85, 100]

On the basis of the cloud model generation method, the cloud model parameters corresponding to each grade are obtained and shown in Tab. 4.

Table 4 Digital characteristics of the standard cloud for evaluation criteria

Valuation Grade	Grade Interval	Standard Cloud Digital Characteristics
Poor	[0.0, 30.0)	(15.0, 5.0, 0.5)
Bad	[30.0, 60.0)	(45.0, 5.0, 0.5)
Average	[60.0, 75.0)	(67.5, 2.5, 0.5)
Good	[75.0, 85.0)	(80.0, 1.6667, 0.5)
Excellent	[85.0, 100.0]	(92.5, 2.5, 0.5)

The forward cloud generator is used to generate the standard cloud for the risk grade, and the standard cloud graph is given in Fig. 2.

The indicators are determined on the basis of expert opinions, and the scoring values are set within the range [0, 100]. Scores are assigned in accordance with the actual risk level of each indicator. To ensure the objectivity of the evaluation, the scoring is not entirely based on subjective impressions. Instead, 15 experts (5 from the port authority, 5 from the energy system research institute and 5 from the green logistics academic experts) were selected from the three sectors. The inclusion criteria require at least 10 years of professional experience in port energy management or related engineering. The 15 invited experts first reviewed the normalized actual operational data of Shanghai Port for each indicator. Based on these normalized objective data, experts assigned scores according to a unified mapping rule: indicators achieving the optimal target value receive 90-100 points, those meeting the expected value receive 80-89 points, those at the average level receive 70-79 points, and those below the threshold receive 70 points. The scored values are then input into the reverse cloud generator to obtain the cloud-model characteristic parameters of the secondary indicators, as shown in Tab. 5.

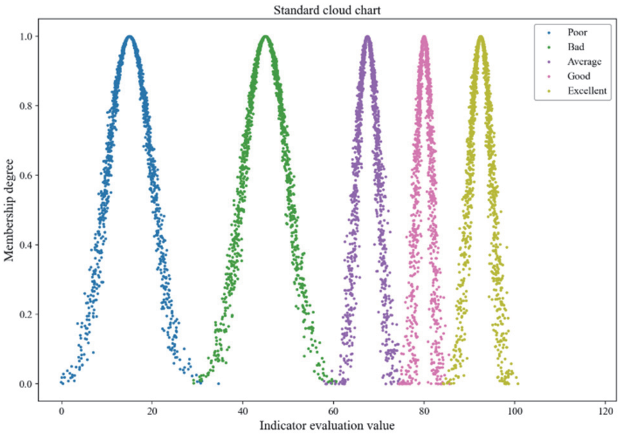

Figure 2 Standard cloud graph

Table 5 Cloud-model characteristic parameters of secondary indicators

Indicator	Symbol	Expectation *Ex*	Entropy *En*	Hyperentropy *He*
Payback Period	B11	76	3.6764	1.1582
Net Present Value	B12	77.8	4.9798	1.3943
Internal Rate of Return	B13	76.2667	4.4117	1.2664
Carbon Emission Reduction	B21	86.4	7.1857	2.7938
Pollutant Emission Reduction	B22	78.6	5.3809	1.727
Proportion of Clean Energy	B23	78	9.191	3.5318
Energy Utilization Rate	B31	75.6667	8.2997	2.9888
Penetration Rate of Renewable Energy	B32	81.4667	7.7984	2.9722
Equipment Utilization Rate	B33	83.8667	3.331	1.1215
Energy Self-Sufficiency Rate	B41	83.6667	7.7427	2.4195
Peak Load Self-Sufficiency Rate	B42	85	4.5119	0.8862
Power Supply Reliability	B51	85.5333	7.13	2.7513
Energy Supply Stability	B52	82.8	3.9438	1.1755
Equipment Failure Rate	B53	75.3333	4.7347	1.2388
System Disaster Resistance Capability	B54	84.1333	6.5507	1.6262

Tab. 2 shows the cloud-model characteristic parameters, including expectation (*Ex*), entropy (*En*), and hyperentropy (*He*), of each secondary indicator in the self-sufficient energy system of Shanghai Port. The expectation value reflects the comprehensive score of each indicator. Among the indicators, carbon emission reduction has the highest score, and equipment failure rate has the lowest score. The entropy value reflects the fuzziness and dispersion degree of the indicator. The entropy of the proportion of clean energy is the largest, and that of equipment utilization rate is the smallest. Hyperentropy characterizes the randomness of cloud droplets. The hyperentropy of the proportion of clean energy is also the largest, and that of peak load self-sufficiency rate is the smallest.

Tab. 6 shows the cloud-model characteristic parameters of the comprehensive evaluation results of the self-sufficiency energy system of Shanghai Port. The expectation of the comprehensive evaluation cloud is 80.938, indicating that the overall safety level of the system is within a high range. The entropy is 6.0257, reflecting that the fuzziness and dispersion degree of the evaluation results are moderate. Hyperentropy is 1.8581, indicating that the randomness of the cloud droplets is small, and the evaluation results have good stability and reliability. This comprehensive cloud model provides a quantitative basis for judging the overall safety status of the system.

Table 6 Evaluation results

Indicator	Expectation *Ex*	Entropy *En*	Hyperentropy *He*
Comprehensive Evaluation Cloud	80.938	6.0257	1.8581

On the basis of the calculation results, the forward cloud generator is used to generate a comprehensive evaluation cloud graph of the development level of the port's self-sufficient energy system. The graph is shown in Fig. 3.

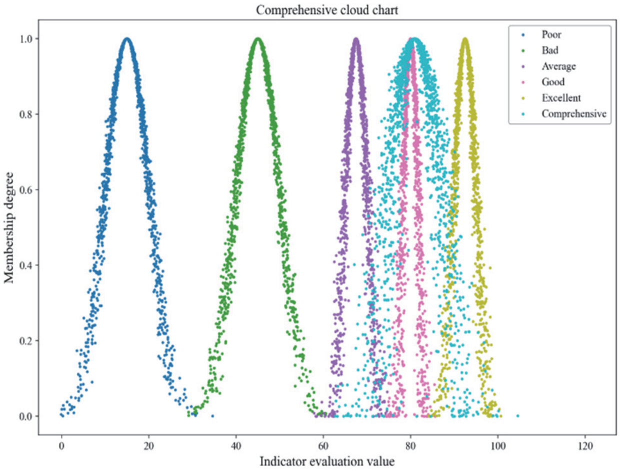

Figure 3 Comprehensive evaluation cloud graph

4.4 Discussion

First, in terms of indicator weights, the G1-CRITIC combination method considers subjective experience and the objective laws of data. The combined weights in Tab. 2 show that among the criterion levels, the indicator weights of reliability and energy efficiency are generally high. The weight of equipment utilization rate is the highest, followed by the weight of the system's disaster resistance. Expert opinions and the degree of data dispersion suggest that the stable operation and efficient utilization of port energy systems are the key to evaluating the self-sufficiency level. Specifically, for the Equipment Utilization Rate (B33), its high weight under both the G1 method (subjective) and the CRITIC method (objective) reflects a strong consensus. From an objective data perspective (CRITIC), the high volatility and distinct contrast of this indicator among different operational scenarios grant it high information content; from a subjective expert perspective (G1), port energy systems involve high initial investments in assets such as wind turbines and photovoltaics. A low utilization rate directly signifies resource idleness and prolonged payback periods, which undermines both economic feasibility and energy efficiency. Therefore, the engineering significance of this consensus lies in that: improving equipment utilization rate is the most direct and critical lever to balance the economic and technical performance of port self-sufficient energy systems, thereby avoiding overcapacity and ensuring cost-effectiveness.

Second, in terms of the cloud parameters of secondary indicator evaluation, the expected values of all indicators are between 75 and 87. The expected value of carbon emission reduction is the highest, falling within the interval from good to excellent, which indicates that under the background of the dual-carbon goal, the environmental benefits of port energy systems are highly recognized. The expected value of equipment failure rate is the lowest and is at the junction of average and good, suggesting that the reliability of port equipment and maintenance management still need continuous optimization. From the perspective of entropy (*En*), the entropies of the proportion of clean energy and energy utilization rate are large, indicating that certain differences exist in the experts' scores for these indicators; these differences may stem from the differences in resource endowments and technical routes of different ports. The overall hyperentropy (*He*) is small, indicating that the experts' scoring is highly consistent and that the evaluation results are reliable.

Finally, the expected value of the comprehensive evaluation cloud is 80.938, which corresponds to the good level in the comment set, indicating that the overall planning scheme of the self-sufficiency energy systems of the Shanghai Port is at a safe level, and the risks are within an acceptable range. The entropy of the comprehensive evaluation cloud is moderate, reflecting that the evaluation results have a certain degree of uncertainty, which stems from the complexity of the indicators and the fuzziness of the experts' cognition. The hyperentropy value is small, indicating that the cohesion of the cloud droplets is high and that the comprehensive evaluation results are stable. Comparison of the comprehensive evaluation cloud chart in Fig. 3 with the standard cloud chart shows that the comprehensive cloud mainly covers the good interval and overlaps with the average and excellent intervals. This finding not only verifies the robustness of the evaluation results but also indicates potential for further optimization for some indicators.

5 CONCLUSIONS

This study addresses the comprehensive evaluation issue of port self-sufficient energy system planning schemes. A comprehensive evaluation method on the basis of G1-CRITIC combination weighting and the cloud model is constructed, and empirical analysis is performed with Shanghai Port in China as the research object. The following main conclusions are derived.

(1) A comprehensive evaluation index system for port self-sufficient energy systems is constructed; it covers five criterion levels (economic feasibility, environmental effect, energy efficiency, self-sufficiency, and reliability) and 15 secondary indicators. This system systematically reflects the multidimensional performance characteristics of port self-sufficientenergy systems and provides a scientific index basis for comprehensive evaluation.

(2) The G1-CRITIC combination weighting method is used to determine the index weights in consideration of subjective experience judgment and objective data laws. The results of the combined weights show that the weights of equipment utilization rate, system disasterresistance, and net present value rank in the top three. This result indicates that the operation efficiency, riskresistance, and economic benefits of port energy systems are the core dimensions for evaluating the self-sufficiency level.

(3) On the basis of cloud model theory, the evaluation cloud parameters of each secondary indicator are generated through the reverse cloud generator. The results show that the expected value of carbon emission reduction is the highest, and the environmental benefits are highly recognized; the expected value of equipment failure rate is the lowest, suggesting that equipment reliability still needs to be improved. The entropy and hyperentropy of the proportion of clean energy are the largest, indicating large differences among the experts' evaluations of this indicator and reflecting the notable differences in the application of clean energy among different ports.

(4) The comprehensive evaluation value is 80.938, which corresponds to the good level, indicating that the overall planning scheme of Shanghai Port's self-sufficient energy system is at a safe level, and the risk is within an acceptable range but needs to be strengthened for prevention. The entropy and hyperentropy of the comprehensive evaluation cloud are at a moderate level, verifying the stability and reliability of the evaluation results. The comprehensive cloud chart shows that the evaluation results mainly cover the good interval and have a moderate overlap with the average and excellent intervals, reflecting the robustness of the evaluation and revealing that some indicators still have room for optimization.

In summary, the evaluation method on the basis of the G1-CRITIC-cloud model can effectively deal with the fuzziness and randomness problems in the evaluation of port self-sufficient energy systems. The evaluation results objectively reflect the comprehensive level and improvement direction of the planning scheme and can provide methodological support and reference for the green transformation and scientific decision-making of port energy systems. In the future, in-depth analysis can be conducted for indicators with large entropy values, the evaluation system can be further optimized, and the overall performance and reliability of port self-sufficient energy systems can be improved.

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