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Original Research

Study on Sustainability Evaluation and Analysis for Offshore Wind Power Projects Oriented Low-Carbon

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Abstract

With the stability, high power generation and low environmental impact of offshore wind resources, offshore wind power is being used as the core power supply to promote the development of global low-carbon economy in the future. Firstly, combined with the characteristics of offshore wind power projects, this paper establishes a reasonable sustainability evaluation system from economy, reliability, environmental protection and safety. Then, in this paper, the mixed-cross weighting based on the coefficient of variation method-order relation method is constructed to determine the weight of project sustainability evaluation indexes. Finally, the function interval and form of the common origin gray clustering evaluation method are modified to determine the sustainability level of the projects. In order to verify the scientificity of the sustainability indexes and the accuracy of the evaluation model, combined with the case background of S offshore wind power project in J Province, the results show that the index that has the greatest impact on the sustainability of offshore wind power is the group participation of projects. At the same time, the improved evaluation method overcomes the problems of the inaccuracy of the rate change of the gray-crossing and membership degree of the common origin gray clustering function and makes the evaluation results more reasonable and authentic. This paper provides a reference for the investment decision of the offshore wind power project to be constructed.

Keywords: low-carbon, offshore wind power projects, sustainability evaluation, mixed-cross weighting, improved common origin gray clustering evaluation method

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Introduction

With the growth of population and economy, China will need more energy supply. At the same time, driven by the 2009 World Climate Conference in Copenhagen, "low-carbon" economy has become an important topic that current world economy grows [1]. Under the framework of the Paris Agreement, as the country with the largest carbon emission in the world, China proposes that the carbon emission per GDP in 2030 should be reduced by 60%~65% compared with that in 2005, and the proportion of non-fossil fuels should be increased to about 20%, the carbon emission will peak around 2030 and strive to reach the peak as soon as possible [2, 3]. By the end of 2020, the installed capacity of clean energy power generation in China is 820GW, accounting for 40.8% of the total installed capacity [4]. In order to speed up the large-scale development and efficient utilization of clean energy, China proposes that by 2030 and 2050, the installed capacity proportion of clean energy power generation will reach 59% and 86% respectively, the power generation proportion will reach 48% and 83% respectively, and non-fossil fuels proportion will reach 23% and 59% [5].

Offshore wind power started late, but it is being used as the core energy supply to promote the development of global low-carbon economy in the future with the stability, high power generation and low environmental impact of offshore wind resources [6]. By the end of 2020, 146 offshore wind farms have been put into operation all over the world, with a cumulative installed capacity of 27.2GW and a growth rate of 24% [7]. According to GlobalData, global offshore wind farms will grow at a growth rate of 16.2% from 2020 to 2030, and the cumulative installed capacity of offshore wind power will reach 142GW by 2030. According to statistics, a wind farm with installed capacity of 100MW and annual utilization hours of 2000h can save about 152200 t coal and reduce about 304400t carbon emission [8]. Therefore, implementing the national low-carbon development strategic deployment, developing clean energy, especially offshore wind power, and accelerating the implementation of low-carbon construction are important ways to achieve the sustainable development.

In this background, combined with the characteristics of offshore wind power projects, this paper establishes a reasonable sustainability evaluation system and puts forward an appropriate sustainability evaluation model, which provides a reference for the investment decision of offshore wind power projects to be constructed.

Literature Review

Offshore wind power evaluation is a research hotspot and important direction of clean energy power generation. The existing offshore wind power evaluation research mainly focuses on a single goal such as economy and reliability. In terms of economy, Castro-Santos et al. [9] combined the leveled cost of energy (LOCE) and the weighted average cost of capital (WACC) to study the economic parameter selection of two tariff schemes of offshore wind farm. In addition, if also add the electric tariff, the other economic parameters can be calculated: the internal rate of return (IRR) and the net present value (NPV). Alessandro et al. [10] investigated how the lowest cost for green hydrogen can be achieved. A model proposing an integrated design of the hydrogen and offshore electric power infrastructure, determining the levelized costs of both hydrogen and electricity, was proposed. Wu et al. [11] studied macro economic risks of wave-wind-solar-compressed air energy storage project, such as high initial investment, high operation and military cost, financing risk, unclear feed in tariff policy and so on, through hesitant fuzzy linguistic term sets improved triangular fuzzy number and fuzzy comprehensive evaluation method. Cheng-Ting et al. [12] collected information through questionnaire interviews and expert opinions, summarized the cage aquaculture management data regarding 3 species, including fry stocking size, fry unit price, stocking density, culture cycle, survival rate, market size, per unit area yield, sales price, feed unit price, and assessed the economic feasibility of cage aquaculture in the offshore wind farm area of Changhua, Taiwan. In terms of reliability, Yang et al. [13] employed a process-based life cycle inventory (LCI) model to calculate the life-cycle energy and emissions of offshore wind power in China based on the country's first offshore wind energy project. Horn et al. [14] designed the wind farm based on a conservative downtime fraction would lead to design conservatism with respect to the foundation, which would be quantified using a structural reliability analysis, and investigated the impact on lifetime estimation of an offshore wind turbine by introducing a stochastic model for the availability. Cevasco et al. [15] investigated trends based on the deployment parameters for the influence of design characteristics and environmental conditions on the onshore wind turbines' reliability and availability. Li et al. [16] determined reliability characteristics of a floating offshore wind turbine such as failure probability, failure rate, and mean time to failure of the floating offshore wind turbine according to the Bayesian Network predictive analysis. Gulski et al. [17] discussed offshore power cables from the perspective of reducing the risks of failure and increasing supply reliability based on international experience gathered from various projects over the last few years as well as international references. Sheng et al. [18] presented an overall simulation-based procedure to assess the fragility and reliability of offshore wind turbines (WTs) subjected to tropical cyclone (TC) hazard.

The sustainable evaluation model of offshore wind power projects is different from the evaluation of general power grid projects. There are relatively mature power grid project evaluation models, and there is no systematic research on the sustainable evaluation according to the characteristics of offshore wind power projects. Li et al. [19] applied a combination of granular computing and order relation analysis to determine the weight of each index and employed the matter-element extension evaluation model to seek the global optimal decision during the risk assessment of two different investment schemes of a transnational high voltage direct current transmission project. Li et al. [20] proposed the least squares method which combines the order relation method and the factor analysis method in order to improve the rigidity and power of weight determination, and combined technique for order preference by similarity to an ideal solution (TOPSIS), gray relation analysis method and vector projection method, effectively overcome the limitation of the one-way evaluation of power grid interconnection projects. Wang et al. [21] proposed a risk assessment method of transnational power grid projects combined with risk theory and probabilistic model, which can not only consider the uncertainties but also integrate the probability of accidents with consequences. Hu et al. [22] established a dynamic comprehensive evaluation model of power industry development level by aggregating the static evaluation model for each time period based on a time-ordered weighting vector calculated using time-ordered information entropy. Tan et al. [23] constructed an integrated weight model with subjective and objective weight method, and proposed the ideal matter element extension evaluation model and the gray clustering evaluation model for the wind farms site selection. Liu et al. [24] used the entropy method to determine the index weight that affect the collaborative decision-making of wind-storage combined power generation systems, and designed three collaborative decision-making models, namely, a collaborative decision-making model based on the entropy weight method-fuzzy comprehensive evaluation method, a collaborative decision-making model based on the entropy method-TOPSIS, and a collaborative decision-making model based on fuzzy TOPSIS.

Referring to the above literature, this paper establishes a reasonable sustainability evaluation system of offshore wind power projects from the economy, reliability, environmental protection and safety. At the same time, the mixed-cross weighting method based on the coefficient of variation method-order relation method and the improved common origin gray clustering evaluation method based on centralized parabolic function are innovatively proposed to evaluate the sustainability of offshore wind power projects, which makes the evaluation results more reasonable and authentic.

Sustainability Evaluation Index System of Offshore Wind Power Projects

Sustainability Evaluation Index System

Firstly, compared with onshore wind power, the operation and maintenance cost of offshore wind power is higher [25], and the construction time of offshore wind power projects should be determined according to sea conditions and tide level. Secondly, the environment of offshore wind power projects is strong wind, high salt and high humidity, project reliability should be fully considered in the design and material selection. Then, with the gradual transfer of wind power layout to the eastern and southern regions, the environmental protection problem of offshore wind power projects development and construction is becoming more

Table 1. Sustainability evaluation index system of offshore wind power projects.

Object	First-Level Index	Second-Level Index
Sustainability evaluation index system of offshore wind power projects G	Economy A	Unit cost of electricity A1
		Financial net present value A2
		Payback period A3
	Reliability B	Average annual availability of offshore wind turbine B1
		Group participation of projects B2
		Energy availability B3
	Environmental protection C	Comprehensive energy consumption efficiency C1
		Constrained amount of coal resource consumption C2
		Reduced greenhouse gas emissions C3
	Safety D	Adaptability of offshore wind turbine D1
		Maturity of offshore wind power technology D2
		Mean time between failures of the project D3

and more important. The national development and reform commission issue the notice on relevant requirements for wind power construction management in 2005 to further clarify the environmental protection requirements. Finally, according to the latest report of G + global offshore wind health and safety organization, 252 "high-risk accidents" and 62 personal injury accidents occurred in the global offshore wind power industry in 2020, with a significant increase [26]. Based on the above factors, from the national level and the whole industrial chain, offshore wind power projects must develop in a balanced way. This paper selects representative sustainability evaluation index system of offshore wind power projects from the perspective of economy, reliability, environmental protection and safety, as shown in Table 1.

Analysis of the Sustainability Evaluation Index

Economy

1. Unit Cost of Electricity

Unit cost of electricity L_c is the power generation cost obtained by leveling the comprehensive cost and power generation in the life cycle of offshore wind power project, that is, the ratio of cost present value and power generation in the life cycle. Its calculation method is shown in formula (1).

$$L_c = \frac{I - \frac{V_R}{(1+i)^{n_p}} + \sum_{t=1}^{n_p} \frac{(P_t + Q_t)}{(1+i)^t}}{\sum_{t=1}^{n_p} Y_t} \tag{1}$$

Where I is the total investment of the project; V_R is the residual value; n_p is the operating cycle; i is the social discount rate; P_t, Q_t and Y_t are the operation and maintenance cost, interest and actual power generation of the project in year t, respectively.

2. Financial Net Present Value

Financial net present value NPV is the difference between the present value of the total income and the total expenditure of the project investment scheme, that is, the sum of the net cash flow during the life of the project. Its calculation method is shown in formula (2).

$$NPV = \sum_{t=1}^{n_p} \frac{G_t}{(1+i)^t} \tag{2}$$

Where G_t is the net cash flow in year t; n_p is the operating cycle; i is the social discount rate.

3. Payback Period

Payback period T_p is the time required for the net income of each year to recover all the investment from the project construction and operation. Its calculation method is shown in formula (3).

$$\sum_{t=1}^{T_p} G_t = \sum_{t=0}^{T_p} (B - C)_t = I \tag{3}$$

Where I is the total investment of the project; B_t and C_t are the income and expenditure in year t, respectively; G_t is the net cash flow in year t.

Reliability

1. Average annual availability of offshore wind turbine

Average annual availability of offshore wind turbine μ is an important parameter for evaluating the operation reliability of offshore wind power and ensuring the return of project capital [27]. Its calculation method is shown in formula (4) and formula (5).

$$\mu_r = \frac{T_r^k}{8760 - T_r^f} \times 100\% \tag{4}$$

$$\mu = \frac{\sum_{r=1}^{N} \mu_r}{N} \tag{5}$$

Where μ_r is the annual availability of offshore wind turbine $r(r = 1, 2, ..., N)$; N is the number of offshore wind turbines; T_r^k and T_r^f are the available hours and shutdown hours not the responsibility of the bidder of offshore wind turbine r, respectively; 8760 is the annual hours.

2. Group participation of projects

Group participation of projects is the degree of group participation or understanding of offshore wind power projects. The index value can be obtained by questionnaire survey.

3. Energy availability

Energy availability η is the ratio of actual power generation to theoretical power generation [28, 29]. Its calculation method is shown in formula (6).

$$\eta = \frac{\sum_{t=1}^{n_p} Y_t}{\sum_{t=1}^{n_p} X_t} \tag{6}$$

Where Y_t and X_t are the actual power generation and theoretical power generation, respectively. They can be counted by the data acquisition and monitoring control system.

Environmental Protection

1. Comprehensive energy consumption efficiency

Offshore wind power projects can improve the comprehensive energy consumption efficiency E' of society. According to the relevant provisions of general rules for calculation of comprehensive energy consumption (GB/T 2589-2020), the comprehensive energy consumption efficiency reflects the energy-saving effect produced by the construction and implementation of the projects [30]. Its calculation method is shown in formula (7).

$$E' = \frac{E}{O} \tag{7}$$

Where E is comprehensive energy consumption value of the project in the current year; O is the net output.

2. Constrained amount of coal resource consumption

Offshore wind power projects realize the clean substitution of regional traditional thermal power through the grid connected transmission of clean energy, so as to effectively reduce the combustion and utilization of fossil energy resources such as coal in the power industry and optimize the energy structure. The calculation method of constrained amount of coal resource consumption τ^* is shown in formula (8).

$$\tau^* = \tau' - \tau \tag{8}$$

Where τ' and τ are average coal resource consumption of the power industry after the project construction and at present, respectively.

3. Reduced greenhouse gas emissions

The construction of offshore wind power projects will contribute to the development and utilization of clean energy, reduce greenhouse gas emissions and achieve the temperature control objectives of the United Nations Framework Convention on climate change. The calculation method of Reduced greenhouse gas emissions θ^* is shown in formula (9).

$$\theta^* = \theta' - \theta \tag{9}$$

Where θ' and θ are average greenhouse gas emissions of the power industry after the project construction and at present, respectively.

Safety

1. Adaptability of offshore wind turbine

The adaptability of offshore wind turbine is the safety of the turbine and the adaptability of the complex offshore environment. The safety of the wind turbine is that the selected wind turbine shall meet the requirements of the safe wind speed of the wind farm. The adaptability of the complex offshore environment mainly includes that the wind turbine must have strong performance of moisture resistance, salt fog resistance, corrosion resistance, icing resistance and low temperature resistance. The index value can be obtained by expert consultation.

2. Maturity of offshore wind power technology

The maturity of offshore wind power technology is the ability of integrated design of offshore wind turbine. The index value can be obtained by expert consultation.

3. Mean time between failures of the project

The mean time between failures of the project σ is the mathematical expected value of the operation time between two adjacent failures of the offshore wind power project, that is, the average value of the operation time between each two adjacent failures. Its calculation method is shown in formula (10).

$$\sigma = \frac{n_p}{k_p} \tag{10}$$

Where n_p is the operating cycle; k_p is the number of adjacent failures during the operating cycle n_p.

Sustainability Evaluation Model of Offshore Wind Power Projects

Based on the construction of the sustainability evaluation index system of offshore wind power projects, this paper proposes the mixed-cross weighting method based on the coefficient of variation method-order relation method and the improved common origin gray clustering evaluation method to establish the sustainability evaluation model. The specific process is shown in Fig. 1.

The Mixed-Cross Weighting Method Based on the Coefficient of Variation Method-Order Relation Method

Among the methods for determining the weight of sustainability evaluation, it mainly includes the analytic hierarchy process and the order relation method [31] for subjectively determining the weight of evaluation indexes, and the coefficient of variation method [32] for making full use of the objective information of data to determine the evaluation indexes. In order to effectively avoid the disadvantage that the order relation method or the coefficient of variation method cannot reflect the objective data information or the subjective intention of decision-making. Then, in this paper, the ratio of importance degree of adjacent indexes is determined by the coefficient of variation method, instead of the order relation method, the mixed-cross weighting based on the coefficient of variation method-order relation method is constructed. Its basic step is as follows:

Step 1: Determine the ordering relation of importance degree of sustainability indexes $\{x_i\}(i = 1, 2, ..., m)$.

Step 2: Introduce the index data of m similar projects, and calculate the variation coefficient V_i of the sustainability index i. Its calculation method is shown in formula (11) and formula (12).

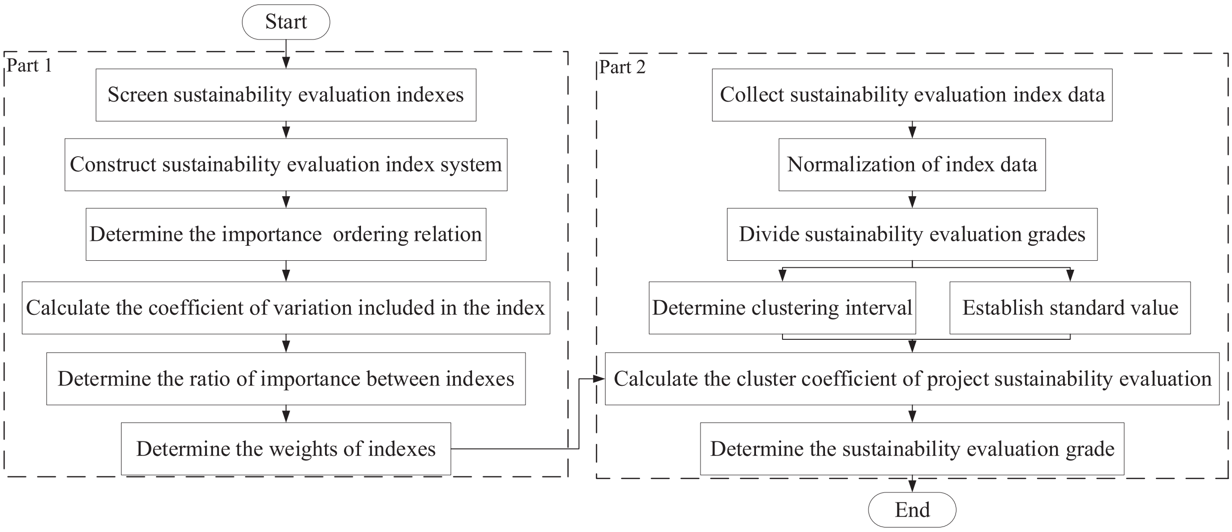

Fig. 1. Flow chart of sustainability evaluation model of offshore wind power projects.

$$\sigma_i=\sqrt{\frac{\sum_{j=1}^{n}\left(c_{ij}-\overline{C}_i\right)^2}{n}} \tag{11}$$

$$V_i=\frac{\sigma_i}{\overline{C}_i} \tag{12}$$

Where σ_i is the standard deviation of the index i; c_{ij} is the standardized data of the index i in the project j, (i = 1, 2, ..., m; j = 1, 2, ..., n); $\overline{C}_i$ is the average index value of the index i.

Step 3: The ratio r_i of importance degree of adjacent indexes x_{i-1} and x_i is determined by the coefficient value of variation, which is shown in formula (13).

$$r_i=\begin{cases}\frac{V_{i-1}}{V_i}, V_{i-1}\geq V_i\\ 1, \quad V_{i-1}<V_i\end{cases} \tag{13}$$

Step 4: According to the value r_i, the mixed cross weight w_m of the sustainability index m can be obtained in formula (14).

$$w_m=\frac{1}{1+\sum_{z=2}^{m}\prod_{i=z}^{m}r_i} \tag{14}$$

Step 5: The calculation method of the weight of the sustainability index m–1, m–2, ...,1 can be obtained from the weight w_m, that is shown in formula (15).

$$w_{i-1}=r_iw_i, i=m, m-1, ..., 3, 2 \tag{15}$$

Where w_{i-1} and w_i are the mixed-cross weight of the index i–1 and i, respectively.

The Improved Common Origin Gray Clustering Evaluation Method

The common origin gray clustering analysis method [33] uses the common origin to determine the clustering function. When the evaluation index and the corresponding sustainability grade are determined, take the standard value of each sustainability grade as the center, fuzzy extension is carried out to both sides, and the left side is the common origin, so as to finally distinguish the evaluation grade of each index under its sustainability cluster.

Although the common origin gray clustering has been applied in some fields, in the primitive function, when the standard value λ of each gray clustering has small differences, the gray interval of clustering k is crossed with that of clustering k+1 or above, so that the same sustainability index distributed in different gray clustering intervals, and the evaluation results are unreasonable. At the same time, the sustainability index under the primitive function changes at a fixed rate from one grade to another, which does not reflect the gravitational effect of clustering. In view of the problems existing in the common origin gray clustering method, this paper modifies the primitive function interval, which is constructed with the (λ_k, 1) of clustering k as the maximum membership point, the (λ_{k-1}, 0) and (λ_{k+1}, 0) of clustering k–1 and k+1 as the starting point and end point. Combined with the trend of quadratic function and the increasing change of membership degree, this paper constructs the composite „S" function form of two quadratic function, and innovatively proposes an improved common origin gray clustering evaluation method based on centralized parabolic function, which not only overcomes the problem of intersection of multiple gray clustering intervals of the primary function, but also when the sustainability index just enters a certain gray clustering interval, it is in the adaptation stage, and the gravitational effect increases gradually. When the membership function value of sustainability index reaches 1/2, the sustainability index begins to approach the standard value, and the gravitational effect gradually tends to be stable, so that the evaluation results more reasonable and authentic. Assuming that the standardized data of sustainability index x_i is c_i, it is divided into h gray clustering, and the standardized data of the gray clustering $k(k = 1, 2, ..., h)$ is λ_{ik}, the basic steps of the improved common origin gray clustering evaluation method are as follows:

Step 1: Combined with the trend of quadratic function, take 1/2 as the turning point to construct the composite "*S*" function form of two quadratic function, and finally connect $(\lambda_{i\cdot(k-1)}, 0)$, $\left(\frac{\lambda_{i\cdot(k-1)}+\lambda_{ik}}{2}, \frac{1}{2}\right)$, $(\lambda_{ik}, 1)$, $\left(\frac{\lambda_{ik}+\lambda_{i\cdot(k+1)}}{2}, \frac{1}{2}\right)$, $(\lambda_{i\cdot(k+1)}, 0)$ with smooth curves as the clustering function $f_k(x_i)$ of index x_i in clustering k, which is shown in formula (16), formula (17) and formula (18).

$$f_k(x_i)=\begin{cases} 1 & c_i\in[0,\lambda_{ik}) \\ 1-\dfrac{2c_i^2-4\lambda_{ik}\cdot c_i+2\lambda_{ik}^2}{\lambda_{ik}^2+\lambda_{i\cdot(k+1)}^2-2\lambda_{ik}\cdot\lambda_{i\cdot(k+1)}} & c_i\in\left[\lambda_{ik},\dfrac{\lambda_{ik}+\lambda_{i\cdot(k+1)}}{2}\right) \\ \dfrac{2c_i^2-4\lambda_{i\cdot(k+1)}\cdot c_i+2\lambda_{i\cdot(k+1)}^2}{\lambda_{ik}^2+\lambda_{i\cdot(k+1)}^2-2\lambda_{ik}\cdot\lambda_{i\cdot(k+1)}} & c_i\in\left[\dfrac{\lambda_{ik}+\lambda_{i\cdot(k+1)}}{2},\lambda_{i\cdot(k+1)}\right) \end{cases} \quad k=1 \tag{16}$$

$$f_k(x_i)=\begin{cases} \dfrac{2c_i^2-4\lambda_{i\cdot(k-1)}\cdot c_i+2\lambda_{i\cdot(k-1)}^2}{\lambda_{i\cdot(k-1)}^2+\lambda_{ik}^2-2\lambda_{i\cdot(k-1)}\cdot\lambda_{ik}} & c_i\in\left[\lambda_{i\cdot(k-1)},\dfrac{\lambda_{i\cdot(k-1)}+\lambda_{ik}}{2}\right) \\ 1-\dfrac{2c_i^2-4\lambda_{ik}\cdot c_i+2\lambda_{ik}^2}{\lambda_{i\cdot(k-1)}^2+\lambda_{ik}^2-2\lambda_{i\cdot(k-1)}\cdot\lambda_{ik}} & c_i\in\left[\dfrac{\lambda_{i\cdot(k-1)}+\lambda_{ik}}{2},\lambda_{ik}\right) \\ 1-\dfrac{2c_i^2-4\lambda_{ik}\cdot c_i+2\lambda_{ik}^2}{\lambda_{ik}^2+\lambda_{i\cdot(k+1)}^2-2\lambda_{ik}\cdot\lambda_{i\cdot(k+1)}} & c_i\in\left[\lambda_{ik},\dfrac{\lambda_{ik}+\lambda_{i\cdot(k+1)}}{2}\right) \\ \dfrac{2c_i^2-4\lambda_{i\cdot(k+1)}\cdot c_i+2\lambda_{i\cdot(k+1)}^2}{\lambda_{ik}^2+\lambda_{i\cdot(k+1)}^2-2\lambda_{ik}\cdot\lambda_{i\cdot(k+1)}} & c_i\in\left[\dfrac{\lambda_{ik}+\lambda_{i\cdot(k+1)}}{2},\lambda_{i\cdot(k+1)}\right) \end{cases} \quad k=2, 3, ..., h-1 \tag{17}$$

$$f_k(x_i)=\begin{cases} \dfrac{2c_i^2-4\lambda_{i\cdot(k-1)}\cdot c_i+2\lambda_{i\cdot(k-1)}^2}{\lambda_{i\cdot(k-1)}^2+\lambda_{ik}^2-2\lambda_{i\cdot(k-1)}\cdot\lambda_{ik}} & c_i\in\left[\lambda_{i\cdot(k-1)},\dfrac{\lambda_{i\cdot(k-1)}+\lambda_{ik}}{2}\right) \\ 1-\dfrac{2c_i^2-4\lambda_{ik}\cdot c_i+2\lambda_{ik}^2}{\lambda_{i\cdot(k-1)}^2+\lambda_{ik}^2-2\lambda_{i\cdot(k-1)}\cdot\lambda_{ik}} & c_i\in\left[\dfrac{\lambda_{i\cdot(k-1)}+\lambda_{ik}}{2},\lambda_{ik}\right) \\ 1 & c_i\in[\lambda_{ik},\infty) \end{cases} \quad k=h \tag{18}$$

Step 2: Combined with the weight w_i of index x_i, the clustering coefficient η_k of sustainability evaluation in clustering k is calculated in formula (19).

$$\eta_k=\sum_{z=1}^{m} w_z\cdot f_k(x_z) \tag{19}$$

Step 3: According to the principle of maximum membership, if $\eta_q = \max\{\eta_k\}$, the sustainability belongs to grade q.

In summary, when the standard value λ of each gray clustering has small differences in the primitive function, the gray interval of clustering k is crossed with that of clustering k+1 or above, so that the same sustainability index distributed in different gray clustering intervals, and the evaluation results are unreasonable. This paper improves the primitive function interval, which is constructed with the $(\lambda_k, 1)$ of clustering k as the maximum membership point, the $(\lambda_{k-1}, 0)$ and $(\lambda_{k+1}, 0)$ of clustering k–1 and k+1 as the starting point and end point, overcomes the problem of intersection of multiple gray clustering intervals of the primary function.

Meanwhile, the primary common origin gray clustering function is in a straight line, where the sustainability index under the primitive function changes at a fixed rate from one grade to another, and does not reflect the gravitational effect of clustering. This paper constructs the composite "*S*" function form of two quadratic function combined with the trend of quadratic function and the increasing change of membership degree. When the sustainability index just enters a certain gray clustering interval, it is in the adaptation stage, and the gravitational effect increases gradually. When the membership function value of sustainability index reaches 1/2, the sustainability index begins to approach the standard value, and the gravitational effect gradually tends to be stable, so that the evaluation results are more reasonable and authentic.

Case Study

On the basis of the case background of the study [34], combined with the existing case background of S offshore wind power project in J Province, this paper perfects and supplements the necessary parameters and data not clearly given in the study, makes a case study by using the evaluation index system and evaluation model established in this paper, and briefly analyzes the evaluation results.

Data Collection of Project Sustainability Evaluation Indexes

Collect the sustainability evaluation index data of S offshore wind power project from the project operation unit, and feedback the evaluation index data to experienced offshore wind power project operation management personnels and experts, and then according to the Normalization Standard, such as the Economic Evaluation Methods and Parameters of Construction Projects (Third Edition) and the provisions on the content and depth of Feasibility Study of Power Transmission and Transformation Project of State Grid Corporation of China (for Trial Implementation), the experts score the collected evaluation index data according to the project experience to obtain the normalization results as shown in Table 2.

It can be seen from Table 2 that the financial net present value, average annual availability of offshore wind turbine, group participation of projects, energy availability, mean time between failures of the project are good sustainability indexes, but the comprehensive energy consumption efficiency and payback period are poor. The sustainability of offshore wind power project S is difficult to determine. This paper uses the mixed-cross weighting method based on the coefficient of variation method-order relation method and the improved common origin gray clustering evaluation method proposed in this paper to comprehensively evaluate the project S.

Weight Calculation of Project Sustainability Evaluation Indexes

According to the needs of the project, this paper provides selected evaluation index to 10 experts in the fields of offshore wind power technology, economy, environmental protection, project safety and so on.

Table 2. Each index data and normalization results of offshore wind power project S.

Index	Index data	Normalization result
A1	1.12 yuan/kwh	0.71
A2	1237 million	0.87
A3	10.5 years	0.68
B1	99.25%	0.88
B2	92.43%	0.82
B3	97.84%	0.91
C1	1400 tons standard coal/ million	0.59
C2	142534 million tons	0.74
C3	374685 million tons	0.77
D1	84/100	0.84
D2	86/100	0.86
D3	3726 h	0.93

1. After discussion by 10 experts and combined with the characteristics of project sustainability evaluation, the ordering relation of evaluation indexes is finally determined: B2>A2>B1>D1>A1>C2>A3>C1>C3>D3>D2>B3.
2. This paper introduces the relevant data of 10 similar project cases, calculates the numerical difference of each index, and obtains the coefficient of variation V_i of each index, as shown in Table 3.
3. According to $r_i = \begin{cases} \frac{V_{i-1}}{V_i}, V_{i-1} \geq V_i \\ 1, \quad V_{i-1} < V_i \end{cases}$, the ratio r_i of index importance degree is shown in Table 4.
4. According to $W_{B3} = \frac{1}{1+\sum_{k=2}^{12}\prod_{i=k}^{12} r_i}$, $W_{B3} = 0.0008$ is calculated. Then, the weight of each index is obtained through $W_{i-1} = r_i W_i$, as shown in Table 5.

It can be seen from Table 5 that the index that has the greatest impact on the sustainability of offshore wind power projects is the group participation of projects, with a weight of 0.1977, because it can make the project sustainable only if the whole society fully understands the offshore wind power projects. The second is the financial net present value, with a weight of 0.1601, because the direct benefits brought by the construction and operation of a project should be reflected in the economic benefits brought by the project. This paper studies the sustainability evaluation of offshore wind power projects oriented low-carbon, so the environmental protection index of offshore wind power projects also accounts for a large proportion, with a total weight of 0.1965.

Grade Determination of Project Sustainability Evaluation Indexes

1. The sustainability evaluation grade of offshore wind power projects is divided into five different grades: worse, bad, general, good and batter, corresponding to $N = (N_1, N_2, N_3, N_4, N_5)$. The score range of each grade is divided as shown in Table 6.
2. The evaluation grade and index system are fed back to the experts in relevant fields of offshore wind power projects. The experts divide each sustainability evaluation index grade of offshore wind power project into gray grades according to the project experience, as shown in Table 7.
3. The standard value under each grade is determined according to the mean value of the upper and lower limits of each index grade in Table 7. The calculation results are shown in Table 8.
4. In this paper, the clustering coefficients of sustainability evaluation of offshore wind power projects are calculated according to the primitive and improved common origin gray clustering evaluation function. The calculation results are shown in Table 9.

Table 3. The coefficient of variation of each index of offshore wind power project S.

Index	A1	A2	A3	B1	B2	B3
Coefficient of variation	1.4234	2.5520	1.2816	1.7391	3.1513	0.0128
Index	C1	C2	C3	D1	D2	D3
Coefficient of variation	1.0058	1.3135	0.8129	1.6769	0.4399	0.5324

Table 4. The ratio of index importance degree of offshore wind power project S.

r_i	$r_2\left(\frac{D2}{B3}\right)$	$r_3\left(\frac{D3}{D2}\right)$	$r_4\left(\frac{C3}{D3}\right)$	$r_5\left(\frac{C1}{C3}\right)$	$r_6\left(\frac{A3}{C1}\right)$	$r_7\left(\frac{C2}{A3}\right)$
Value	34.5000	1.2101	1.5269	1.2373	1.2742	1.0249
r_i	$r_8\left(\frac{A1}{C2}\right)$	$r_9\left(\frac{D1}{A1}\right)$	$r_{10}\left(\frac{B1}{D1}\right)$	$r_{11}\left(\frac{A2}{B1}\right)$	$r_{12}\left(\frac{B2}{A2}\right)$	
Value	1.0837	1.1781	1.0371	1.4675	1.2349	

Table 5. The weight of each index of offshore wind power project S.

Index	A1	A2	A3	B1	B2	B3
Weight	0.0893	0.1601	0.0804	0.1091	0.1977	0.0008
Index	C1	C2	C3	D1	D2	D3
Weight	0.0631	0.0824	0.0510	0.1052	0.0276	0.0334

Table 6. Division rule of grades.

Evaluation Grade (*N*)	N_1	N_2	N_3	N_4	N_5
Score range	[0, 0.6]	[0.6, 0.7]	[0.7, 0.8]	[0.8, 0.9]	[0.9, 1]
Evaluation effects	Worse	Bad	General	Good	Better

Table 7. Index grade division of sustainability evaluation of offshore wind power project S.

Index	Worse	Bad	General	Good	Better
A1	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
A2	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
A3	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
B1	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
B2	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
B3	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
C1	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
C2	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
C3	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
D1	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
D2	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1
D3	0~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1

Table 8. The standard value of sustainability evaluation of offshore wind power project S.

Index	Worse	Bad	General	Good	Better
A1	0.30	0.65	0.75	0.85	0.95
A2	0.30	0.65	0.75	0.85	0.95
A3	0.30	0.65	0.75	0.85	0.95
B1	0.30	0.65	0.75	0.85	0.95
B2	0.30	0.65	0.75	0.85	0.95
B3	0.30	0.65	0.75	0.85	0.95
C1	0.30	0.65	0.75	0.85	0.95
C2	0.30	0.65	0.75	0.85	0.95
C3	0.30	0.65	0.75	0.85	0.95
D1	0.30	0.65	0.75	0.85	0.95
D2	0.30	0.65	0.75	0.85	0.95
D3	0.30	0.65	0.75	0.85	0.95

Table 9. Comparison on sustainability evaluation results calculated two different ways

Index	The primitive evaluation function					The improved evaluation function				
	Worse	Bad	General	Good	Better	Worse	Bad	General	Good	Better
A1	0.00	0.91	0.95	0.84	0.75	0.00	0.32	0.68	0.00	0.00
A2	0.00	0.66	0.84	0.98	0.92	0.00	0.00	0.00	0.92	0.08
A3	0.00	0.95	0.91	0.80	0.72	0.00	0.98	0.18	0.00	0.00
B1	0.00	0.65	0.83	0.96	0.93	0.00	0.00	0.00	0.82	0.18
B2	0.00	0.74	0.91	0.96	0.86	0.00	0.98	0.18	0.82	0.00
B3	0.00	0.60	0.79	0.93	0.96	0.00	0.00	0.00	0.32	0.68
C1	0.02	0.91	0.79	0.69	0.62	0.06	0.28	0.00	0.00	0.00
C2	0.00	0.86	0.99	0.87	0.78	0.00	0.02	0.98	0.00	0.00
C3	0.00	0.82	0.97	0.91	0.81	0.00	0.08	0.92	0.08	0.00
D1	0.00	0.71	0.88	0.99	0.88	0.00	0.00	0.02	0.98	0.00
D2	0.00	0.68	0.85	0.99	0.91	0.00	0.00	0.00	0.98	0.02
D3	0.00	0.57	0.76	0.91	0.98	0.00	0.00	0.00	0.08	0.92
η_k	0.00	0.76	0.88	0.92	0.84	0.00	0.32	0.24	0.54	0.06

It can be seen from Table 9 that the evaluation results calculated by two different ways are the same, which are „good". By analyzing the sustainability indexes of project S, it can be found that the project S has better profits, more reliable technical support and better social benefits. Therefore, the sustainability evaluation result is „good", which is same with the evaluation result calculated by the improved common origin gray clustering evaluation method.

But each index of the primitive evaluation function basically intersects across different gray clustering intervals, which is inconsistent with the reality. The improved evaluation function obviously overcomes this point and the calculation is more simple.

Conclusions

Offshore wind power started late, but it is being used as the core energy supply to promote the development of global low-carbon economy in the future with the stability, high power generation and low environmental impact of offshore wind resources. Under this background, combined with the characteristics of offshore wind power projects, this paper establishes a reasonable sustainability evaluation system of offshore wind power projects from the economy, reliability, environmental protection and safety, and the evaluation indexes are more comprehensive. At the same time, an innovative method to determine the weight is proposed, so that the weight can reflect the objective information and the subjective intention of decision-makers at the same time. From the weight results, it can be seen that the index that have the greatest impact on the sustainability of offshore wind power projects are the group participation and financial net present value of offshore wind power projects, and the environmental protection indexes also account for a large proportion. The improved common origin gray clustering evaluation method overcomes the shortcomings of evaluation problems to a certain extent and improves the accuracy of evaluation. At the same time, it also provides a reference for the investment decision of the offshore wind power project to be constructed.

From the perspective of sustainable development, this paper puts forward some measures and suggestions on the economy, reliability, environmental protection and safety of offshore wind power industry:

1. Based on the existing marine survey and research results in China, combined with the preliminary results of the planning and site selection of offshore wind farms in coastal provinces (municipalities directly under the central government and autonomous regions), select representative survey areas, arrange marine hydrometeorological observation towers, carry out marine wind energy resource observation and storage evaluation, analyze the seabed conditions, geological conditions, hydrodynamic conditions, and conduct a comprehensive survey of basic data.
2. Comprehensively investigate and evaluate the construction and operation of existing offshore wind farms, including the construction progress of wind farms under construction, the operation of existing wind farms, practical problems in the process of construction and operation, and the investment income of wind farms, so as to provide a basis for the scientific development of offshore wind power industry.
3. Through the construction of offshore wind power demonstration base and multi energy complementary independent demonstration power station, establish and improve standards and procedures and specifications in engineering survey, basic design, wind turbine selection, wind farm construction technology, operation management and maintenance. At the same time, strengthen the management of technical specifications for wind farm construction, and implement the technical standards and regulations of wind power equipment.

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Conflict of Interest

The authors declare no conflict of interest.

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