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Research on Wind Turbine Location and Wind Energy Resource Evaluation Methodology in Port Scenarios

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Abstract: Wind energy is widely distributed in China as a renewable energy source. Aiming to alleviate the issues resulting from fossil fuel consumption faced by developing and developed countries (e.g., climate change) and to meet development needs, this study innovatively proposed methods for the location selection of wind farms and wind turbines in port areas based on the fuzzy comprehensive evaluation method. Considering that the wind turbine location is crucial to wind power generation, this paper focuses on locating wind turbines within a specific set of sea ports. The primary objectives of this paper are to evaluate the potential of wind power generation under different port scenarios and develop a method for assessing the potential of wind energy resources in wind farm areas. Firstly, a method is proposed for identifying the boundaries of wind farms in the port areas and locating wind turbines at sea ports. Furthermore, this study used the National Aeronautics and Space Administration (NASA) wind speed database to test the proposed method with the real-world wind power projects of the Ports of Tianjin, Shanghai, Xiamen, Shenzhen, and Hainan, which are top ports within five major coastal port clusters in China. It is found that the potential power generation capacity of the wind power farms at the above ports is 30.71 GWh, 19.82 GWh, 16.72 GWh, 29.45 GWh, and 24.42 GWh, respectively. Additionally, sensitive results for different types of wind turbines are conducted in the following experiment. The results of this study are fundamental for enriching the research of evaluating wind energy resources of sea ports and promoting the development and use of clean energy in practical environments. Further, the method proposed in this study is essential for optimizing the location and construction of wind turbines, which may help ports in adopting a low-carbon and green development path, thereby mitigating air pollution, and promoting sustainable development.

Keywords: port scenarios; wind turbine location; wind resource evaluation; wind power generation evaluation; indicator evaluation system

1. Introduction

With the continuous depletion of non-renewable energy sources, such as coal and oil, the shortage of fossil energy and the search for renewable energy have become new problems facing the development of the world. The primary sources of renewable energy are the sun, wind, ocean, etc., which have the advantages of large reserves and low emissions, among which wind energy is also considered as renewable energy with the most potential for development [1]. Based on a recent estimation, China has abundant wind energy resources, and reserves have reached 4350 GW [2]. Furthermore, with the current technical support, about 1000 GW of land-based wind energy and about 200 GW of



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Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). offshore wind energy can be developed [3]. Meanwhile, the 18th Party Congress report released by China's government also pointed out that it was urgent to strengthen energy conservation and reduce consumption to support the development of energy-saving, low-carbon industries and the development of new energy, renewable energy, to ensure national energy security [4]. Therefore, it is crucial to carry out relevant research on wind energy development. At present, development of wind energy is primarily distributed in its western part and the coastal regions [5]. This paper focuses on wind power generation within the coastal port area. Specifically, this paper targets a study of how to locate the wind farm area and wind turbines scientifically and rationally and proposes the corresponding methods. Following the location decision-making process, this paper further proposes methods for evaluating the scale of wind energy resources and wind power generation in port areas.

Based on a literature review, it is found that substantial research efforts by scholars have been dedicated to determining optimal locations for wind farms, which can be categorized into the locations of onshore or offshore wind farms. This dichotomy highlights the importance of considering distinct environments for developing wind energy projects. Beyond location selection, a parallel line of inquiry has emerged, emphasizing the necessity for a rational and scientific approach to site wind farms. Scholars in this domain investigate not only the geographical aspect but also delve into the broader implications of wind farm locations, including their impacts on the life cycle of wind farms and pricing of the electricity market. Moreover, the specific decision-making process regarding the location of individual wind turbines within a wind farm has been a focal point in numerous studies. Researchers have explored innovative methods and technologies to optimize turbine locations within a given wind farm, considering factors such as safety, efficiency, and environmental impact.

The literature review carried out for this paper also underscores the existence of mainstream databases, such as ECMWF, AROME, ERA5, and CERRA2, proposed and developed for evaluating wind energy resources and power generation. These databases serve as valuable tools for researchers, providing data for comprehensive assessments. However, it is noted that while extensive research has been conducted on wind farm locations and resource evaluations, there remains a relative shortfall of studies focusing on evaluating the potential of wind power at different locations. In addition, the majority of existing research has concentrated on offshore wind farm optimization, leaving a gap in the exploration of onshore port areas for wind farm locations and wind power generation. This highlights the need for further investigation and is the basis for this study.

Therefore, this paper targets developing a method for locating the wind farm and turbine in port areas and further studies methods for evaluating wind resources and power from port turbines. Firstly, based on the proposed methods, the boundary of the port wind farm is defined, and then a facility location method for port wind farm and port turbine selection is proposed. After reasonable wind farm and turbine sites are selected, this paper proposes methods to evaluate wind resource and wind power generation from wind turbines in port areas. Finally, this paper takes the wind power generation projects in China's coastal port clusters as examples to test and validate the proposed model.

Thus, the main contributions of this paper are as follows: (1) novel methods for selecting wind farms and turbine sites, and (2) novel methods for evaluating wind resource and power generation from wind turbines in port areas.

The remainder of this paper is organized as follows: Section 2 presents the literature review. Section 3 investigates the methodology for locating wind farm areas and wind turbines. Section 4 examines the methodology for evaluating wind energy resources and wind power generation in port areas. Section 5 provides the case study based on the wind power generation projects at China's coastal port clusters. Section 6 presents the results and discussion. Section 7 presents the conclusions, limitations, and future recommendations.

2. Literature Review

In recent years, scholars have conducted extensive research for determining the locations of wind farms using different methods, which can be divided into two categories: onshore wind farm location selection and offshore wind farm location selection. In the field of onshore wind farm location selection, existing research mainly adopts the multiple criteria decision making (MCDM) method, multiple attribute decision making (MADM) methods, and mathematical modelling to realize location selection. With regard to the MCDM or MADM method, Yeh et al. [6] examined the key factors considered in determining the locations of wind farms. Then, many methods to optimize the wind farm location were proposed. Gigović et al. [7] developed a reliable model for the identification of locations for the installation of wind farms. Konstantinos et al. [8] presented a methodology based on AHP and GIS to determine the most suitable locations for wind farm installation. Xenitidis K. et al. [9] proposed a methodology based on computational geometry and geographical information systems (GIS) to cluster the locations of wind turbines (WT) and define the boundaries of the areas that are affected by them. Saraswat et al. [10] looked into the technical, economic, and socio-environmental aspects of solar and wind farm locations in India to determine how suitable they are spatially in relation to the mathematical model. Wimhurst et al. [11] introduced a logistic regression model that predicts suitable sites for state-level and nationwide wind energy development in the United States. In the field of offshore wind farms location selection, existing research also mainly adopts the multiple criteria decision making (MCDM) method, multiple attribute decision making (MADM) methods, and mathematical modelling to realize location selection. With regard to the MCDM or MADM method, in order to support the Republic of Ghana's aim for the growth of renewable energy, Fahd et al. [12] looked into the site counter of wind farms and proposed a novel method for locating and optimizing the site contour of wind farms within the framework of transmission expansion plans. Díaz and Soares [13] developed a decision tool for planning offshore wind farm locations, combining multi-criteria decision analysis and geographic information systems. Díaz H. et al. [14] introduced a novel procedure to optimize wind turbines' placement in a wind farm. With regard to mathematical modelling, Díaz et al. [15] created a Monte Carlo simulation process that applies decision makers' subjective judgments along with key decision factors to determine the best locations for wind farms. Irawan, Salhi, and Chan [16] introduced a novel algorithm that integrates a genetic algorithm, variable neighborhood search, and a Weiszfeld-based algorithm to examine the integrated continuous location. Díaz H. and Soares C. G. [17] proposed a cost and financial evaluation model for floating wind farm designs. Acaroğlu and Márquez took the utilization of alternative power systems as prominent for energy transmission, supply, and security into consideration, and conducted an economic analysis for offshore wind farms. Taking into account the importance of alternative power systems for energy transmission, supply, and security, Márquez [18] carried out an economic study for offshore wind farms.

Additionally, other scholars explored the need for rational and scientific wind farm locations and studied the impact of wind farm location on the life-cycle of wind farms, electricity market prices, etc. Vicente D.-C. and Laura C. S. [19] ascertained the impact that the site has on the life cycle of an offshore floating wind farm. Awad et al. presented a probabilistic-based bi-level optimization approach for evaluating the impacts of the wind farm location and control strategy on the penetration level of wind farms and electricity market prices. A probabilistic-based bi-level optimization technique was introduced by Awad et al. [20] to assess how wind farm site and control strategy affect wind farm penetration and electricity market prices. McWilliam et al. [21] determined the wind farm structure that produced power at the lowest possible cost by utilizing population, wind resource, and transmission line locations. Gao et al. [22] used a life cycle perspective to analyze energy consumption and the environmental impacts of wind farms and compared the results to a biomass power plant.

Moreover, the location decision for wind turbines within a wind farm has been a subject of numerous studies. Spielhofer et al. [23] demonstrate how a state-of-the-art evolutionary optimization algorithm can inform policy makers in leveraging various planning policies to optimize the location of wind turbines. Using GH WindFarmer and WAsP software, Mohamed et al. [24] improved the placement of wind turbines in the Kaberten park and reduced losses as a result of the trail's influence. Li et al. [25] selected fourteen small- to medium-sized commercially available wind turbines in Urumqi and Xining in China and analyzed their mean energy outputs and capacity factors. Adaramola and Oyewola [26] examined the performance of selected small- to medium-sized wind turbines in three selected locations in Oyo state. Using a well-established Jen-sen wake model and ISO-9613-2 noise calculation, Mittal et al. [27] carried out a wind farm layout optimization to maximize energy generation and minimize noise propagation. This involved a multi-objective tradeoff between minimizing noise propagation and maximizing the wind turbine location.

This paper also investigates the method of evaluating wind energy resources and wind power generation. As a result, it is necessary to review the research. At present, there are several mainstream databases constructed for the evaluation of wind energy resources and wind power generation, such as ECMW, AROME, ERA5, CERRA2, etc. [28-30]. Then, numerous studies are applied to the evaluation of wind energy resources and wind power generation based on these databases. In the field of wind energy resource evaluation, Jin et al. [31] proposed a multi-scale coupling numerical simulation method based on atmospheric stability to investigate a wind energy resource assessment. Prasad et al. [32] processed validated long-term reanalysis datasets (1979-the present) to find the most reliable reanalysis datasets for a wind resource assessment. For the evaluation of offshore wind, Elshafei et al. [33] suggested a hybrid method combining measurements and results from numerical models. A study of a sensitivity analysis in a wind resource assessment was given by Tsvetkova and Ouarda [34], who provided classifications based on the sensitivity analysis output variable (or model), method, application, nation, and software. Elshafei et al. [35] proposed a hybrid approach to combine the merits of measurements and simulations for the assessment of offshore wind resources. Patel et al. [36] re-assessed offshore wind resources and analyzed the wind climate along the Indian coast using the latest ERA5 near-hub-height wind products. Dayal et al. [37] summarized an assessment of the wind resources at selected locations in Fiji for the potential of future utility-scale wind power development. Ayik et al. [38] conducted an initial evaluation of South Sudan's wind resources. A early evaluation of the offshore wind resource up to around 80 km off the coast of Mexican territory was suggested by López and Badaoui [39]. Moreover, in the field of wind power generation assessments, Chen et al. [40] introduced an innovative framework for multi-task learning and used it to achieve regional wind-photovoltaic combined power generation forecasting. Han et al. [41] proposed a methanol-based energy storage system to meet regional power demand by combining a hybrid wind-solar source. Chen et al. [42] proposed a novel multi-objective optimized recurrent neural network with temporal pattern attention (TPA) to address the randomness and uncertainty of wind farms in regional wind power prediction. Wilberforce et al. [43] presented extant wind turbine designs and evaluated the potential for micro-wind production under poor wind quality situations, such as those seen in densely populated, suburban, or sparsely forested regions.

In summary, numerous research studies on wind farm location and wind resource evaluation and relatively little research on wind power measurement have been executed. However, most of them are focused on the location optimization of offshore wind farms, and there are relatively few studies on the location selection of onshore port area wind farms. In the field of wind resource evaluations and wind power generation measurements, most of the studies are focused on the evaluation of wind turbine potentials and wind resource potentials, or the evaluation of wind power generation, and there are relatively few studies on the evaluation of wind power generated by wind turbines. This section first defines the scope and boundary of the wind farm area and introduces the location selection method for the wind farm area. Taking into consideration that this paper mainly studies the location selection method for the wind turbine and that the wind turbine is constructed into the wind farm area, so the location selection principles and method of the wind turbine are introduced in turn in this section.

3.1. The Scope and Boundary of the Wind Farm Area

Before constructing wind turbines in the port area, a more critical step is to define the scope and boundary appropriate to conduct wind power generation in the port area, which is named the wind farm area. Generally, according to the relevant port development and planning documents formulated by local maritime authorities, the scope and boundary of the port area can be clarified. Additionally, because the wind farm area is resolved and located in the port area, as a result, after figuring out the scope and boundary of the port area, the scope of the wind farm area is obtained.

Normally, the principles of selecting the wind farm area are given as follows:

- (1) The chosen wind farm area cannot interfere with the port's production routine;
- (2) The wind farm area should be defined as an area with high wind speed and abundant wind energy resources;
- (3) The wind farm area should be adequate, sufficient, and able to accommodate the proposed wind turbines.

As shown in Figure 1, the scope and boundary of the port area are enclosed by port shoreline A, port extents B and D, and port land boundary C. The defined scope E represents the designated port area where port production activities take place. These five parts are spatially separate areas. Then, port routine production is carried out in this area. Based on the authors' on-the-spot research on the wind power generation layout and management in Jiangyin Port and Tianjin Port, the alternative space of the wind farm area is proved within the scope of port extents B and D and port land boundary C, rather than scope E and shoreline A. The reason is principle 1 referred to above.



Figure 1. The scope and boundary of the wind farm area.

3.2. Location Selection Method for the Wind Farm Area

Wind farm location selection, in general, can be divided into two types: locations in the macro-region area and the micro-region area. The former aims at optimizing the wind farm area spatially, and the latter aims at optimizing the wind turbine constructed into wind farm area spatially. This paper focuses on the location selection method for wind farm areas that can be used in the macro-region area.

According to the literature review of existing research, the location selection of wind farm areas at the macro stage is mainly categorized into two types: a location selection method with real-time wind speed data and a location selection method without real-time wind speed data. Therefore, there exist different methods for these two types. When facing no efficient real-time wind speed data, based on the technical regulations for the selection of a wind farm area delivered by national public service platform for standards information, the (1) topographic and geomorphologic features discrimination method, (2) vegetation deformation discrimination method, (3) wind-forming geomorphology discrimination method, and (4) residents' survey method are commonly used means to determine the scope and location reasonably. Nevertheless, when there are valid real-time wind speed data for the corresponding research of the wind farm area, mesoscale meteorological data such as ERA5 and Merra2, meteorological stations in the port area, wind speed and direction data in and around the port area, and experts' experience or other data are mainly adopted to determine the scope and location of the wind farm area reasonably.

3.3. Wind Turbine Location Selection Principles and Method

As described above, this paper mainly studies the location selection method for the wind turbine, and the wind turbine is constructed into the wind farm area; so, only after figuring out the location selection method of the wind farm area can it be further clarified how to carry out the optimal location selection method of the wind turbine, and the location selection principles and method for the wind turbine are stated below.

3.3.1. Wind Turbine Location Selection Principles

Wind turbine location selection is the process of screening out suitable location points for wind turbine construction within the planned port boundary scientifically and reasonably based on a comprehensive consideration of the wind turbine, such as construction conditions, the wind resource distribution, and the economy. Consequently, the following principles are derived from a comprehensive review of the existing literature in this domain:

- (1) The selected location for the wind turbine should meet the requirements of national industrial policy, local development, and port space planning. Documents, such as territorial spatial planning, control detailed planning, construction detailed planning, and port space planning, should be collected and studied thoroughly to figure out the scope and boundary of the port area. The areas within the port boundary that have been used for other planning purposes or occupied by other projects should be excluded. Meanwhile, areas in the port area, such as basic farmland, ecological red line, national public welfare forests, nature reserves, important mineral deposits, military areas, etc., should be discarded. Then, a location point can be selected within the rest of the port area.
- (2) The selected locations of wind turbines should have abundant wind energy resources, characterized a high wind speed and stable wind direction. Regions with higher wind speeds generally exhibit greater wind energy potential. In addition, a stable wind direction is conducive to the standardized layout of the wind turbine and reduce the frequent yawing faults and energy consumption, thus obtaining a more ideal wind power generation effect. Thus, in alignment with principle (1), the wind speed, wind direction, and other data can be further collected from the remaining available areas in the port area to rationalize the decision-making process of the wind turbine location.
- (3) The selected location of wind turbines should consider the construction requirements, safety requirements, state grid access requirements, environmental protection requirements, and economic requirements designed during the construction process to rationalize the layout. This implies that the selected location should have simple terrain, little construction difficulty, and better transportation conditions within the remaining available area of the port area. The safety construction requirements during the construction period, the requirements for grid access that exist after the completion of construction (e.g., close to the substation or grid that meets the conditions for grid access), as well as environmental protection requirements (e.g., away from the needs of the residential area, the CBD, etc.), and the economic requirements for wind turbine construction during the whole cycle (input–output ratio) should be maximized, which is convenient to achieve ideal and fast wind power generation construction.

This paper mainly constructs the indicator evaluation system for the wind turbine location and adopts the hierarchical analysis and fuzzy comprehensive evaluation method to evaluate the indicator system efficiently.

(1) Indicator evaluation system

Through a thorough literature review and multiple rounds of expert consultations, the indicator evaluation system mainly includes four level 1 indicators: regional wind energy resources, grid access situation, project environmental factors, and meteorological and geological conditions.

Within wind energy resources, four level 2 indicators are included: wind speed, wind energy density, wind direction, and the number of available hours per year. For grid access situations, two level 2 indicators are considered: the length of grid access lines and located transportation conditions. The project economy category comprises four level 2 indicators: unit power generation cost, total project investment, payback period, and net capital utilization rate of the project. Lastly, meteorological and geological conditions contain two level 2 indicators: the topographic slope and land suitability. The specific structure of the indicator evaluation system is shown in Figure 2.



Figure 2. Indicator evaluation system.

(2) Hierarchical analysis and fuzzy comprehensive evaluation method

Hierarchical analysis and fuzzy comprehensive evaluation methods are used to evaluate each wind turbine location candidate point, and the purpose is to evaluate a series of reasonable wind turbine location points from all selected turbine candidates to improve the efficiency and effectiveness of wind turbine power generation. The methodology is described below.

(1) The weights of indicators need to be determined. Firstly, we should figure out the importance ranking of indicators; that is, we should compare them to decide which one is more important when we choose any two indicators. Then, the comparison results are quantified and ranked on a scale of 1–9, and the judgment matrix of indicators is obtained. The scale of 1–9 is described following Table 1, the scale points 2, 4, 6, and 8 are the medium values in the judgment matrix.

Table 1. Scale and de	escription.
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Scale	Description
1	Two indicators are equally important
3	One indicator is slightly more important than the other indicator
5	One indicator is obviously more important than the other indicator
7	One indicator is especially more important than the other indicator
9	One indicator is extremely more important than the other indicator

Take the four key indicators as an example and set A_1 , A_2 , A_3 , A_4 to represent regional wind energy resources, the grid access situation, project environmental factors, and meteorological and geological conditions. Then, the judgment matrix is obtained and expressed as follows: a_{12} represents the comparison result between the indicator regional wind energy resources and grid access situation.

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}$$
(1)

According to the obtained judgment matrix, we adopt a hierarchical analysis to calculate the relative importance of the indicators and figure out the weight of each indicator. After figuring out the weights of indicators, it is necessary to test the consistency of the judgment matrix. When the consistency result is less than 0.1, it is generally considered that the judgment matrix has a satisfactory consistency; otherwise, it needs to be adjusted to make it satisfactory. Thus, the corresponding weight of each indicator in the wind turbine location evaluation indicator system is obtained.

(2) The fuzzy evaluation matrix needs to be determined. The values of all indicators in the evaluation system of each wind turbine location candidate point are collected to obtain the relative affiliation matrix of each wind turbine location candidate point. To preserve the information of each indicator, it is necessary to standardize the indicators that belong to the larger and better type. The standardized formula is stated below.

$$r_{ij} = \frac{x_{ij}}{x_{\max ij} + x_{\min ij}} \tag{2}$$

On the contrary, the standardized equation for indicators that belong to the smaller and better type is stated below.

$$r_{ij} = \frac{x_{\max ij} + x_{\min ij} - x_{ij}}{x_{\max ij} + x_{\min ij}}$$
(3)

In this formula, x_{ij} represents the indicator value, and $x_{\max ij}$, $x_{\min ij}$ are the maximum and minimum values of row *i* in the collected sample set, respectively.

$$R_k = \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix}$$
(4)

In this formula, R_k is the fuzzy evaluation matrix of indicator k in level 1. r_{nm} represents the comparison results of indicators in level 2.

③ Fuzzy matrix composite operations need to be executed.

After determining the indicator evaluation system, the indicator weights, and the fuzzy evaluation matrix for each wind turbine location candidate point, based on the

collected indicator values of samples, the fuzzy matrix composite operation of the level 2 indicators is carried out to derive the fuzzy evaluation matrix of the level 1 indicators.

$$S_{k} = W_{k} \times R_{k} = (W_{k1}, W_{k2}, \cdots, W_{kn}) \times \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} = (s_{k1}, s_{k2}, \cdots , s_{km})$$
(5)

In this formula, matrix W_k represents the weights of all level 2 indicators that belong to the level 1 indicator k. In addition, the final fuzzy evaluation matrix T is calculated and obtained based on the fuzzy matrix composite operations.

$$T = W \times S = (W_1, W_2, \cdots W_k) \times \begin{bmatrix} s_{11} & \cdots & s_{1m} \\ \vdots & & \vdots \\ s_{k1} & \cdots & s_{km} \end{bmatrix} = (t_1, t_2, \cdots t_m)$$
(6)

W represents the weights of all level 1 indicators.

④ The composite assessment value needs to be determined.

$$Q = T \times D \tag{7}$$

In this formula, matrix *D* is the quantitative matrix of adaptability evaluation for a wind turbine candidate location point, and the specific value of matrix *D* is given as $(d_1, d_2, \dots, d_m)^T$ so that the final adaptability evaluation of a single wind turbine candidate location point can be derived.

4. Methodology for Evaluating Wind Energy Resources and Wind Power Generation in the Port Area

The methodology in Section 3 describes how to select suitable wind farm areas as well as wind turbine locations, and so the next step is how to evaluate the wind energy resources and wind power generation based on the selected wind farm areas and wind turbine locations. At present, China has issued a series of national and industrial standards around wind energy resource measurement [44–47]. Additionally, at the same time, according to the existing literature [48], in the process of wind energy resource evaluation, mainly including the average wind speed, the average air density, the average wind energy density, etc., and through the calculation of these indicators, we can ultimately obtain the total generation of the regional wind energy resources.

Consequently, Section 4 describes the methodology for evaluating the wind energy resources and the methodology for assessing wind power generation in the port area.

4.1. Methodology for Evaluating Wind Energy Resources

4.1.1. Air Density Measurement

If equipment for measuring pressure and temperature and recording data is available at the wind farm area in the port area, the air density is calculated according to Equation (8):

$$\rho = \frac{P}{R \times T} \tag{8}$$

 ρ is the air density, *P* is the annual mean atmospheric pressure, *R* is the air constant, and *T* is the annual mean air absolute temperature in Kelvin.

If there is no equipment and recorded data for measuring pressure and temperature in the wind farm area in the port area, the air density is calculated according to Equation (9):

$$\rho = \frac{353.05}{T} \times \exp^{-0.034 \times \frac{z}{T}} \tag{9}$$

4.1.2. Mean Wind Speed Calculation and Wind Speed Distribution Fitting

Based on the equipment in the wind farm area to obtain the observed wind speed data in periods, the average wind speed can be obtained using Equation (10), where V_i represents the observed wind speed data and $\overline{V_E}$ represents the average wind speed. At the same time, based on the observed wind speed data, the probability distribution function of wind speed in a continuous time frame can be carried out using the Weibull distribution model, and the parameters μ , c, k and σ of the Weibull model can be estimated using the results of the mean wind speed and the standard deviation of the wind speed with the formulas shown in Equations (11) and (12).

$$\overline{V_E} = \frac{\sum_{i=1}^{n} V_i}{n} \tag{10}$$

$$\mu = \overline{V_E}, \sigma = S \times v \times \frac{\sum_{i=1}^{n} V_i}{n}$$
(11)

$$k = \left(\frac{\sigma}{\mu}\right)^{-1.086}, c = \frac{\mu}{\Gamma(1 + \frac{1}{k})}$$
(12)

4.1.3. Average Wind Power Density Measurement

Average wind power density refers to the wind power in the area of the wind turbine perpendicular to the wind direction, which can directly reflect the scale of the wind power in the port area to be evaluated, and the expression of the average wind power density for the set period is shown in Equation (13).

$$D_{wp} = \frac{1}{2n} \times \sum_{i=1}^{n} \rho \times v_i^{3}$$
(13)

 D_{wp} is the average wind power density, *n* is the number of records in the set period, ρ represents the air density, and v_i^3 is the cube of the *i*th recorded wind speed value. When calculating the average wind power density, it is necessary to use the average value of the hourly wind power density in the set period.

It can be seen that the average wind power density is closely related to the wind speed and air density. Although the air density is relatively stable, the wind speed is always changing. As a result, in order to calculate the average wind power density more reasonably, the current research is mainly conducted by simulating the wind speed data to analyze the change style of the wind speed in a period of time.

At present, the main simulation models, Weibull distribution, Rayleigh distribution, gamma distribution, and lognormal distribution included are adopted to simulate the change style of the wind speed, and many studies believe that the Weibull distribution can better simulate the change of wind speed [49,50]. The cumulative probability density function of the Weibull distribution is shown in Equation (14):

$$F_{(v)} = 1 - EXP\left[-\left(\frac{v}{c}\right)^k\right]$$
(14)

F(v) is the cumulative probability density, v is the wind speed, c is the Weibull scale parameter, and k is the Weibull shape parameter.

Additionally, the derivative of the Weibull cumulative probability density function is the Weibull wind frequency distribution probability density function, as shown in Equation (15):

$$f_{(v)} = \frac{k}{c} \left(\frac{v}{c}\right)^{(k-1)} EXP\left[-\left(\frac{v}{c}\right)^k\right]$$
(15)

 $f_{(v)}$ is the Weibull wind frequency distribution probability density. Therefore, the Weibull distribution is used for wind speed fitting and average wind power measurement in this paper. Additionally, the wind power density is calculated as in Equation (16) based on the Weibull distribution.

$$P_{i} = \frac{1}{2}\rho \int_{i}^{i+1} v^{3} f_{(v)} dv$$
(16)

 P_i is the representative wind power density value of the *i*th area in the Weibull distribution function.

4.2. Methodology for Evaluating Wind Power Generation

Firstly, based on the observed data from the wind farm area, the data of atmospheric pressure, temperature, altitude, wind speed, etc., which are multi-recorded in periods, are obtained. Then, the atmospheric pressure, temperature, and altitude data are used to calculate the average air density based on Equations (8) and (9), and then the average wind power density results are obtained based on Equations (10)-(16). Finally, based on the average wind power density and Equations (17) to (19), the total generation of wind energy resources is calculated.

$$E_1 = \frac{1}{100} \sum_{i=1}^n (S_i \times P_i \times \cos \alpha), 0 \le a < \frac{\pi}{2} \text{ or } \frac{3\pi}{2} \le \alpha \le 2\pi$$
(17)

$$E_{2} = \frac{1}{100} \sum_{i=1}^{n} (S_{i} \times P_{i} \times (-\cos \alpha)), \frac{\pi}{2} \le \alpha < \frac{3\pi}{2}$$
(18)

$$E = E_1 + E_2 \tag{19}$$

 α represents the angle between the wind direction and the due north direction. Currently, 0 degrees is specified as the due north wind direction, 90 degrees is specified as the due east wind direction, 180 degrees is specified as the due south wind direction, and 270 degrees is specified as the due west wind direction, and the wind direction varies from 0 to 360 degrees. S_i is the *i*th area between the contour lines of wind power density in the annual average wind power density Weibull distribution map. E_1 is the part of wind power generation in which α belongs to $[0, \frac{\pi}{2}]$ or $[\frac{3\pi}{2}, 2\pi]$; E_2 is the part of wind power generation in which α belongs to $\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$. *E* is the total wind power generation.

Because the wind direction continues to change, the effective wind power density is different and can be calculated using trigonometric functions, and the effective wind power generation is calculated based on Equations (17) to (18) according to different wind directions. As a result, the total effective wind power generation is calculated based on Equation (19).

It should be noted that here, only the wind direction factor is considered in the calculation of wind power generation, and the effect of wake losses is not taken into account. The main reason is that the number of wind turbines constructed in port scenarios is often limited and in a single distribution to ensure the normal operation of the port. Normally, the number is no more than 5 based on actual research in China coastal ports and the wind turbines are constructed in different port areas. As a result, this paper does not consider the wake losses in the wind power generation calculation process.

5. Case Study

5.1. Case Description

In this study, the empirical analysis is based on the example of port wind power generation projects in China's coastal port clusters, as shown in Figure 3, which mainly include the Bohai rim port cluster, the Yangtze River Delta port cluster, the Pearl River Delta port cluster, the Southeast coastal port cluster, and the Southwest coastal port cluster. The Bohai rim port cluster mainly includes all the ports in Liaoning, Tianjin, Hebei, and Shandong provinces; the Yangtze River Delta port group mainly includes all the ports in Zhejiang, Shanghai, and Jiangsu provinces; the Pearl River Delta mainly includes all the ports in Fujian province; and the Southwest coastal port group includes all the ports in Fujian province; and the Southwest coastal port group mainly includes all the ports in Guangdong provinces.



Figure 3. China's coastal port clusters.

This paper selects Tianjin Port, Shanghai Port, Xiamen Port, Shenzhen Port, and Hainan Port wind power generation projects as examples for analysis. Based on the wind turbine location method proposed in this paper, the decision-making analysis of each project is applied, and the final locations of each project are shown in Figure 4, represented by the red pot in the figure.



(e) Hainan Port

Figure 4. Wind power generation project. (**a–e**) represent the wind power generation projects in Tianjin Port (latitude 39.02, longitude 117.81), Shanghai Port (latitude 31.35, longitude 121.62), Shenzhen Port (latitude 22.57, longitude 114.28), Xiamen Port (latitude 24.43, longitude 118.13), and Hainan Port (latitude 19.8, longitude 110.8), respectively.

Then, this section takes the wind turbine construction project as an example to illustrate the location selection process. The candidate location points of the wind turbine in Tianjin Port are shown in Figure 5, which are represented by one, two, and three. Based on the actual data from Tianjin Port and expert scores, the weights of the indicators and the level 2 indicator scores of each candidate wind turbine point are shown in Tables 2 and 3. The Tables 2 and 3 are calculated based on Section 3.3.2. The weights and scores are determined after comparing the indicators and figuring out the importance ranking of indicators based on Table 1 and Equations (1) to (7).



Figure 5. Wind turbine location candidate points of the wind power project in Tianjin Port.

Table 2. Indicator weights.

Level 1 Indicator	Weights	Level 2 Indicator	Weights
		Wind speed	0.4
Regional wind energy	0.3	Wind power density	0.1
lesources		Wind direction	0.2
		Number of available hours per year	0.3
Crid access situation	03	Length of grid access lines	0.7
Gift access situation	0.0	Located transportation conditions	0.3
		Unit power generation cost	0.2
Project environmental	0.2	Total project investment	0.3
lactors		Payback period	0.3
		Net capital utilization rate of the project	0.2
Meteorological and	0.2	Topographic slope	0.6
geological conditions 0.2		Land suitability	0.4

Level 2 Indicator	Point 1 Score	Point 2 Score	Point 3 Score	
Wind speed	7	5	7	
Wind power density	8	6	8	
Wind direction	7	8	9	
Number of available hours per year	7	7	7	
Length of grid access lines	9	7	5	
Located transportation conditions	9	6	4	
Unit power generation cost	7	7	7	
Total project investment	8	7	7	
Payback period	8	7	7	
Net capital utilization rate of the project	6	7	7	
Topographic slope	9	8	6	
Land suitability	9	9	6	

Table 3. Indicator scores of each candidate point.

We provide the calculation process to obtain the final score of point 1. Based on the weight results and indicator scores results, the scores of level 1 indicators are obtained using Equations (20) to (23). After obtaining the weights and scores of indicators, the final score of location candidate point 1 is obtained using Equation (24), and the result score is 8.15. The final scores of point 2 and point 3 can be calculated in the same way, and the results for point 2 and point 3 are 6.31 and 5.79, respectively. As a result, the scores of each candidate point in other four wind power generation projects can be calculated in the same way.

Level 1 indicator: regional wind energy resources

$$7 \times 0.4 + 8 \times 0.1 + 7 \times 0.2 + 7 \times 0.3 = 7.1 \tag{20}$$

Level 1 indicator: Grid access situation

$$9 \times 0.7 + 9 \times 0.3 = 9 \tag{21}$$

Level 1 indicator: Project environmental factors

$$7 \times 0.2 + 8 \times 0.3 + 8 \times 0.3 + 7 \times 0.2 = 7.6 \tag{22}$$

Level 1 indicator: Meteorological and geological conditions

$$9 \times 0.6 + 9 \times 0.4 = 9 \tag{23}$$

Final score:

$$7.1 \times 0.3 + 9 \times 0.3 + 7.6 \times 0.2 + 9 \times 0.2 = 8.15 \tag{24}$$

5.2. Wind Energy Resource Evaluation

Based on the longitude and latitude of the wind power generation project in each port (represented by a red pot), we can acquire the wind speed and direction according to the prediction of a worldwide energy resource (POWER) | data access viewer enhanced (DAVe) database of NASA. In this study, wind speed and direction data at 50 m for the past year are collected based on the database for the period from 1 October 2014 to 31 September 2023. The wind speed and direction of each wind power generation project are shown in Figure 6.



(e) Hainan Port

Figure 6. Wind speed and direction of wind power generation projects. (**a**–**e**) represent the wind speed and direction of wind power generation projects in Tianjin Port, Shanghai Port, Shenzhen Port, Xiamen Port, and Hainan Port, respectively.

In the actual wind monitoring process, the wind direction is generally expressed in terms of angles, i.e., the circumference is divided into 360 degrees, with 0 degrees (i.e., 360 degrees) being the northerly wind direction (N), 90 degrees being the easterly wind direction (E), 180 degrees being the southerly wind direction (S), and 270 degrees being the westerly wind direction (W), and the rest of the wind directions can be calculated in this form.

According to the actual research, we obtained the report of the wind turbine construction project at Tianjin Port, which adopts wind turbines with a generating capacity of 4.5 MW. As a result, this paper adopts the parameters of this kind of wind turbine in the Tianjin report to conduct a case study.

Consequently, the parameters of the turbines deployed in each wind power generation project are shown in Table 4. Additionally, each wind power generation project needs to install two wind turbines with a generating capacity of 4.5 MW. The average air density is 1.223 kg/m³.

Table 4. Each wind turbine parameters.

Parameters	Value	
Manufacturer	GoldWind	
Product name	GW155-4.5	
Capacity	4.5 MW	
Impeller diameter	155 Meters	
Annual utilization hours	2395.8 h	
Wind energy loss coefficient	81.05%	
Wind turbine price	40 million yuan	

Based on the statistically obtained wind speed and wind direction data, we adopted the wind speed and wind direction data from 1 October 2022 to 30 September 2023 to conduct a wind energy resource evaluation.

The wind energy resource evaluation is described below. The monthly average wind speed at 50 m of each wind power generation project is calculated according to Equation (10), and the average wind speed results for each project are shown in Figure 7. In addition, according to the Weibull distribution calculation process, the final windspeed probability density results of these five ports based on the Weibull distribution are shown in Figure 8. Taking the final windspeed probability density results into account, the average wind power density is then calculated according to Equations (13) to (16). Finally, the monthly and annual average wind power density results for each wind power generation project are shown in Figures 9 and 10.



Figure 7. Monthly average wind speed at 50 m.



Figure 8. Probability density of windspeeds based on the Weibull distribution.



Figure 9. Monthly average wind power density at 50 m.



Figure 10. Annual average wind power density at 50 m.

5.3. Wind Power Generation Evaluation

The evaluation of wind power generation is applied as follows: the diameter of the wind turbine is 155 m according to Table 4, and so the fan blade area is $\pi^*(155/2)^2 = 18,869 \text{ m}^2$. The annual utilization hours of each wind turbines is 2395.8 h; meanwhile, the annual average wind power density of each wind power generation project is shown in Figure 10. As a result, the wind power generation (also known as total wind resource reserves) of each wind turbine in the project is calculated according to Equation (17) to Equation (19), which is demonstrated in Figure 11.



Figure 11. Wind power generation evaluation of each wind power generation project.

6. Discussion

The evaluation process of the wind power generation project is stated below. Taking the project in Tianjin, for instance, the annual average wind power density at 50 m in Tianjin

is 270.45, thus, the wind power generation in Tianjin is calculated as follows according to Equations (17) to (19):

$$18869 \bullet 2395.8 \bullet 270.45 = 12226.19 \text{ Mw} \bullet h$$
 (25)

Combined with the research to obtain the wind turbine wind energy loss coefficient of 81.05% and the two sets of constructed wind turbines in Tianjin Port, the final wind power generation is calculated as follows:

$$12226187.1 \bullet 81.05\% \bullet 2 = 19818.65 \text{ Mw} \bullet h$$
 (26)

The wind power generation evaluation of other projects can be calculated in this way.

6.1. Comparison of Different Types of Wind Turbines

In this paper, the types and parameters of the wind turbines are given directly in the case study, but in the actual situation, there are often a variety of wind turbine types to choose from and decide. Moreover, the parameters of different types of wind turbines are different; as a result, their power generation efficiency and economic costs tend to be different. Thus, it is necessary to carry out a sensitivity analysis on the type of wind turbine.

The relevant values of different kinds of wind turbines are given in Table 5. Additionally, these kinds of wind turbines are divided into case types and substitute types. The case type is adopted in the case study of this paper.

Table 5. Wind turbine parameters.

Parameter	Value (Case)	Value (Substitute Type 1)	Value (Substitute Type 2)
Manufacturer	GoldWind	Envision Group	Envision Group
Product name	GW155-4.5	WTG175-5	WTG140-4
Capacity	4.5 MW	5 MW	4 MW
Impeller diameter	155 Meters	175 Meters	140 Meters
Annual utilization hours	2395.8 h	2420 h	2360 h
Wind energy loss coefficient	81.05%	83.06%	79.35%
Wind turbine price	5.71 million dollars	6.43 million dollars	5.43 million dollars

According to the parameters and calculation method in Section 5.3, the final wind power generation results are calculated and shown in Table 6. The results show significant differences. Additionally, taking the construction cost of wind turbines and the price of electricity into consideration, these results issue a game theory. Nowadays, the price of electricity of China is 0.55 yuan/kwh, and substitute type 1 obtains a benefit when compared with the case type. The scale is shown in Equation (27), but the substitute type 1 costs 5 million yuan more than the case type.

$$(25.52 - 19.82)*10^{6}*0.55 = 3,135,000$$
 yuan = 0.45 million dollars (27)

Table 6. Wind power generation results.

Parameter	Value (Case)	Value (Substitute Type 1)	Value (Substitute Type 2)
Wind power generation (GWh)	19.82	25.52	15.93

Additionally, the calculation can be applied in the same way for substitute type 2. The result is that substitute type 2 obtains a loss when compared with the case type; the

scale is shown in Equation (28), but the substitute type 2 costs 2 million yuan less than the case type.

$$(19.82 - 15.93)*10^{6}*0.55 = 2,139,500$$
 yuan = 0.31 million dollars (28)

In conclusion, substitute type 2 is the most appropriate if the judgments are only applied from the perspective of economy. However, the actual situation is often more complex, e.g., the capacity of a wind turbine type in the real-world Tianjin wind turbine construction project is required to be larger or equal to 4.5 MW under the consideration of future wind power generation development from the limited number of wind turbines. Thus, it is necessary to make decisions from multiple perspectives of the problem for the selection of wind turbine types.

6.2. Sensitivity Analysis of Different Types of Wind Turbines

The above section lists three types of wind turbines, which contain the parameters of wind turbine capacity, impeller diameter, annual utilization hours and wind energy loss. Considering that the capacity, impeller diameter, and energy loss parameters of the wind turbines are fixed once the wind turbine type is identified, this section mainly focuses on the sensitivity analysis of the annual utilization hours and obtains the final sensitivity analysis results for the three types of wind turbines, as shown in Figure 12.



Figure 12. Sensitivity results for three types of wind turbines.

7. Conclusions and Recommendations

This paper innovatively proposed methods for locating wind farms and wind turbines in port areas based on a fuzzy comprehensive evaluation method. After choosing reasonable and optimum locations for wind turbines, an evaluation method of wind resource and power generation from wind turbines in port areas is proposed based on the national standard. In addition, a case study was conducted with the wind power generation projects in China's coastal ports, which validates the validity of the methods and models proposed in this paper, and this contributes to technically promoting the construction of wind power generation projects in China.

(1) Regarding the facility location method for locating wind turbines in different port scenarios, this paper constructs an index system containing four level 1 indicators and twelve level 2 indicators, and adopts the fuzzy comprehensive evaluation method to calculate the weights of indicators and the indicator values. Finally, this paper takes the location design of wind turbines in Tianjin Port as an example for empirical validation, and effectively selects one site from three candidate sites of wind turbine for the location and construction of wind turbines.

- (2) Based on the proposed evaluation method of wind resources in port areas and the evaluation method of power generation of wind turbines, this paper analyzes the wind power construction projects in Tianjin Port, Shanghai Port, Xiamen Port, Shenzhen Port, and Hainan Port, and obtains final power generation capacities of 30.71 GWh, 19.82 GWh, 16.72 GWh, 29.45 GWh, and 24.42 GWh, respectively.
- (3) Based on the results of the case study, this paper further analyzes the sensitivity of the type of wind turbine, and ultimately finds that if analyzed purely from the economic point of view, substitution type 2 is better, but in the real-world environment, the construction of the wind turbine should also be considered from various aspects.

However, there are still deficiencies in this paper's research, e.g., the method proposed in this paper involves many human factors. Thus, more practical methods for locating wind turbines and evaluating wind resources in the port areas can be developed in the future. Moreover, methods for locating the wind turbines and evaluating wind resources in other scenarios can also be studied.

In summary, the methods proposed in this study are essential for optimizing the location and construction of wind turbines, which may help ports in adopting a low-carbon and green development path, thereby mitigating air pollution and promoting sustainable development.

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