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Evaluation of the Spatial Suitability of Offshore Wind Farm—A Case Study of the Sea Area of Liaoning Province

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Abstract: Actively promoting the development of offshore wind power is an inevitable choice if the People's Republic of China plans to fulfill its international commitments, respond to climate change, ensure energy security, and improve energy infrastructure. Inevitably, offshore wind power development will conflict with other marine activities, including mariculture and shipping. Therefore, learning how to develop offshore wind power without affecting the environment or conflicting with other marine activities is crucial to the conservation of spatial marine resources. The rapid development of offshore wind power in Liaoning Province has allowed researchers to develop an index system that can be used to evaluate the suitability of offshore wind power development sites by considering costs, environmental protection, and sea management. Spatial analysis and a multi-attribute evaluation method integrating a fuzzy membership function were used to evaluate offshore wind farm placement in Liaoning. The results classified 5%, 18%, 21%, and 56% offshore areas of Liaoning as very suitable, relatively suitable, somewhat unsuitable, and unsuitable for wind power development, respectively. The results of this paper can provide a reference for decision makers who plan for offshore wind farm locations under the constraints of high-intensity development.

Keywords: offshore wind farm; suitability evaluation; multiple attribute decision making; geographic information system

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1. Introduction

Offshore wind power is an important direction of renewable energy development in the world. From 2010 to 2020, the average annual growth rate of global offshore wind power was nearly 30% [1]. By the end of 2020, the cumulative installed capacity of global offshore wind reached 3.43×10^7 kW. The new installed capacity in 2020 was 6.06×10^6 kW, continuously maintaining a high growth trend [2]. Europe is a pioneer in the development of offshore wind power and is in a leading position in terms of installed capacity and technical level. In Europe, the UK and Germany are countries with the fastest and best development. In 2020, the new installed capacity of offshore wind power in the UK and Germany was 4.38×10^5 kW and 2.40×10^5 kW, respectively, accounting for 8.2% and 14.9% of the new installed capacity of offshore wind power in Europe [2,3].

China's offshore wind power development began in 2007. Compared with developed countries, China started relatively late but developed rapidly. Especially since 2014, China has vigorously promoted the development of offshore wind power and formulated offshore wind power development plans [4] and a generous and stable on-grid price policy [5]. Since 2017, the cumulative installed capacity of offshore wind power has increased by more than 50% year-on-year growth [6–8]. In 2020, the new installed capacity of offshore wind power nationwide was 3.06×10^6 kW, which exceeded the total installed capacity of all offshore wind power in China before 2019 and also exceeded the total installed capacity of all offshore wind power in Europe in 2020.

In 2020, at the United Nations General Assembly, the People's Republic of China (PRC) proposed that the PRC should strive to reach peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. Under the trend of working to reach a "carbon peak" and "carbon neutralization", China has accelerated the pace of switching to new types of energy. The introduction of green energy on a massive scale, such as wind power, has ushered in a period of rapid energy resource development. The "Action Plan for Carbon Dioxide Peaking Before 2030" [9] issued by the State Council of the PRC points out that by 2030, non-fossil energy in the PRC will account for about 25% of primary energy consumption, and the total installed capacity of wind power and solar energy will reach above 1.2×10^9 kW. As of September 2021, the combined installed capacity of wind (the installed capacity of onshore wind power being 2.84×10^8 kW and offshore wind power being 1.32×10^7 kW) and solar power generation in the PRC was only 5.75×10^8 kW [10], which was still far from the 2030 target, which means that the scale of wind power and solar power generation will need to double in nine years. The plan also points out that we should vigorously promote the large-scale and high-quality development of wind power, pay equal attention to land- and sea-based windfarms, and encourage the construction of offshore wind power bases. The PRC has about 1.8×10^4 km of continental coastline, and the technical development of wind power resources within 50 m water depth along the coast is about 5.1×10^9 kW [11]. The potential for the development of offshore wind power is massive. Compared with onshore wind power, offshore wind power has the advantages of having continuous and stable wind resources, high wind speeds that generate a large amount of power, not occupying land resources, and being located close to load-intensive urban areas. Therefore, offshore wind power will become the inevitable choice for the PRC, allowing the country to vigorously develop renewable energy.

The development of offshore wind power also involves long-term and large-scale occupation of marine space and interferes with the environment of marine life. The average water depth of the 1853 wind turbines built in China before the end of 2019 is about 14.1 m, and the average offshore distance is about 19.6 km, which occupies a large amount of coastal waters [12]. According to the plans to develop offshore wind farms in various parts of the PRC, continuing the previous wind power layout mode, most of the offshore wind farm planning primarily has considered only the wind resource conditions, whereas less attention has been paid to coordination between the need for offshore wind power and the existing development and use of marine resources [13–15]. In fact, more than 90% of the PRC's sea area development and use is concentrated in the nearshore area within the −30 m isobath. The unit density of shoreline aquaculture in the offshore area is more than ten times the world average level, and the scale of coastal ports ranks first in the world [16]. Therefore, in the site selection of wind farms, in addition to considering the economic and technical feasibility of wind power generation, the potential conflicts with other marine industries should be fully considered.

Since the site selection process of offshore wind power involves many factors such as economy, ecology, and geography, the integration of the multiple attribute decision making (MADM) method and geographic information system (GIS) was widely applied to the research of site selection [17–26]. From literature review and specific region of our study case, the following research gaps are identified: (1) Under the background of high-intensity development of offshore waters in China, the site selection of offshore wind power may have a conflict with other sea use types. Thus, the conflict should also be taken into the site selection process. (2) Although there were many studies on multi-factor evaluation of offshore wind farm location using the MADM method, only a limited number of studies focused on how to reduce the uncertainty of the index normalization process with fuzzy membership function. The fuzzy membership function can standardize the evaluation factors when the standard value of the index is not known. Compared with the traditional standardization method, it can reflect the actual situation of the index objectively.

In recent years, although offshore wind power in Asian countries, including the PRC, has developed rapidly, compared with European countries, such as Britain and Germany, which have entered the large-scale stage of offshore wind power development, the industry is still in the initial stage of commercial development [27–29]. When the construction boom of offshore wind power had just begun to develop, planning was centered on site selection and scientifically determining areas that were the most suitable for effective wind power construction and operation. Blind layout was avoided so as not to adversely affect ecologically important protected areas and to not conflict with other sea use activities to avoid any unreasonable loss of spatial sea resources. Therefore, this study aims to determine suitable areas for offshore wind power in Liaoning Province of China by combining the fuzzy membership functions, the analytic hierarchy process (AHP), and GIS. The sea area of Liaoning has a higher degree of development and utilization: 38% of the sea area is important species and fish habitats, 25.8% of the sea area has been developed for fish farming [30], and the port and shipping industry is developed [31]. Therefore, this study takes ecological protection and conflicts with other sea use activities into consideration in suitability evaluation. In order to reduce the uncertainty caused by subjective judgment, the fuzzy membership function is used to normalize each evaluation index to make the evaluation result more objective.

2. Summary of the Research

The selection of suitable construction space for offshore wind power needs to consider wind resources, construction capacity, economic costs, environmental impacts, and other aspects; complex factors will influence site selection. The main limiting factors for wind power site selection will vary by region. Existing research mainly has selected different elements to construct evaluation index systems based on the actual characteristics of each study area. For example, Vasileiou (2017) [17], Mahdy (2018) [18], and Gaveeruoux (2019) [19] adopted different indicators, such as distance analysis (coastline, port, fishing area, land power grid, route, and mineral mining area), wind speed, and water depth to evaluate the areas they found suitable for offshore wind power in the Aegean Sea of Greece, the Red Sea of Egypt, and Hong Kong of the PRC, respectively. Argin (2019) [20] evaluated the suitability of locations for developing offshore wind farms in Turkey by considering water depth, main wind direction, and distance offshore. Zhao et al. [21] (2017) evaluated the location of offshore wind farms based on the marine functional zoning and route distribution in Tianjin City, China, by using the non-linear set pair analysis method.

The evaluation of site suitability for offshore wind power involves many elements, which usually are evaluated by multiple attribute decision making. At present, the commonly used methods include the analytic hierarchy process (AHP), the network analytic hierarchy process (ANP), and the preference ranking organization method (PROMETHEE). Kaya and Kahraman (2011) [22] proposed an AHP–TOPSIS model for energy planning decisions under a fuzzy environment and applied it to a factual site selection of offshore wind farms in the Eastern China Sea. Aragonesbeltran et al. (2014) [23] applied AHP and ANP to help the managing board of a solar-thermal power plant in Spain and determined the order of priority of the project in the company's portfolio. Wiguna et al. (2016) [24] studied the location choice for renewable energy infrastructure using AHP and PROMETHEE. Ziemba et al. (2017) [25] proposed an extended PROMETHEE method based on a sustainability assessment and constructed a decision-making framework for selecting the locations of offshore wind farms in Poland. Wu et al. (2019) [26] proposed a decision framework for selecting sites for offshore wind power station locations based on a triangular intuitionistic fuzzy number method, ANP, and PROMETHEE. Among these methods, the AHP method offers the advantages of being systematic, flexible, and simple to use and has obvious advantages in solving unstructured decision problems; therefore, it has been widely used in evaluating the suitability of offshore wind farm locations. ANP performs well in the complex index system, but it involves the use of too many paired comparison matrices making the calculation process complex. Meanwhile, the original data do not need to be processed by PROMETHEE, reducing the loss of information and deviation in the results caused by data pre-processing. However, the PROMETHEE method requires that the utility and weight values of each attribute in the scheme have a proportional scale, so it cannot deal with uncertain information, which limits its scope of application.

Generally, the current research results on the suitability of offshore wind power sites are mostly concentrated in European and American countries, whereas the domestic research in the PRC has focused on introducing methods based on the advanced experience of offshore wind power construction in Europe along with an analysis of the development status and technical problems of offshore wind power sites in the PRC [27–29,32–34]. However, in European and American countries, the intensity of marine development is relatively low. In the evaluation of the spatial suitability of offshore wind power sites, coordination between wind farm construction and other sea use activities has not yet been considered. Therefore, the international research cannot be rigidly applied to China's current social and economic environment. It is necessary to screen the indicators employed in suitability evaluation based on the actual situation of sea area use.

In terms of research methods, the AHP method is widely used in the field of site selection. Therefore, this study takes AHP as the main method of suitability evaluation. In most studies, the standardization of evaluation factors by the AHP method is based on expert experience and traditional standardization methods. Such methods usually require researchers to determine the standard or reference value of various evaluation factors before the actual evaluation so that subjective factors will strongly influence the results. In this paper, the fuzzy membership function is introduced to standardize the indicators; as a result, the evaluation factors can be standardized when the appropriate range of the research object has not been known. Compared with the traditional standardization method, it can more objectively reflect the actual situation.

3. Overview of the Study Area

The study area covered the coastal waters of Liaoning (Figure 1) in the northernmost coastal province in the PRC, which features excellent marine resources and lies near the Yellow Sea and the semi-enclosed Bohai Sea. The mainland coastline in this province is 2110 km long, making it the fifth longest in the PRC. Six coastal cities in Liaoning dot the coastline; from east to west, these are Dandong, Dalian, Yingkou, Panjin, Jinzhou, and Huludao.

Liaoning is rich in coastal wind energy resources. According to the global wind energy resource model simulated by the International Renewable Energy Agency, the average annual wind speed at 100 m height in the Bohai Sea of Liaoning is about 7.0–8.0 m/s, and the wind power density is about 550–680 W/m^2. The average annual wind speed at 100 m height is about 6.5–7.5 m/s, and the wind power density is about 500–580 W/m^2 [6]. The wind directions of these two sea areas are relatively concentrated, typically are not affected by typhoons, and have a good potential for the development and use of wind energy resources.

At present, the offshore wind farms built in Liaoning are mainly concentrated in the Dalian Zhuanghe area of the Yellow Sea. By the end of 2021, the installed capacity of offshore wind power in Liaoning is expected to reach 5.84 $\times$ 10^5 kW. In the next ten years, Huludao, Yingkou, Dalian, Dandong, and other cities in the region have vigorously proposed the idea of developing offshore wind power. Only Dalian and Dandong have planned offshore wind farms with an installed capacity of more than 1.0 $\times$ 10^7 kW [15]. In general, offshore wind power in Liaoning will soon enter a stage of large-scale development.

At the same time, the offshore area of Liaoning supports intensive marine activities and diverse types of sea use. By the end of 2020, the sea area used in Liaoning had exceeded 10,000 km^2, with about 85% of the sea area concentrated in an area with water -25 m deep [30]. Therefore, planners of offshore wind power in the sea area of Liaoning will face the problem of needing to determine how to coordinate various sea use activities. Taking this sea area as an example, the present study evaluates the spatial suitability of installing offshore wind power in this region while providing a typical and realistic scenario for developing wind power in an area needing sea area evaluation.

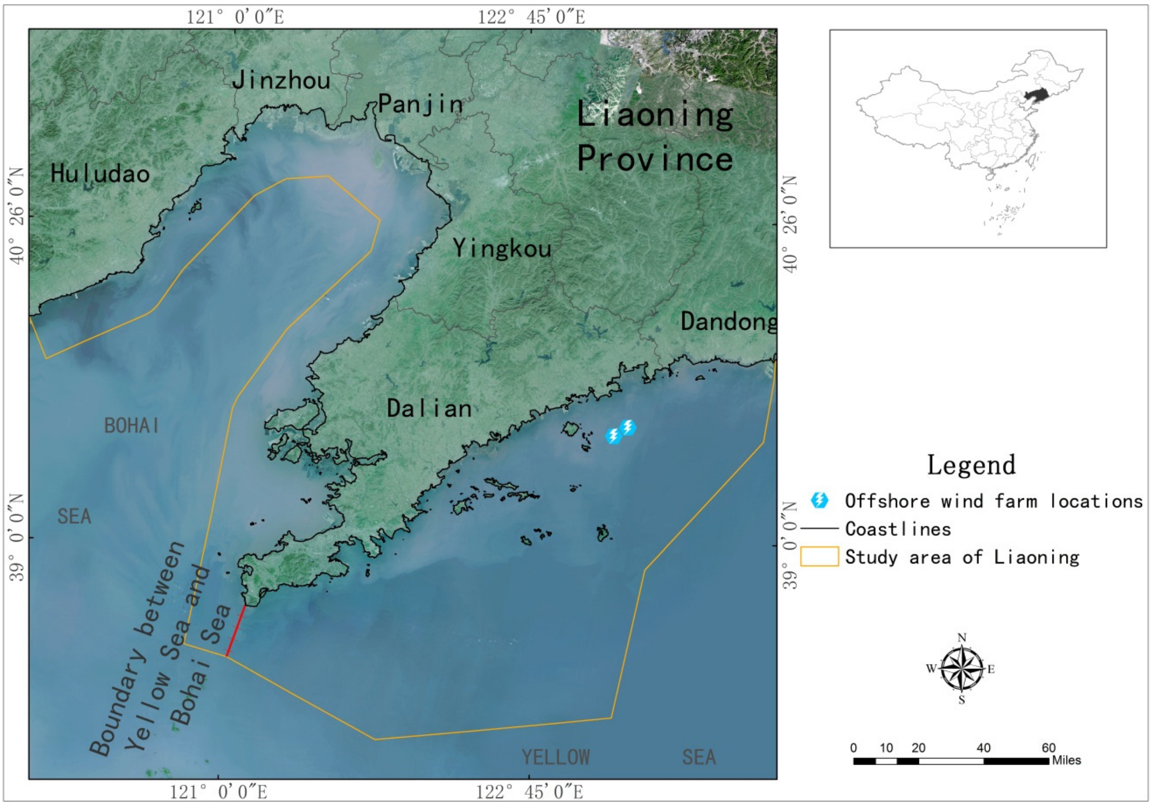

Figure 1. Map of the study area along the coast of Liaoning Province, China. An inset map shows the location of the province within the administrative areas of China.

4. Data and Research Methods

4.1. Research Framework

In 2016, the former State Oceanic Administration of the PRC proposed that the layout of offshore wind farms should comply with the "Double Ten" principle [35], with the goal of minimizing the impact of offshore wind farm construction as it applies to the reasonable use of resources and protection of the environment in the coastal waters. Specifically, the Double Ten principle means that the distance from the shore to a wind farm should not be less than 10 km and the depth of the sea area should not be less than 10 m when the width of the tidal flat exceeds 10 km. Therefore, we designated a no construction area in the study area as being located within about 10 km from the coastline with a water depth of less than 10 m.

On this basis, the present study involved carrying out a suitability evaluation for wind power using the following steps: (1) Screening indicators were developed based on wind resource conditions along with transportation and construction conditions; marine ecological protection-sensitive sea areas, current sea use, and other uses were considered. A system of indicators was constructed and used for evaluating the suitability of locations for wind power installation. (2) The management sea area was divided into several 1 km × 1 km grids as evaluation units by using a standard grid division method. Next, ArcGIS software (ESRI, Redlands, CA, USA) was used to obtain the spatial distribution of each index through spatial interpolation and grid processing. (3) A fuzzy membership function was used to normalize each evaluation factor. (4) AHP was used to determine the normalized index weights of each indicator and to quantify the degree of influence of each index on the suitability of offshore wind farm site selection. (5) A weighted linear model was used to calculate suitability, and a GIS spatial analysis allowed for visualization of the areas suitable for wind farms spatially. The research framework is shown in Figure 2, and a technical roadmap is shown in Figure 3.

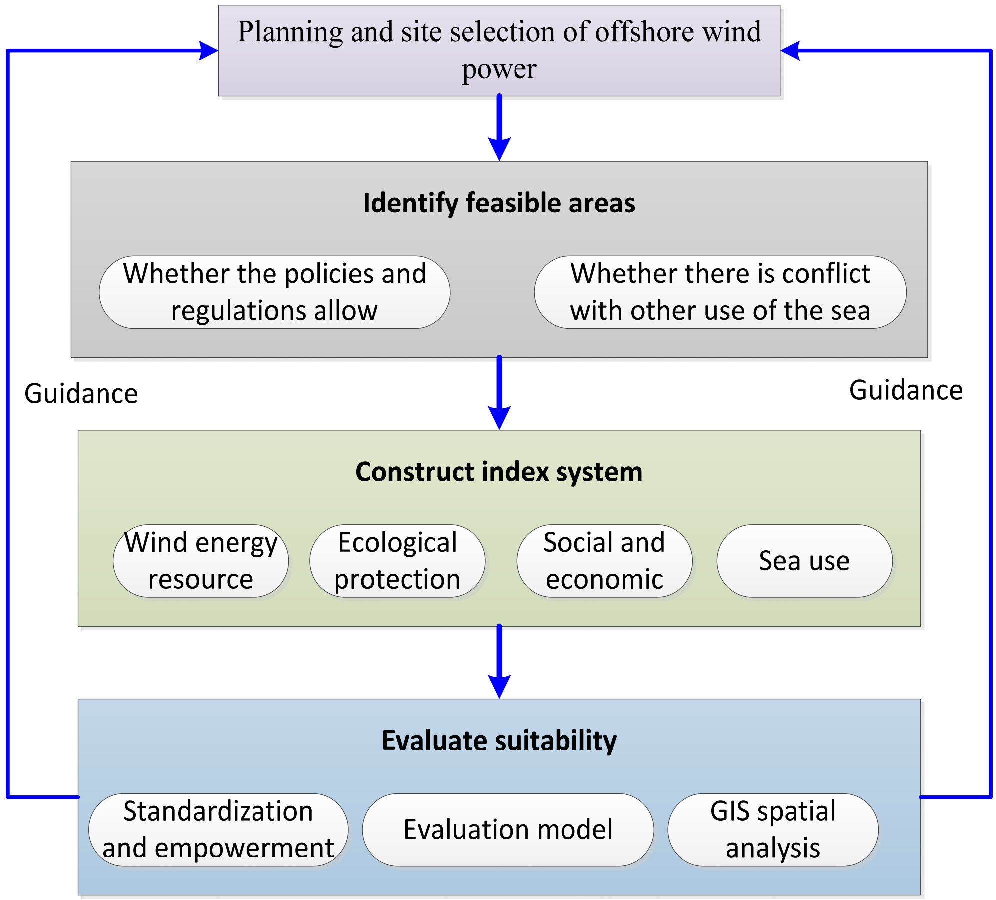

Figure 2. Research framework for determining the suitability of a site for offshore wind power.

4.2. Index System and Data Sources

On the basis of existing research, the main factors influencing the selection of offshore wind power sites include the following: (1) natural factors, such as wind energy, geology, and meteorology; (2) economic factors, including construction costs and logistics, grid connection, transportation, and other conditions that determine the economic cost and difficulty of wind power construction; (3) consideration of ecological elements, including the impact of wind power construction on birds and important marine habitats; and (4) co-ordination with other sea use activities, including an analysis of potential conflicts between wind power and other sea use activities. For example, mariculture trawling operations may affect the power grid line of offshore wind power, and wind power construction may interfere with fish migration and foraging.

On the basis of these ideas, and combined with the actual situation of natural characteristics as well as social and economic activities in the sea area of Liaoning, according to the principles of integrity, operability, and hierarchy during index selection, this paper selected seven indices (numbered C_1 to C_7) to establish a spatial suitability evaluation index system for offshore wind farms (Table 1).

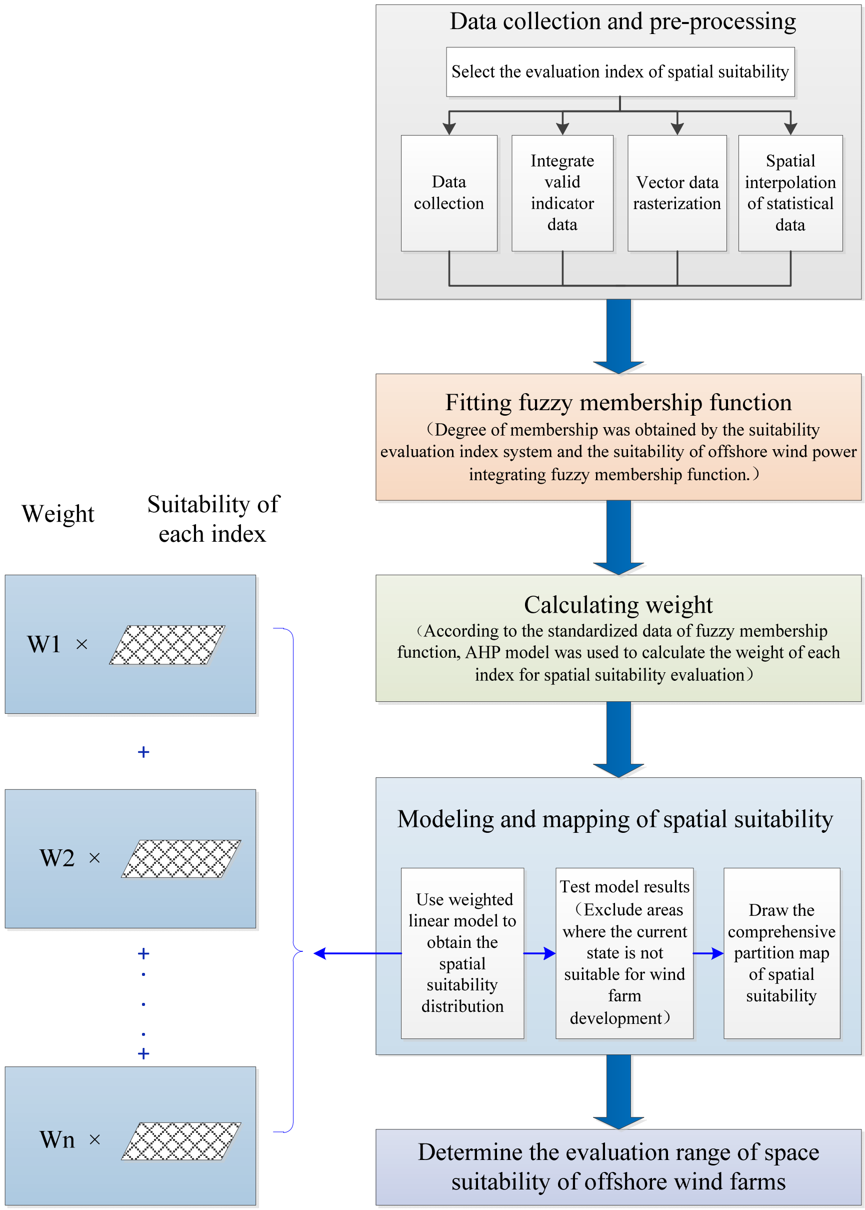

Figure 3. Technical roadmap for determining the suitability of a site for offshore wind power.

In terms of natural conditions, wind speed (C_1) was selected as an evaluation index. Wind speed index is directly related to the energy production and financial return on investment in offshore wind power [17–20,25,26,36,37], which is an important standard used to evaluate the spatial suitability of wind farm locations.

In terms of economic factors, water depth (C_2) and distance from the nearest port (C_6) were selected as evaluation indicators. The water depth index has great technical and economic influence when managers chose the locations of offshore wind farms [17,38]. The greater the water depth, the higher the cost of construction, design, maintenance, control, and energy transfer. The distance from the nearest port index provides another basis for assessing the cost of installation, construction, and operation of wind farms [39]. Therefore, the site selection for offshore wind farms should involve areas as close to ports as possible to minimize the cost of construction, maintenance, and repair [36].

In terms of ecological impact, the distance from the nearest protected area and ecological protection redline (which is an area designated by China that has special and important ecological functions and must be strictly protected) (C_5) was selected as an evaluation index. Although offshore wind farms provide environment-friendly energy production, they may negatively affect the migration of birds and change the habitat of marine benthic organisms [40,41]. When choosing suitable areas for the construction of offshore wind farms, it is necessary to avoid sensitive sea areas, such as important fishing areas, typical marine ecosystems, estuaries, bays, sandbanks, straits, and natural historical site reserves. Natural areas with protected marine resources and marine ecological conservation red-line areas in the PRC include the noted types of marine ecologically and environmentally sensitive areas.

Because of the high level of development intensity of the coastal waters of the PRC, the coordination between wind power and other sea use activities should be considered during the process of offshore wind power site selection. Therefore, this paper selected the distance from coastline (C_3), shipping routes (C_4), and developed water areas (C_7) as the main indicators used to evaluate the coordination between offshore wind power and other sea use activities.

The distance from the nearest coastline index is an important factor used to determine the suitability of offshore wind farm sites [42]. The shorter this distance, the lower the cost of submarine cables and of wind farm maintenance, design, and construction. However, offshore wind farms will generate noise and may negatively affect the visual landscape of the coastline during operation. Therefore, the closer offshore wind farms are located to residential and tourism areas, the greater the negative impact the farms will have on urban living and coastal tourism. When evaluating the spatial suitability of offshore wind farms, it is necessary to find a balance point for the distance of farms from coastlines.

Distance from shipping lanes ensures the safety of shipping lanes, as they compete with the need for the development of offshore wind farms [43–45]. A safe distance should be maintained between these farms and shipping lanes to ensure the safety of maritime traffic and avoid conflicts related to maritime sea use. According to the relevant research, [35] this distance should be more than 2 km.

During the process of selecting sites for offshore wind power generation, it is necessary to consider avoiding military facilities, shipping lanes, submarine pipelines, offshore platforms, and important tourist areas [46], with the goal of reducing potential conflicts in sea area use. In this paper, the sea use activities with sea area use right certificates were considered in developing C_7.

Table 1. Evaluation index system and data sources used for determining the spatial suitability of offshore wind farm locations in Liaoning Province.

Index Number	Index	Units	Numerical Range	Data Sources
C_1	Wind speed	m/s	4.2–4.8	Adopted the wind speed data of Liaoning on August 2018 [47–49]
C_2	Water depth	m	10–60	Water depth data points were interpolated based on data measured by the Chinese National Marine Environmental Monitoring Center in 2005.
C_3	Distance from coastlines	km	10–136	These data were obtained by remote sensing and site reconnaissance.
C_4	Distance from shipping lanes	km	0–113	These data were based on the navigational charts [50]
C_5	Distance from protected areas and ecological conservation redlines	km	0–47	Marine Function Zoning of Liaoning [51]
C_6	Distance to the nearest port	km	0–144	Marine Function Zoning of Liaoning
C_7	Distance from sea use activities with sea area use right certificates	km	0–62	Marine Function Zoning of Liaoning and National Sea Area Use Dynamic Supervision System

4.3. Evaluation Method

4.3.1. Normalization of Indicators

According to the hypothesis of the fuzzy set, the selected evaluation index was represented as a fuzzy set. In the fuzzy set, the function represents the degree of membership of the fuzzy set index Z by determining a value between 0 (not satisfied) and 1 (fully satisfied). Different types of membership functions can be used to build fuzzy sets. The trapezoidal membership function was used in this study, where Equation (1) shows the linear growth fuzzy function and Equation (2) shows the linear decreasing fuzzy function:

$$\overline{MF}(z_i) = \begin{cases} 0 & , z_i < q_i \\ \frac{z_i - q_i}{p_i - q_i} & , q_i \le z_i \le p_i \\ 1 & , z_i > p_i \end{cases} \tag{1}$$

$$\underline{MF}(z_i) = \begin{cases} 1 & , z_i < p_i \\ \frac{z_i - q_i}{p_i - q_i} & , p_i \le z_i \le q_i \\ 0 & , z_i > q_i \end{cases} \tag{2}$$

where $\overline{MF}$ is a linear growth fuzzy function, $\underline{MF}$ is a linear decreasing fuzzy function, z_i is the Spatial Suitability Evaluation Index of offshore wind farm, q_i is a lower threshold (control point) of wind farm fuzzy set index z_i, and pi indicates that all values beyond this point have a complete membership relationship with the fuzzy set (i.e., completely suitable).

Of the seven indicators listed earlier and given in Table 1, C_1, C_3, C_4, C_5, and C_7 used a linear growth function, whereas the remaining indicators used a linear decreasing function. Table 2 shows the fuzzy functions and control points of each evaluation index. The fuzzy set representation of all evaluation indices is shown in Figure 4a–g.

The range of index control points was determined by referring to the index control points in the existing literature [18,38,52]. The maximum value of the linear growth function corresponds to the average value of the corresponding value in the literature, whereas the minimum value should be extended. The linear decreasing function was evaluated in the same way.

Table 2. Membership function and control points.

Serial Number	Index	Type	Fuzzy Function	q	p
C_1	Wind speed	Growth	$\overline{MF}$	6.5 m/s	8 m/s
C_2	Water depth	Decreasing	$\underline{MF}$	60 m	30 m
C_3	Distance from coastlines	Decreasing	$\underline{MF}$	20 km	10 km
C_4	Distance from lanes	Growth	$\overline{MF}$	2 km	3 km
C_5	Distance from protected areas and ecological conservation redlines	Growth	$\overline{MF}$	1 km	5 km
C_6	Distance from ports	Decreasing	$\underline{MF}$	25 km	1.5 km
C_7	Distance from sea use activities with sea area use right certificates	Growth	$\overline{MF}$	1 km	5 km

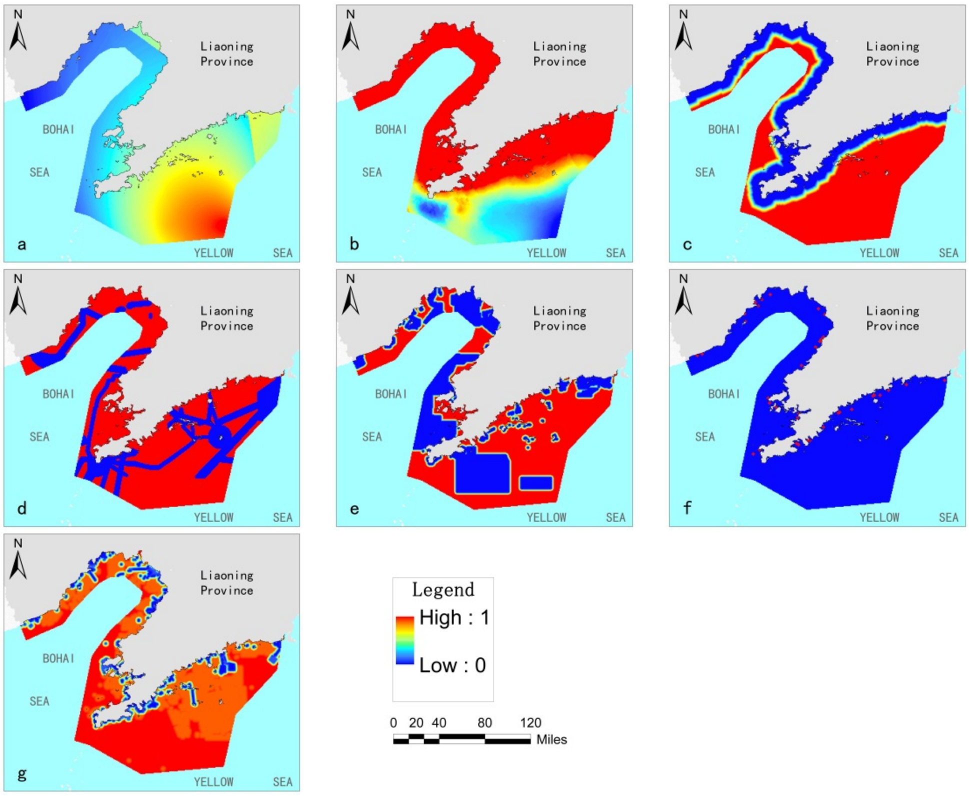

Figure 4. Suitability distribution diagram of evaluation indicators (0 represents unsuitable, 1 represents the most suitable areas for the development of offshore wind power): (**a**) wind speed, (**b**) water depth, (**c**) distance from coastlines, (**d**) distance from shipping lanes, (**e**) distance from protected areas and ecological conservation redlines, (**f**) distance from ports, and (**g**) distance from sea use activities with sea area use right certificates.

4.3.2. Index Weight Determination

AHP was used to evaluate the weight of each index in this study. First, the importance values of each two indicators on the same level were compared, and a judgment matrix was created according to the nine-scale method [53–55] (Table 3); then, the maximum eigenvalue of the judgment matrix and its corresponding eigenvector were calculated, after which the eigenvector was normalized to obtain the weight component vector of each evaluation factor. If the resulting consistency proportionality coefficient was less than 0.1, this indicated that the judgment matrix meets the consistency test criterion and the corresponding weight can be obtained; otherwise, there is no consistency, and the judgment matrix needs to be rebuilt until the consistency proportionality coefficient of less than 0.1 is obtained. The weight coefficient results of each evaluation factor are shown in Table 4. The consistency proportionality coefficient of the judgment matrix in this study was 0.061186, which meets the consistency test.

Table 3. Comparison matrix of the evaluation index system used for determining the spatial suitability of offshore wind farm locations.

Evaluation Factors	Wind Speed	Water Depth	Distance from Coastlines	Distance from Shipping Lanes	Distance from Protected Areas and Ecological Conservation Redlines	Distance from Ports	Distance from Developed and Currently Used Water Locations
Wind speed	1	3	1	1	1	3	5
Water depth	1/3	1	1/3	1/3	1/3	1	3
Distance from coastlines	1	3	1	1	1	3	5
Distance from shipping lanes	1	3	1	1	1	3	5
Distance from protected areas and ecological conservation redlines	1	3	1	1	1	3	5
Distance from ports	1/3	1	1/3	1/3	1/3	1	3
Distance from sea use activities with sea area use right certificates	1/5	1/3	1/5	1/5	1/5	1/3	1

Table 4. Weight of each index used for determining the spatial suitability of offshore wind farm locations.

Serial Number	Index	Weight
C_1	Wind speed	0.1805
C_2	Water depth	0.1169
C_3	Distance from coastlines	0.1805
C_4	Distance from shipping lanes	0.1805
C_5	Distance from protected areas and ecological conservation redlines	0.1805
C_6	Distance from ports	0.1169
C_7	Distance from sea use activities with sea area use right certificates	0.0442

4.3.3. Evaluation Model

This study adopted the weighted linear combination method [56] to evaluate wind farm site suitability. This method weighted the normalized indices to obtain the results of suitability evaluation. The higher the evaluation score, the better the suitability of a site selected for a possible offshore wind farm location. Equation (3) shows the calculation of the weighted linear evaluation model:

$$E(A) = \sum_{i=1}^{n} W_i \times x_{ij} \tag{3}$$

where $E(A)$ is the offshore wind energy suitability index of unit j, W_i is the relative importance weight of standard i, and x_{ij} is the standardized score of unit j of standard i.

At present, no unified classification standard exists for determining the suitability of a potential site for an offshore wind farm. According to existing research, the actual situation in the study area, and the competitive relationship between the locations of shipping lanes and offshore wind farm developments, the waterway area (comprehensive score 0.64) was classified as unsuitable in this study. The areas with a comprehensive evaluation above 0.64 were classified into three grades of suitability (somewhat unsuitable, relatively suitable, and very suitable) by the natural fracture method; unsuitable areas were also designated.

5. Results and Analysis

5.1. Analysis of Suitability Evaluation Results

The suitability evaluation results for sites of offshore wind farms in Liaoning calculated based on GIS and AHP are shown in Figure 5. This figure shows the areas of very suitable, relatively suitable, somewhat unsuitable, and unsuitable areas for offshore wind farms in Liaoning covered 1152 km^2 (accounting for 5% of the total area), 4240 km^2 (18%), 4998 km^2 (21%), and 13,169 km^2 (accounted for 56%) of the total offshore area, respectively.

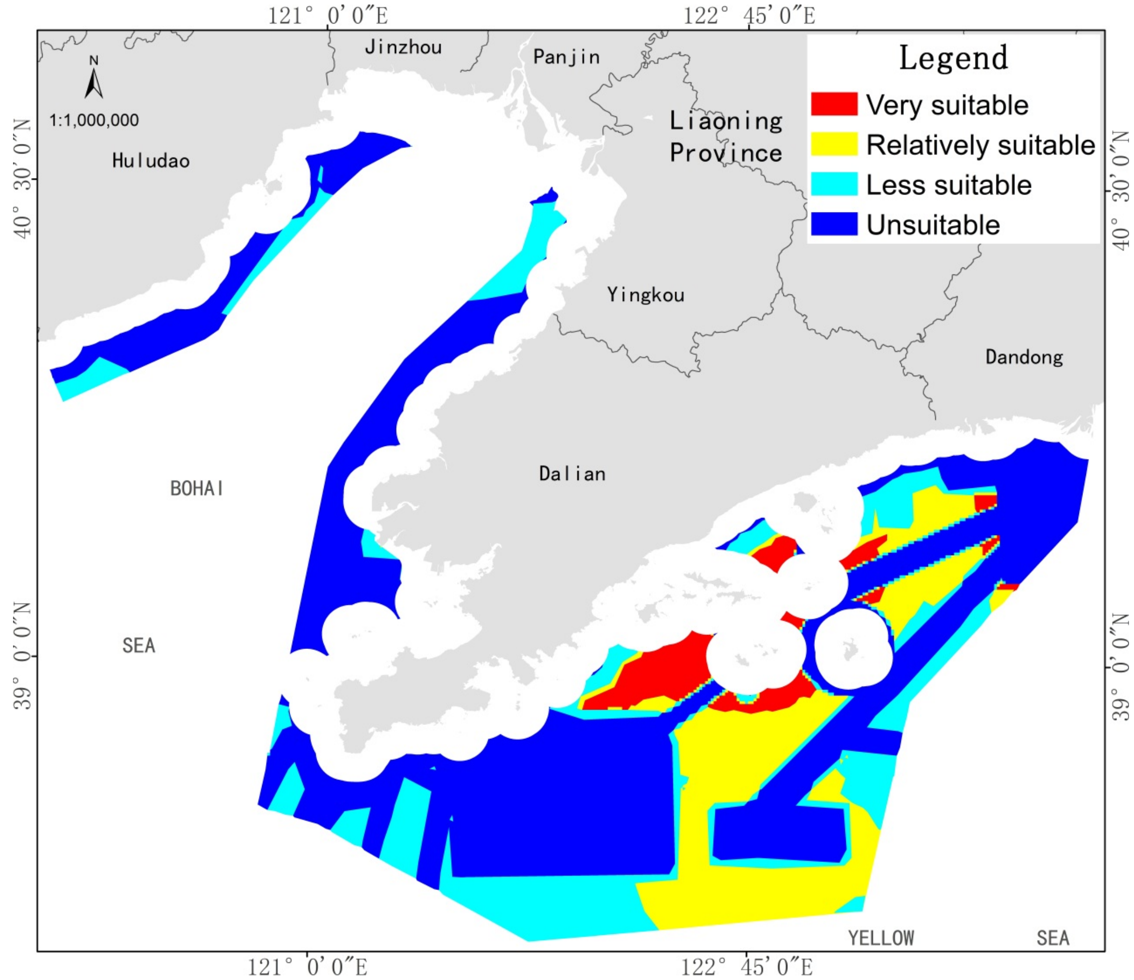

Figure 5. Spatial suitability evaluation of offshore wind farm locations in Liaoning Province.

The evaluation results show that wind speed is the most important factor when selecting sites for offshore wind farms and has the greatest impact on suitability evaluation. Figure 4 shows that the most suitable and relatively suitable areas were concentrated in the Yellow Sea area of Liaoning, mainly including the areas south of Dandong, south of Zhuanghe, and some sea areas of Changhai. The wind speed in these areas gradually increases from near to farther offshore, with an average wind speed of 7 m/s creating excellent wind energy resources (Figure 4a). In addition, the degree of marine development and use in the area is low, while few protected areas exist in this area, so the potential for conflict between wind power and the needs for ecological protection and other sea use activities is small (Figure 4g).

The somewhat unsuitable and unsuitable areas were distributed mainly in the Bohai Sea area of Liaoning, the Southern Yellow Sea area of Liaoning, and the southern Lushun Sea area where the Bohai and Yellow Seas converge (Figure 5). Among these areas located on the Bohai side of Liaoning, although the water is shallow and many ports line the shore, the area typically has low wind speed and lacks adequate energy resources. Although similarly classified areas in the southern Yellow Sea of Liaoning have higher wind speeds and adequate wind energy resources, these areas are close to protected fishery areas where the construction and operation of offshore wind farms would have a negative impact on the spawning grounds of fishery resources (Figure 4e). The evaluation results reflect the fact that, compared with a traditional site selection method based on wind energy and construction and maintenance costs, a comprehensive evaluation method considering ecological protection, wind energy, and the conflicts between different types of sea use as developed in this study is more in line with the PRC's current development strategy, which emphasizes ecological priorities.

5.2. Analysis of Evaluation Effectiveness

This study compares and analyzes the factors influencing wind farm site selection that need to be considered in some policy documents related to wind farms development that are issued at the national and local levels; the goal is to explain whether the construction of the index system is reasonable. According to the technical specifications for wind farm site selection issued by the National Energy Administration of China, wind farm site selection should comprehensively consider various factors, such as wind energy resources, landform, transportation, wind power networking, and environmental protection; the goal is to ensure that the selection of wind farm sites is done in a scientifically sound and reasonable way so that wind farms can operate stably and efficiently. The tentative management approaches for the ecologically sound construction of wind farms in Liaoning issued by the government of Liaoning Province stipulates that the sites for wind farms should be located in a way that reduces the impact of wind farms on various protected areas and avian habitats. The noted policy requirements are consistent with the standards for constructing the index system in this study, so the suitability index system constructed in this paper is reasonable.

The results of the suitability evaluation were compared with the marine functional zonation in Liaoning to further illustrate the rationality of the results of this study. Marine functional zone designation provides the legal basis for the development and use of marine resources while also providing effective protection for the marine environment. A wide variety of sea use activities should comply with the requirements of functional zonation. The study area was divided into areas such as fishery, transportation, protected, reserved, and industrial areas according to the designation of marine functional zones in Liaoning; the designation of these zones puts forward specific control requirements for each type of functional zone. According to the superposition and analysis of marine functional zones in Liaoning and the results of the present suitability evaluation, we found that the very suitable and suitable areas for offshore wind farms were distributed mainly in current fishery, reserve, and industrial areas. Among them, the main purpose for the designation of fishery areas is to increase the cultivation of fishery resources; nevertheless, this can be compatible with energy development activities, such as wind farms, without affecting the fishery function. The reserved area is reserved for future development; however, its management and control requirements also are compatible with offshore wind farms. Therefore, the suitability evaluation results are consistent with the functional positioning and control requirements of Liaoning functional zones, indicating that the evaluation results of this study are credible.

In addition, Liaoning has built 5.84×10^5 kW of offshore wind power. By comparing the existing offshore wind farms in Liaoning with the suitability evaluation results, we found that all the existing offshore wind farms are located in the very suitable areas as defined in this study. It can be seen that the comprehensive evaluation method proposed in this paper has good feasibility and practicability.

5.3. Development and Mitigation Measures for Offshore Wind Farms in Liaoning

According to the evaluation results of an analysis of the spatial suitability of sites for offshore wind power in Liaoning, Liaoning is rich in offshore wind energy resources; however, because of the high intensity of development and use of sea areas, the proportion of sea areas suitable for the regional management of offshore wind power development is not high. This study proposes the following suggestions related to the development and management of these farms in Liaoning:

1. Give priority to the development of deep-water and areas further offshore for use in wind power development, enhance the value of deep and relatively distant spatial sea resources, and avoid sea use conflicts near shore. Various types of sea use occur in coastal waters. With an increase of the distance from the coastline and in water depth, the types of sea use father offshore mainly include submarine pipelines, military uses, port shipping, and fisheries. By locating wind farms farther away from the shoreline and in deeper water, the impact of offshore wind farms on other sea use types will be reduced.
2. Give priority to regional and centralized planning for the planned layout of farm sites with good resource conditions. Small-scale, de-centralized development will lead to a division of resource enrichment areas and a reduction in overall development efficiency. Coordinate farm placement with access to and management of the power grid so that the offshore wind farm locations can be selected in areas with good resource conditions for unified planning and centralized layout. This will reduce the costs of developing wind farms and their environmental impact.
3. In new spatial planning efforts, comprehensively consider the feasibility of addressing environmental and technical constraints and identify any areas that are suitable for offshore wind farm development through GIS. When the timing has not yet been determined for offshore wind farm development, priority should be given to areas with minimal environmental and technical constraints so that the zonation and management requirements are clear and compatible with offshore wind farms. Offshore wind farms should be arranged in an orderly fashion on the premise that they will not have an important negative impact on either national defense or maritime transportation safety.

6. Conclusions

Because of the strong support the PRC has given offshore wind power, current rapid development has experienced an unreasonable tendency for inadequate planning and layout of wind farms, which poses new challenges to the rational allocation of marine spatial resources. According to the actual situation of marine resource use in Liaoning, this study fully considered the coordination between offshore wind power and currently developed and active sea use activities, constructed a spatial suitability evaluation index system for planning the locations of offshore wind farms, and optimized and improved the current multi-attribute evaluation method based on GIS–AHP. The fusion fuzzy membership function was introduced to process the indicators, which avoided the influence of subjective factors on the indicators. This method comprehensively considered various factors, such as economic cost, ecological protection, and sea use in other industries, which can enable marine area managers to identify the areas suitable for offshore wind power construction under the background of high-intensity development. This study has provided a reference for the planning and site selection of offshore wind power in the PRC and other countries with high-intensity wind resource development in coastal waters.

The research showed that the very suitable, suitable, somewhat unsuitable, and unsuitable areas for offshore wind farm development accounted for 5%, 18%, 21%, and 56% of the Liaoning Sea area, respectively. The evaluation results showed that wind speed was the main factor affecting suitability, followed by ecological protection and coordination among other ongoing sea use activities.

During the future development of offshore wind farms in Liaoning, priority should be given to the development of deep-water and relatively far-shore areas to avoid sea use conflicts near shore; priority also should be given to areas with good resource conditions while allowing for centralized planning and layout. At the same time, very suitable and suitable areas should be preferentially designated as offshore wind farms construction areas; the management requirements compatible with offshore wind farm plants should be specified in zoning or planning documents.

Because of the influence of data availability and accuracy, the suitability index for offshore wind farms failed to take into account some technical and economic indices, such as grid connection conditions, transportation conditions, the locations of seismic fault zones, rock areas, and areas with extreme meteorological conditions. This limitation should be improved in future research.

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