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Feasibility Analysis of Offshore Wind Power Projects in the Caribbean Region of Colombia: A Case Study Using FAHP–GIS

Adalberto Ospino Castro [1,*], Carlos Robles-Algarín [2], Luis Hernández-Callejo [3,*], Yecid Muñoz Maldonado [4] and Amanda Mangones Cordero [1]

1 Departamento de Energía, Universidad de la Costa, Barranquilla 080002, Colombia; amangone@cuc.edu.co
2 Facultad de Ingeniería, Universidad del Magdalena, Santa Marta 470003, Colombia; croblesa@unimagdalena.edu.co
3 Departamento de Ingeniería Agrícola y Forestal, Universidad de Valladolid, 42004 Soria, Spain
4 Facultad de Ingeniería, Universidad Autónoma de Bucaramanga, Bucaramanga 680003, Colombia; ymunoz294@unab.edu.co
* Correspondence: aospino8@cuc.edu.co (A.O.C.); luis.hernandez.callejo@uva.es (L.H.-C.); Tel.: +57-5-3229077 (A.O.C.)

Abstract: Planning for offshore wind energy projects is intricate due to the consideration of multiple variables in identifying optimal project areas. The primary challenge lies in locating suitable sites, a process that often necessitates extensive feasibility studies spanning several years. The primary goal of this study is to apply the Fuzzy Analytic Hierarchy Process (FAHP) to prioritize criteria and sub-criteria, facilitating decision-making in choosing appropriate locations for offshore wind projects in the Colombian Caribbean Sea. The weights derived from FAHP were utilized in a Geographic Information System (GIS) to analyze the physical characteristics of the Caribbean Sea's surface. This tool plays a critical role in evaluating and selecting sites that fulfill established criteria, providing a database of indicators and map visualizations. Four criteria were defined: technical, environmental, social, and economic, along with fourteen sub-criteria, which were prioritized through FAHP based on expert judgment. The results revealed that the most relevant sub-criteria were protected areas and wind speed. Utilizing the ArcGIS Pro software, five zones meeting the predetermined criteria were identified, defining the most feasible areas for offshore wind farm installation, located in the departments of Guajira, Magdalena, Atlántico and Bolívar. The GIS–FAHP methods proved to be useful for feasibility analysis.

Keywords: Fuzzy Analytic Hierarchy Process (FAHP); Geographic Information System (GIS); Multi-Criteria Decision-Making (MCDM); offshore wind projects

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1. Introduction

The world population is experiencing continuous growth [1], leading to an increasing demand for electrical energy. In this context, the integration of renewable energy sources into energy systems near cities becomes a key element in meeting this growing energy demand while mitigating environmental impacts [2]. According to the authors in [3], the concepts of smart cities, sustainability and energy are intrinsically interconnected, giving rise to what is now known as Smart Renewable Cities (SRCs). The goal of these cities is to achieve greater economic competitiveness, sustainability and improved quality of life for their residents. In fact, these goals are practically unattainable without a substantial reliance on renewable energy sources [4].

In this context, the importance of offshore wind energy resides in its capacity to diversify the energy mix in SRCs, mitigate greenhouse gas emissions and ensure a more consistent electricity supply. While the offshore wind industry is relatively recent, the inaugural offshore wind farm was established in Vindeby, Denmark, in 1991 [5]. Subsequently, a multitude of offshore wind farms have been built across Europe [6,7], Asia [8–10] and various countries in the Americas [11,12]. However, before undertaking offshore wind energy projects, it is essential to conduct comprehensive feasibility studies that address key criteria such as wind resource availability, connection infrastructure, environmental and social aspects and economic implications [13].

Geographic Information Systems (GIS), combined with Multi-Criteria Decision-Making techniques like the Fuzzy Analytic Hierarchy Process (FAHP), are emerging as a relevant tool to support informed and strategic decision-making in offshore wind energy planning. These techniques provide stakeholders with valuable information for making well-informed decisions [14]. The combination of GIS and FAHP has been widely employed in the literature to create maps identifying specific suitable locations for offshore wind farm development in different countries, considering social, technical, economic and environmental criteria. This approach has been applied in countries such as Sudan [15], Nigeria [16], Pakistan [17] and India [18].

In Colombia, the Caribbean region stands out for presenting highly favorable conditions for the development of offshore wind energy projects, due to the consistent presence of northeast trade winds [19]. Several studies have confirmed this potential using various data sources, such as reanalysis data [20] and satellite observations [21]. Additionally, projections have been made based on climate change scenarios and long-term wind energy trends [22]. Other authors, as seen in [23,24], have applied multi-criteria spatial analysis techniques that combine the AHP with GIS tools to assess the onshore wind and solar potential in this region of the country.

Nevertheless, the full potential of offshore wind energy in the entire Caribbean region has not been completely determined. Despite the existence of a roadmap for the deployment of offshore wind energy in Colombia [25], it is crucial to initiate additional research to identify techniques with greater adaptability and accuracy in modeling the complexity of the factors involved in selecting areas with significant offshore wind energy resource potential. In this research, a GIS–FAHP approach is employed, as it provides a more robust and realistic framework for decision-making in assessing offshore wind energy potential, enabling better consideration of uncertainty and subjectivity in this analysis. This framework is a contribution of this research, as it can serve as a reference for studies in other regions of Colombia and in other countries, after adjusting the criteria according to the availability of information and local legislation. Additionally, the definition of criteria and sub-criteria for the Colombian Caribbean Region is highlighted as a contribution, which allowed us to obtain a unique hierarchical structure for the region under study.

2. Materials and Methods

In general, this research was conducted in three stages to identify the area in the Colombian Caribbean Sea with the highest feasibility for the implementation of offshore wind projects. The first stage involved an evaluation of various works in the field of offshore wind energy, with a focus on the methods to be implemented (GIS and FAHP). This was performed to select the criteria considered for such projects. Table 1 presents the main criteria that were selected, along with their definitions and some of the key references consulted.

Table 1. General criteria defined for the FAHP.

Criteria	Scope	References
Technical	Assess the feasibility in terms of technical resources and the availability of suitable technologies.	[26–32]
Economic	Assess economic viability and benefits, prioritizing locations with economic advantages.	[12,33–38]
Environmental	Assess the suitability of a specific location based on its impact on the marine environment.	[6,34,39]
Socio-Political	Assess compatibility with local policies and regulations and the mitigation of potential social conflicts.	[6,10,36,40]

In the second stage, all the equations in the FAHP method were implemented using Matlab to obtain the weights for the 4 criteria and 14 sub-criteria defined in the hierarchical structure. Each sub-criterion is associated with a map, for which the country's maritime maps and information provided by territorial entities supported by a GIS were used. Finally, in the third stage, GIS–FAHP was implemented for the identification of feasibility zones for offshore projects in the Colombian Caribbean Sea. Using the ArcGIS Pro software, the 14 maps generated for each proposed sub-criterion (each map with its associated weight obtained from FAHP) were overlaid to create a map displaying all the boundaries and ranges defined in the research.

Spatial data corresponding to each criterion examined in the study were collected, adjusting the approach based on the data availability in public records from governmental and international databases. For example, wind speed data were obtained from the International Renewable Energy Agency (IRENA) database and imported into ArcGIS Pro as a TIFF file. This connection was added as a folder, facilitating the layer's addition to the project and allowing a more detailed exploration of values at each point within the studied areas.

In cases such as hurricane routes, data were downloaded from the National Oceanic and Atmospheric Administration (NOAA) database in KML format, enabling the representation of maps in two or three dimensions. For maritime ports, data from the public portal of the Government of Colombia, provided by the Superintendencia de Transporte, were downloaded as a CSV file, with numerous rows of information. These data were filtered and converted into a distinct CSV file, with the correct column order to export latitude, longitude, name and type for each port. Subsequently, this information was exported as an ArcGIS Pro layer using one of its exclusive features. Additionally, the modeling spatial relationships toolset and raster surface tools, incorporated into ArcGIS Pro, were important in this process.

This comprehensive approach facilitated a suitability analysis and culminated in the successful identification of suitable locations for the development of offshore wind projects along the Colombian Caribbean coast.

2.1. Study Area

The Caribbean Region of Colombia is composed of several departments located on the country's northern coast, which together form a distinctive cultural and geographical region in Colombia. It is renowned for its music, dances, cuisine and traditional festivals. Additionally, it holds economic significance for the country due to its port activity, tourism and agro-industrial production. The departments that are part of the Colombian Caribbean Region include Atlántico, Bolívar, Cesar, Córdoba, La Guajira, Magdalena and San Andrés y Providencia. This region is also characterized by its warm climate, its cultural diversity and the influence of the Caribbean Sea.

The Caribbean Sea is an extensive body of water that shares its boundaries with several nations. To the south, it is bordered by the Republics of Colombia, Venezuela and Panamá. Its western limits encompass Costa Rica, Nicaragua, Guatemala, Honduras and Belice. The Greater Antilles, including Cuba, Jamaica, the Dominican Republic and Puerto Rico, mark its northern boundary, while the Lesser Antilles border the east. Colombia has a total maritime area of 928,660 square kilometers and a coastline that extends for 2900 km. It is the only South American country with coastlines along both the Pacific Ocean and the Caribbean Sea.

The geographical coordinates of the Caribbean Region of Colombia vary along its extensive coastline but generally fall within these ranges:

- Northern Latitude: Approximately 10° to 15° north latitude. This region is situated near the equator and, as a result, experiences a warm climate throughout the year;
- Western Longitude: It varies along the Caribbean coast, but mostly falls between 73° and 75° west longitude.

2.2. Hierarchical Structure with FAHP

The Analytic Hierarchy Process (AHP) is a popular technique for Multi-Criteria Decision-Making, aimed at establishing the importance of criteria and priorities for different alternatives through systematic pairwise comparisons. Recognizing that subjective judgments made during these comparisons can sometimes lack precision, the integration of fuzzy sets with AHP has emerged, commonly referred to as Fuzzy AHP or FAHP [15]. Fuzzy AHP allows pairwise comparison in terms of fuzzy sets instead of precise numerical values. This is because fuzzy sets can provide a framework to address the uncertainty, vagueness or lack of precise information associated with the data [15–17].

In this research, the FAHP method was selected due to its ability to handle uncertainty and subjectivity when working with qualitative data, as it allows for the incorporation of experts' opinions in the field of wind energy for decision-making. Additionally, this method enables the assessment and comparison of multiple criteria and sub-criteria hierarchically. In the case of locating offshore wind farms, numerous factors (environmental, economic, social and technical) may exist, and FAHP allows for the integration of this complexity, generating weighted criteria that can be easily integrated into Geographic Information System analysis. FAHP offers advantages, as it can be adjusted to reflect the specific needs of offshore wind project locations, allowing for the modification of criteria, inclusion of new variables or updating of weights as the project evolves. Moreover, this method involves a validation process and methodological robustness, delivering clear and understandable results that can be easily interpreted by decision-makers.

Figure 1 displays the structure defined in this research for the selection of suitable offshore project areas in the Colombian Caribbean region, which consists of three levels: the goal, 4 criteria and 14 sub-criteria. The selection of criteria was performed through work sessions involving all the authors and several experts in the field, along with a review of literature from similar works, which allowed for the definition of the final hierarchical structure. We eliminated criteria that did not significantly contribute to solving the problem and verified the availability of information for the selected criteria in our study area.

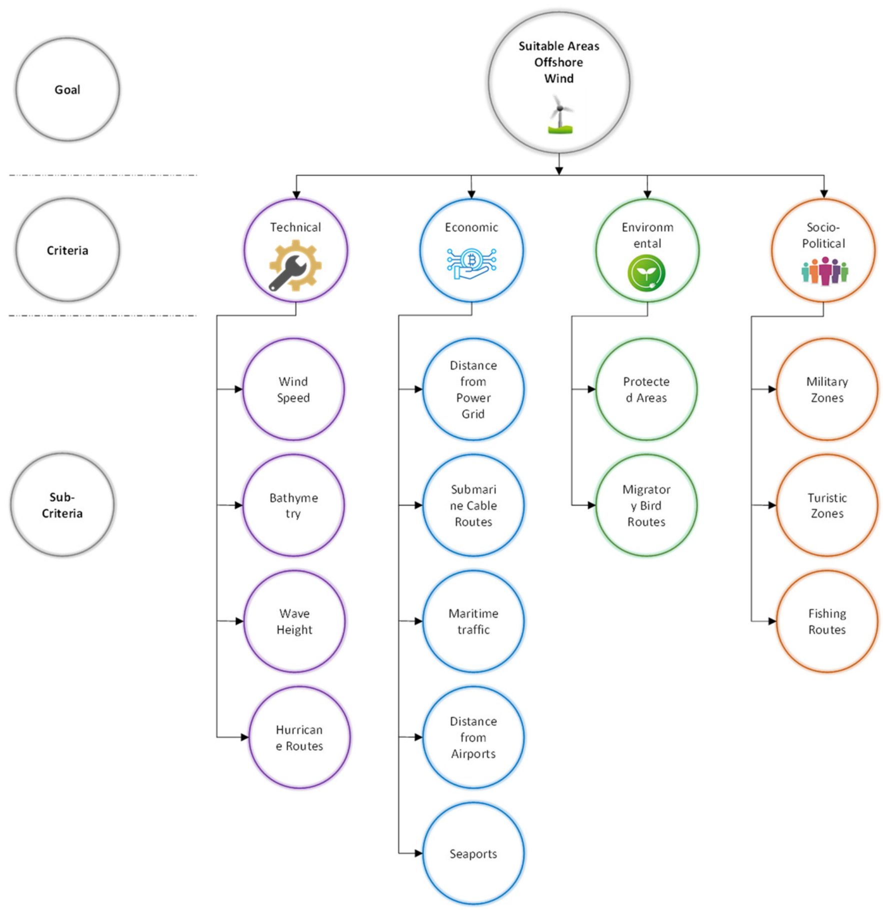

Figure 1. Hierarchical structure for criteria prioritization with FAHP.

2.2.1. Technical Criteria

This section presents the definition and scope of the 4 technical sub-criteria. The maps for each of these criteria can be found in the supplementary material (Figures S1–S4).

- Wind Speed

Wind speed is a critical factor in establishing an economically feasible wind farm. Conventional wind turbines typically necessitate a minimum wind speed ranging from 3 to 3.5 m/s to operate efficiently [38]. On the other hand, wind speeds exceeding 15 m/s can cause turbine damage and require the implementation of sophisticated aerodynamic force control systems. According to the authors [26,27], achieving an annual average wind speed exceeding 6 m/s is essential for the optimal operation of a wind farm installation. Colombia's coastal-marine region with the most substantial wind potential is situated in the Caribbean area, where wind speeds can reach up to 13 m/s. This potential is concentrated along the marine area of the departments of Bolívar, Atlántico, Magdalena and La Guajira, where wind speeds exceed 7 m/s, making them favorable for the development of offshore wind farms (see Figure S1).

- Bathymetry

Bathymetry plays a crucial role, as it directly influences the tower's type and primary cost. Due to continuous technological advancements in fixed and floating foundations, such as monopiles, jackets, tripods, floating and gravity-based [34], fixed-turbine categories can be used in waters up to approximately 50 m deep [28], while floating wind turbines are implemented in water depths ranging from 50 m to 1000 m [29]. In this research, locations with water depths outside of that range (greater than 1000 m) were excluded [41]. Due to the geomorphology, the coastal-marine area of the Colombian Caribbean Sea features depths ranging from 50 m to nearly 25 km from the coast, as seen in the case of Barranquilla, or 30 km from Galerazamba [36], as depicted in Figure S2.

- Wave Height

According to the authors in [30,31], the integrity of offshore wind turbines will be negatively compromised with wave heights exceeding 10 m. In their climatological study of significant wave height in the Colombian basin (between 7° and 22° north latitude and between 69° and 84° west longitude), the authors in [42] estimated significant wave heights, ranging from 4.17 to 5.51 m, which correspond to the wave height map for the Caribbean region shown in Figure S3.

- Hurricane Routes

Hurricanes are a very important factor in the development of offshore wind energy projects, as they directly impact the lifespan of the wind farm. Currently, wind turbines are required to be designed for maximum gusts of 250 km/h, according to current engineering standards, which correspond to the wind speeds of a Category 4 hurricane. According to the National Oceanic and Atmospheric Administration, the Colombian Caribbean (excluding San Andrés y Providencia) has been characterized as a low-probability area for the formation and development of tropical storms, as shown in Figure S4 depicting hurricane paths. Historical distribution percentages place the Atlantic zone, including the Caribbean Sea, at 11% and the western Pacific zone at 39% [32].

2.2.2. Economic Criteria

This section presents the scope and definition of the economic aspects. The 5 maps associated with these criteria can be downloaded from the supplementary material (Figures S5–S9).

- Distance from Power Grid

There are risks and costs associated with building electrical infrastructure for connecting wind farms to the grid. The greater the distance from existing transmission stations to the project site, the higher the installation cost due to cable prices [34]. The distance between the wind farm and the point of connection to the grid should be minimized. Therefore, locations closer to the existing infrastructure are considered more suitable since the existing infrastructure will help to reduce construction costs [38]. In the reviewed literature [33,34], the distances between electrical infrastructure and offshore wind projects vary in a range from 1 km to 207 km. Figure S5 displays the map of the national interconnected electrical system, which demonstrates that the Colombian Caribbean has an extensive electrical grid close to the coasts.

- Submarine Cable Routes

The exclusion of submarine cable routes was based on regulatory frameworks safeguarding these installations. An exclusion area extending 500 m around the submarine cables was established to mitigate potential maintenance issues and prevent cable damage. Previous studies have indicated that these areas were not suitable deployment locations [8,35]. The existence of this infrastructure may limit the available zones deemed appropriate for offshore wind farm development. Submarine cables are susceptible to damage during the construction and upkeep of wind farms. These activities can have drastic financial and social repercussions. In Figure S6, it can be observed that the Colombian Caribbean coast has 8 connection points for submarine cables located in Puerto Colombia, Barranquilla, Tolú, Cartagena, Parque Isla Salamanca, Santa Marta, San Andrés and Riohacha. There are a total of 9 cable routes entering the northern zone of Colombia.

- Maritime Traffic

Offshore wind projects often involve additional risk concerning navigation safety, especially for areas with high boat traffic. For maritime routes, according to [36], a buffer zone of 1 km is recommended due to the risk of collision. Another study [33] recommends installing turbines more than 3 km away from areas with any means of communication, due to the interference that turbines can cause to electromagnetic waves. Figure S7 displays the map of international maritime routes, including the study area.

- Distance from Airports

Wind farms can present a hazard to aviation due to their elevation, which may intersect with low-altitude aircraft flight paths, particularly considering their visibility. One restriction to consider when selecting the turbine locations is their proximity to airport areas for safety and visibility reasons [33]. According to [37], a critical consideration when choosing wind farms is their impact on aviation areas in terms of safety and visibility, so wind turbines should be at least 2500 m away from the airport region [38]. Figure S8 displays a total of 10 airports located in the Colombian Caribbean in the main cities and on San Andrés Island.

- Seaports

The distance from seaports affects the operation and maintenance of offshore wind systems. This is because ports are part of the supply chain that helps to avoid bottlenecks for the implementation and maintenance of these projects [43]. Therefore, it is desirable to have a port in close proximity to offshore wind farms. According to [12], the maximum viable distance to ports is 500 km, considering the types of turbines to be transported. Currently, in the Colombian Caribbean, there are multiple port areas distributed throughout the departments located in the northern part of the country and on the island of San Andrés. Figure S9 displays the different seaports.

2.2.3. Environmental Criteria

This section provides a detailed description of the 3 environmental sub-criteria. The maps corresponding to these criteria can be found in the supplementary material (Figures S10 and S11).

- Protected Areas

Marine protected areas are designated regions acknowledged for their significant natural and ecological worth. These areas are safeguarded by national legislation to ensure the long-term preservation and sustainability of biodiversity [34]. Consequently, installing offshore wind systems in these zones is not feasible [6]. In Figure S10, protected areas designated by various marine and terrestrial ecosystem conservation programs can be observed, including natural protected areas, coral areas, priority conservation sites and biodiversity-protected areas.

- Migratory Bird Routes

Previous studies extensively researched the impact of wind farm installations on birds, indicating minimal effects during operational phases. However, there remains a risk of physical collisions between birds and the blades, towers, nacelles or associated infrastructure [39]. In this study, a restricted zone is established, considering a buffer distance of 1 km around migratory bird routes. The migratory bird route map extracted from the Food and Agriculture Organization (FAO) is shown in Figure S11.

2.2.4. Socio-Political Criteria

This section presents the scope and definition of the 3 socio-political sub-criteria established in this research. The maps corresponding to each of these aspects can be observed in the supplementary material (Figures S12–S14).

- Military Zones

These marine areas are considered unsuitable for the placement of offshore wind systems, as they are used for periodic military operations [6]. On the northern coast of Colombia, there are four military zones near the sea. These areas are exclusively designated for military practices; therefore, in the GIS analysis, they were excluded from the suitable zones for the implementation of offshore systems. Figure S12 shows their locations, which include Riohacha, Santa Marta, Barranquilla and Cartagena.

- Touristic Zones

The installation of wind farms can impact tourist areas, primarily due to the reduced visual appeal caused by the visibility of offshore wind farms from the coastline. This reduction in scenic views can significantly diminish the attractiveness of the affected areas for tourists. According to the Chinese government's policy, the minimum distance of turbines from the coast should be over 10 km [10]. Due to the country's geographical location, Colombia has multiple tourist beaches, as can be observed in Figure S13, which shows that the vast majority of beaches in the Caribbean region are tourist destinations.

- Fishing Routes

These areas have been excluded from feasible sites [36]. Fishing activities are directly affected by offshore wind farms because fishermen are prohibited from operating within these areas or are reluctant to fish within them due to concerns about navigation safety and inadequate space between the turbines for safe fishing deployment. According to [36], a buffer zone of 1 km is recommended due to the risk of collision. The Colombian Caribbean region has several fishing zones and routes in the Caribbean Sea along its coasts. Figure S14 displays the country's fishing routes, with the following regions being the areas with the most fishing activity: La Guajira, Sucre, Córdoba, parts of Antioquia and Chocó.

Once the sub-criteria, scope and map availability for each were defined, the ranges, as shown in Table 2, were established and used to obtain the suitable zones with the GIS. The Appendix A (Table A2) shows the sources consulted to obtain map information for each criterion.

Table 2. Ranges established for each sub-criterion.

Criteria	Sub-Criteria	Range
Technical	Wind Speed	>7 m/s
	Bathymetry	Fixed: 0 m to 50 m Floating: 50 m to 1000 m
	Wave Height	<10 m
	Hurricane Routes	Wind Areas ≤ 250 km/h
Economic	Distance from Power Grid	Between 1000 m and 207 km
	Submarine Cable Routes	>500 m
	Maritime traffic	>1000 m
	Distance from Airports	≥2500 m
	Seaports	<500 km
Environmental	Protected Areas	Not Applicable
	Migratory Bird Routes	>1000 m
Socio-Political	Military Zones	Not Applicable
	Touristic Zones	>10 km
	Fishing Routes	>1000 m

2.3. FAHP Implementation

Once we defined the hierarchical structure, we proceeded to calculate the weights of all the sub-criteria. For this purpose, the triangular numbers scale of the FAHP method was used (Table 3), which allows the collection of expert judgments for the construction of pairwise comparison matrices. This scale more accurately represents pairwise comparisons in terms of fuzzy preferences.

Table 3. Fuzzy relative importance scale for paired comparison.

Scale of Importance	Fuzzy Scale	Fuzzy Reciprocal Scale
Equal	(1,1,1)	(1,1,1)
Intermediate value	(1,2,3)	(1/3,1/2,1)
Moderately more	(2,3,4)	(1/4,1/3,1/2)
Intermediate value	(3,4,5)	(1/5,1/4,1/3)
Significantly more	(4,5,6)	(1/6,1/5,1/4)
Intermediate value	(5,6,7)	(1/7,1/6,1/5)
Extremely more	(6,7,8)	(1/8,1/7,1/6)
Intermediate value	(7,8,9)	(1/9,1/8,1/7)
Absolutely more	(9,9,9)	(1/9,1/9,1/9)

The fuzzy triangular numbers in Table 3 are represented by $\tilde{A} = l, m, n$, corresponding to the upper and lower limits (l and n) and the mean value (m). The reciprocal values of the fuzzy scale are calculated according to Equation (1). Figure 2 illustrates the implementation of the triangular fuzzy scale, in which the triangular numbers in blue represent intermediate values.

$$\widetilde{A}^{-1} = \left(1/n,\ 1/m, 1/l\right) \quad (1)$$

A total of 10 experts with expertise in Geographic Information Systems, renewable energies and offshore wind energy projects were consulted for collecting judgments (see Table A1). Appendix A displays the profile of each of the surveyed experts. These experts were consulted via email using a form created in the online tool QuestionPro. The form consisted of questions organized in a bipolar matrix, where experts selected their preferred relationship between two factors, utilizing the fuzzy scale, as presented in Table 3.

Using pairwise comparisons, matrices were constructed for each level of the hierarchy. These matrices represent the relative importance relationships between elements and are used to derive the final weights [44]. A total of 5 square matrices were implemented for each consulted expert. Tables 4–7 show the matrices with the data provided by the first expert for the sub-criteria. The matrices for the other experts were filled out in a similar manner to proceed with the aggregation process. The matrices with the overall results were obtained using the geometric mean of the 10 consulted experts, as suggested by Saaty for the FAHP [44].

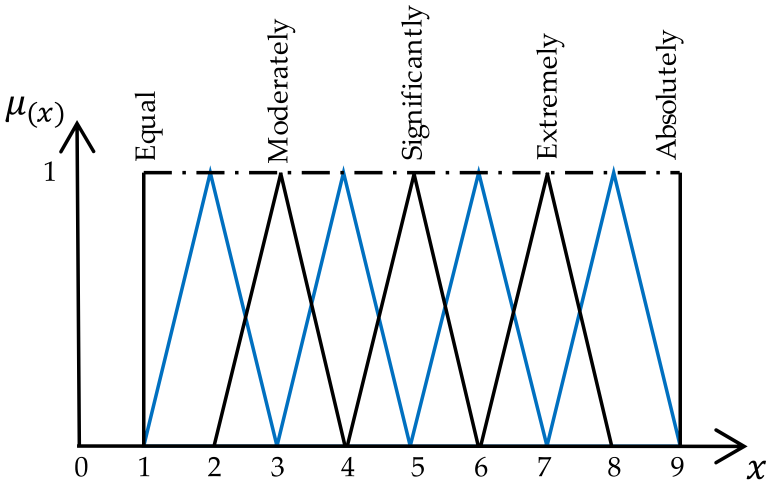

Figure 2. Graphic representation of the implemented fuzzy scale.

Table 4. Pairwise comparison matrix for the technical sub-criteria.

Technical	Wind Speed			Bathymetry			Wave Height			Hurricane Route		
Wind Speed	**1**	**1**	**1**	4	5	6	4	5	6	1/6	1/5	1/4
Bathymetry	1/6	1/5	1/4	**1**	**1**	**1**	1	1	1	1/8	1/7	1/6
Wave Height	1/6	1/5	1/4	1	1	1	**1**	**1**	**1**	1/8	1/7	1/6
Hurricane Route	4	5	6	6	7	8	6	7	8	**1**	**1**	**1**

Criteria: Technical.

Table 5. Pairwise comparison matrix for the economic sub-criteria.

Economic	Distance from Power Grid			Submarine Cable Routes			Maritime Traffic			Distance from Airports			Seaports		
Distance from power grid	1	1	1	1	1	1	4	5	6	2	3	4	4	5	6
Submarine Cable Routes	1	1	1	1	1	1	1	1	1	2	3	4	1	1	1
Maritime Traffic	1/6	1/5	1/4	1	1	1	1	1	1	2	3	4	1	1	1
Distance from Airports	1/4	1/3	1/2	1/4	1/3	1/2	1/4	1/3	1/2	1	1	1	1	1	1
Seaports	1/6	1/5	1/4	1	1	1	1	1	1	1	1	1	1	1	1

Criteria: Economic.

Table 6. Pairwise comparison matrix for the environmental sub-criteria.

Environmental	Protected Areas			Migratory Bird Routes		
Protected Areas	1	1	1	1	1	1
Migratory Bird Routes	1	1	1	1	1	1

Criteria: Environmental.

Table 7. Pairwise comparison matrix for the socio-political sub-criteria.

Socio-Political	Military Zones			Touristic Zones			Fishing Routes		
Military Zones	1	1	1	1/8	1/7	1/6	1/6	1/5	1/4
Touristic Zones	6	7	8	1	1	1	2	3	4
Fishing Routes	4	5	6	1/4	1/3	1/2	1	1	1

Criteria: Socio-Political.

Once the pairwise comparison matrices were defined, we proceeded with the calculation of the fuzzy geometric mean $\tilde{r}_i$ using Equation (2):

$$\tilde{r}_i = [\tilde{a}_{i1} \otimes \cdots \tilde{a}_{in}]^{1/n} \quad (2)$$

where $\tilde{a}_{in}$ corresponds to the fuzzy value of the pairwise comparison between criterion i and criterion n. The multiplication of fuzzy numbers was implemented as shown in Equation (3):

$$\tilde{A}_1 \otimes \tilde{A}_2 \otimes \cdots \tilde{A}_n = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) \otimes \cdots (l_n, m_n, u_n) = (l_1 \times l_2 \times \cdots l_n, m_1 \times m_2 \times \cdots m_n, u_1 \times u_2 \times \cdots u_n) \quad (3)$$

Subsequently, the calculation of the fuzzy weight of each criterion was performed using Equation (4), bearing in mind that the addition operation is performed similarly to the multiplication operation established in Equation (3).

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \cdots \tilde{r}_n)^{-1} \quad (4)$$

Assuming that $\tilde{w}_i$ = [a, b, c], the fuzzy weights were converted into an equivalent positive number using the expression in Equation (5), and then they were normalized using Equation (6):

$$M_i = \frac{a + b + c}{3} \quad (5)$$

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \quad (6)$$

The normalization process described in Equation (6) involves converting the original values of comparisons into relative values. Normalization allows the transformation of subjective values into a relative scale that can be used to perform coherent mathematical calculations. In the case of Equation (6), normalization of the column vectors associated with the criteria is performed, ensuring that the sum of each category is 1. This way, we were able to obtain the weightings for all the criteria based on the judgments of the experts.

In order to assess the consistency of the judgments provided by the experts, the consistency ratio (CR) for each of the matrices was calculated using Equation (7). Each expert was considered consistent if their CR $\leq$ 10%, as suggested by Saaty for the FAHP.

$$CR = \frac{\frac{\lambda_{max} - n}{n-1}}{RI}, \ \lambda_{max} = \frac{\sum_{i=1}^{n} d_i}{n} \quad (7)$$

where n is the dimension of the matrices and RI is the random consistency index. λ_{max} corresponds to the largest principal eigenvalue of a paired reciprocal comparison matrix of size n. In the case where paired comparisons are completely consistent, λ_{max} equals the size of the matrix and the consistency ratio CR is zero. The larger the inconsistency among pairwise comparisons, the greater the value of λ_{max} and, consequently, that of CR.

The values of RI defined for matrices up to 10 × 10 are shown in Table 8. These values were computed by Saaty from 500 matrices of the same size randomly generated [15,17]; hence, each RI value represents the mean of the values obtained for each $n \times n$ matrix.

Table 8. Random consistency index (RI).

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

3. Results

With the implementation of the FAHP method, local weighting was obtained for each of the sub-criteria, following the aggregation process using the geometric mean of the judgments of the 10 consulted experts. Figure 3 displays the results ordered according to the hierarchical structure established in this research. For the technical criteria, wind speed obtained the highest weight at 54.44% (Figure 3a); for economic criteria, the distance from power grid had a weight of 34.72% (Figure 3b); for environmental criteria, protected areas had a weight of 78.36% (Figure 3c) and for socio-political criteria, military zones had a weight of 39.04% (Figure 3d).

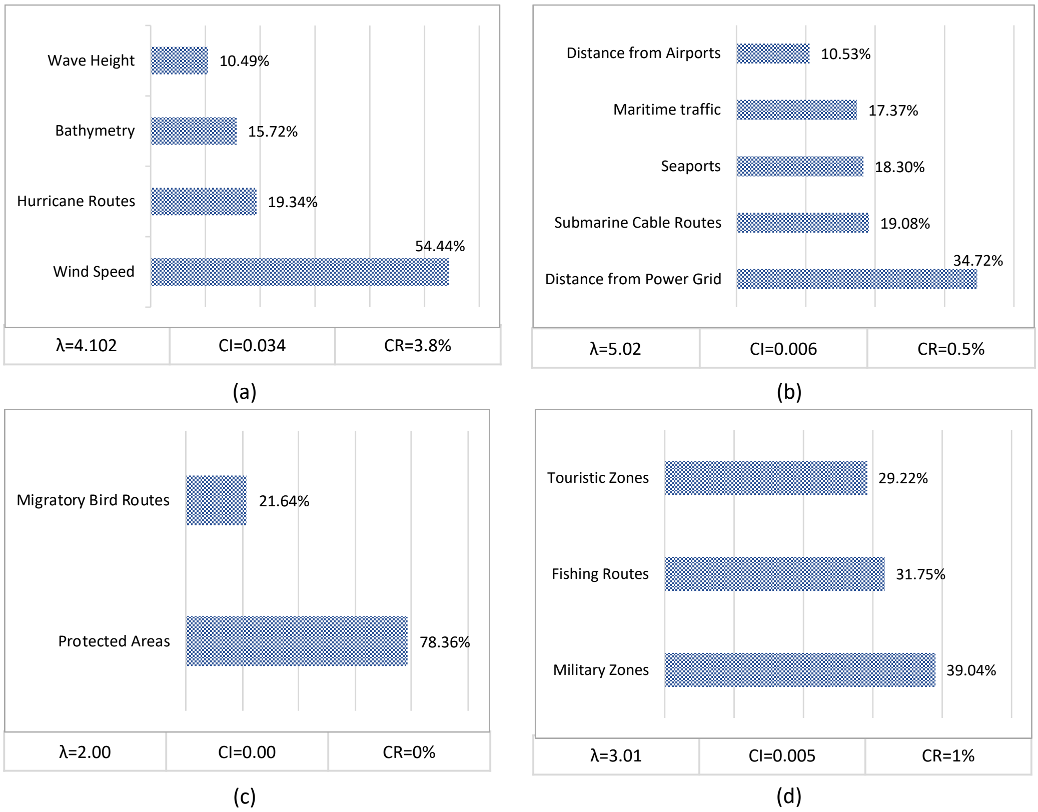

Figure 3. Local weights obtained for the sub-criteria in each category: (**a**) Technical; (**b**) Economic; (**c**) Environmental; (**d**) Socio-Political.

The CR for the combined matrices is shown in Figure 3, with values ranging between 0% and 3.8%. Individually, the CR value for each of the consulted experts was less than 10%, with values ranging from 0% to 9.94%. In general, higher CR percentages were observed for larger-order matrices, which was the case for the technical and economic criteria that had matrices of 4 × 4 and 5 × 5, respectively.

With the local results for the criteria and sub-criteria, the global results for the 14 sub-criteria were obtained. Figure 4 provides a detailed view of the values obtained. It can be observed that the highest weights were for protected areas (19.59%), wind speed (13.61%) and military zones (9.76%), while distance from airports (2.63%) and wave height (2.62%) had the lowest weights. With the weights obtained for the 14 sub-criteria and starting from the geospatial data in GIS for each map, the weights were assigned to their corresponding layer. This implies that the elements were weighted according to their relative importance based on the criteria evaluated through FAHP.

Using the global weights presented in Figure 4 and the defined ranges for each sub-criterion in Table 2, the resulting map was obtained, as shown in Figure 5, after overlaying all the maps corresponding to each sub-criterion.

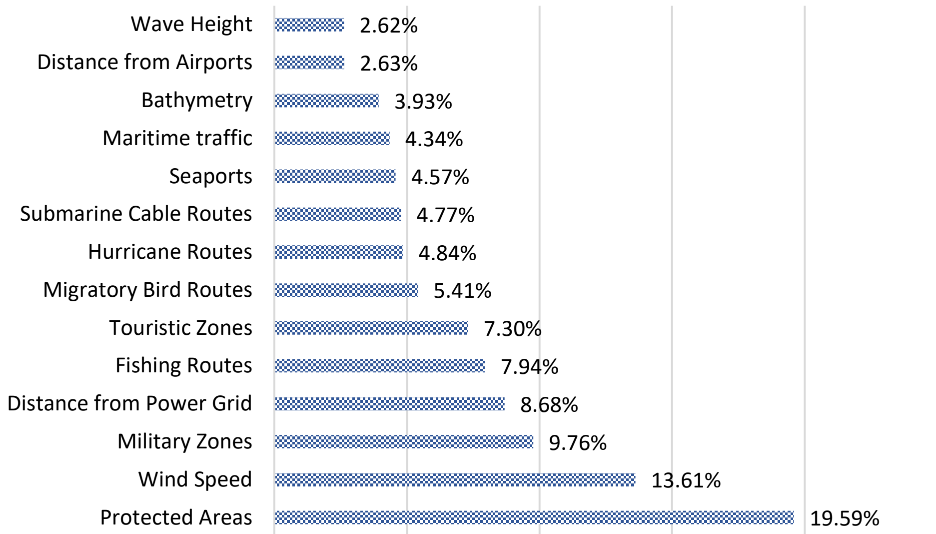

Figure 4. Global weights obtained for the sub-criteria.

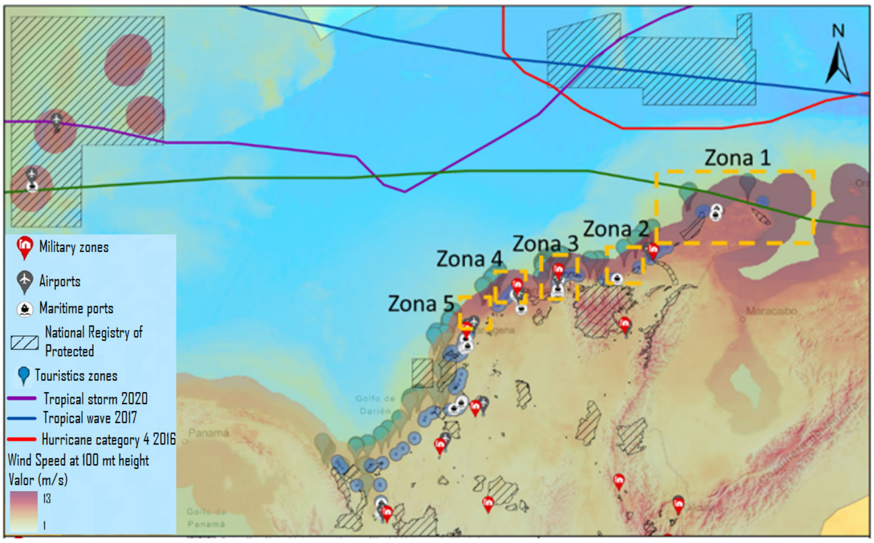

Figure 5. Resulting map: overlay of maps of the sub-criteria.

Subsequently, the areas that were not available for offshore wind farm development were removed based on the restrictions established in the previous sections for each sub-criterion. These areas represent the regions that meet all the technical, economic, environmental and socio-political parameters calculated and evaluated according to the importance assigned by the FAHP method.

The combined analysis of the FAHP methodology and GIS techniques provides a detailed assessment of the suitability of various areas for the development of offshore wind farms. Five zones were identified as promising, as shown in Figure 5, meeting the established criteria and featuring high wind speeds and low wave heights (Table 9). Additional factors, such as bathymetry and wave height, influence the recommendation of anchoring technologies or offshore platforms to be used. The identified zones include the departments of La Guajira, Magdalena, Atlántico and Bolívar, which stand out for lacking critical restrictive factors that could hinder the development of offshore wind projects. In these areas, hurricane trajectories are not observed, eliminating a potential concern for facility safety. Furthermore, the proximity to airports and seaports is favorable for logistical facilitation, and there are no protected areas, migratory bird routes, military zones, touristic zones or fishing routes that limit the feasibility of offshore wind projects. The absence of restrictive criteria in the selected zones is essential when considering the viability and suitability of conducting explorations for potential offshore wind projects in the region.

Table 9. Specific location of exploration areas zones.

Exploration Area	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Coordinates	12.261°, −71.995°	11.189°, −74.350°	11.228°, −74.859°	10.990°, −75.057°	10.818°, −75.266°
Wind Speed	10.9 m/s	8.2 m/s	9.3 m/s	9.5 m/s	8.4 m/s
Bathymetry	−9 m	−418 m	−534 m	−32 m	−9 m
Wave Height	0.6 m	1 m	0.7 m	0.5 m	0.3 m
Marine Platforms	Fixed	Floating	Floating	Fixed	Fixed

Figure 6 shows Zone 1 located in the department of La Guajira, which meets all the search criteria. A low percentage of protected areas at sea can be observed, along with a high wind speed, a single military base that is located on land, two seaports and a nearby airport. The only possible disadvantage is the hurricane path that passes through the northern part of Zone 1, which can be avoided by building the offshore wind park in an area further south.

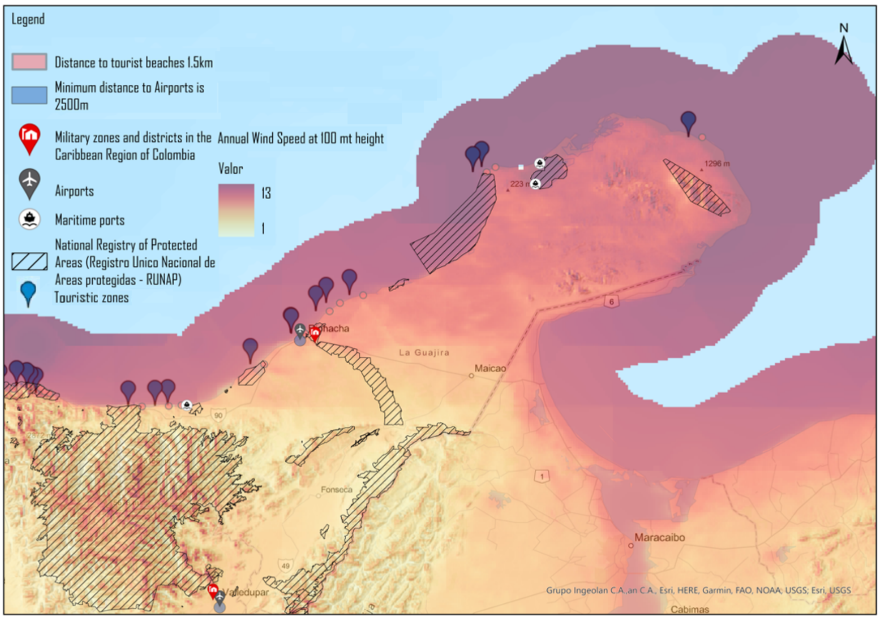

Figure 6. Selected areas: Zone 1.

In Zone 2, located in the department of Magdalena (Figure 7), all the sought-after criteria are met. A significant portion of the area is not designated as protected area; there is a high wind speed, no military bases, an airport and four nearby seaports. Additionally, much of the area is more than 10 km away from tourist beaches.

In Zone 3, located between the boundaries of the departments of Atlántico and Magdalena (Figure 8), bordering Isla Salamanca, all the sought-after criteria are met. Much of the area is not part of marine protected areas there is a high wind speed, no military bases and six nearby seaports, and a significant portion of the area is more than 10 km away from tourist beaches. The shallow bathymetry of the area, ranging from 1 to 50 m, requires that, in the event of installing wind turbines, they should be fixed rather than floating.

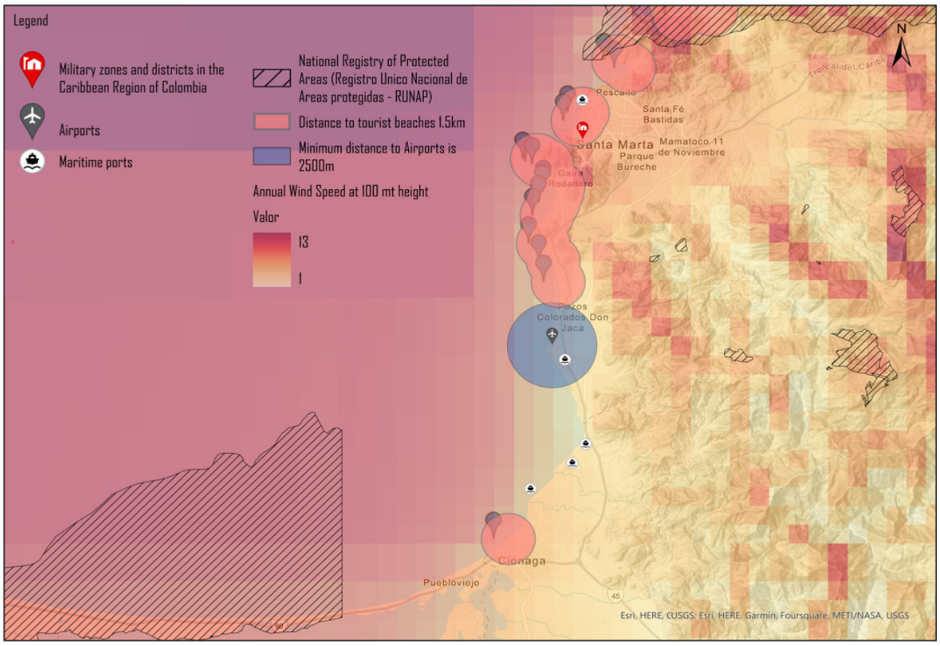

Figure 7. Selected areas: Zone 2.

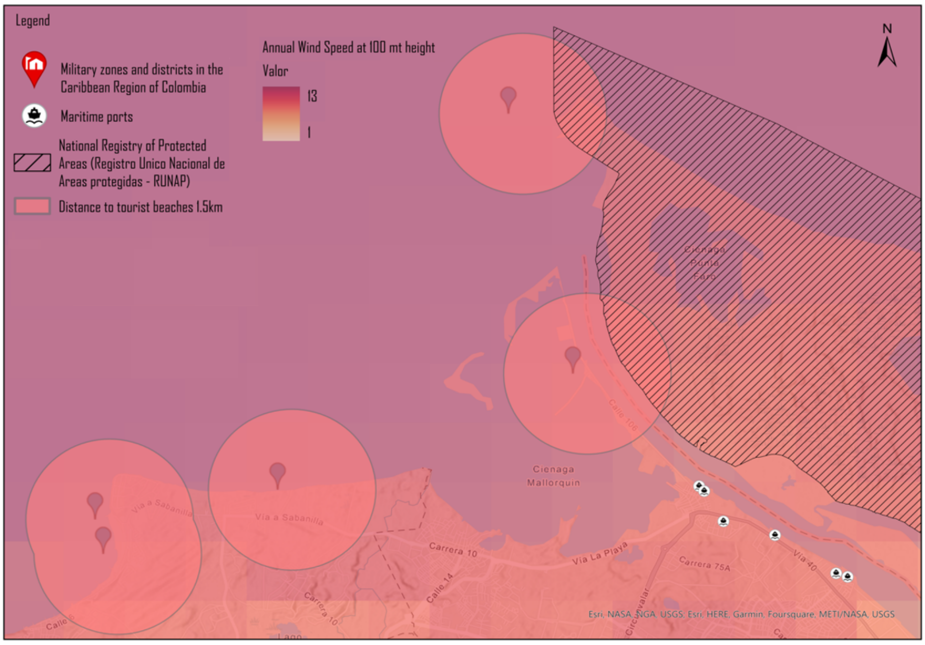

Figure 8. Selected areas: Zone 3.

Figure 9 depicts Zone 4, located in the department of Atlántico, between the municipalities of Puerto Colombia and Tubará. This zone meets all the sought-after criteria, including the absence of protected areas, a high wind speed, no military bases, a nearby seaport (in Barranquilla) and two relatively close airports (Barranquilla and Cartagena), in addition to having no tourist beaches. The bathymetry of this area ranges from 0 to 40 m, making it advisable to use fixed turbines.

Zone 5, located between the departments of Bolívar and Atlántico (Figure 10), specifically from Juan de Acosta (Atlántico) to Clemencia (Bolívar), meets all the sought-after criteria: no marine protected areas, high wind speed, no military bases, two nearby seaports and two relatively close airports (in Barranquilla and Cartagena). Additionally, there are no tourist beaches within 10 km.

Figure 9. Selected areas: Zone 4.

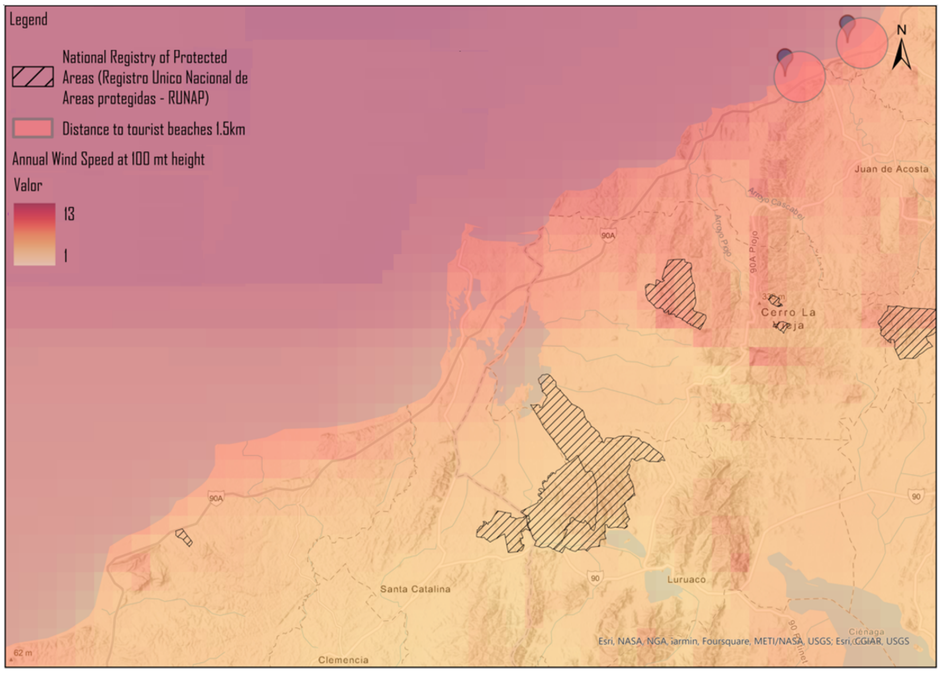

Figure 10. Selected areas: Zone 5.

4. Conclusions

After completing this research, it can be concluded that the FAHP method is a useful tool for collecting expert opinions to weigh important criteria in decision-making processes. In this study, 14 sub-criteria were selected, and the results highlighted the significant influence of protected areas (with 19.59% favorability) and wind speed (with 13.61%) on decision-making. The GIS–FAHP combination allowed the selection of suitable areas for offshore wind energy projects. Five promising zones were identified that meet technical, economic, environmental and socio-political criteria in the departments of Guajira, Atlántico, Bolívar and Magdalena. This multi-criteria assessment approach based on GIS–FAHP not only provides an effective methodology for offshore wind energy projects in the Colombian Caribbean, but also underscores Colombia's potential to harness this marine wind resource on its path toward energy transition. In this way, we fulfilled the objectives established at the beginning of the research related to the identification of important criteria and sub-criteria for the implementation of offshore projects. Additionally, we integrated the weights obtained through FAHP into the analysis conducted using Geographic Information Systems.

The proposed framework in this research offers the potential for various future works in the field of renewable energies in other regions of Colombia, wherein GIS–FAHP methodologies can be implemented for feasibility and suitability studies. The suggested approach can be applied in other countries, with the adjustment of criteria according to local constraints set by researchers and current regulations. Additionally, in our next work, we will focus on conducting an intersectional analysis zone by zone, covering the five zones defined in this research.

One of the main limitations of this approach lies in the construction of the hierarchical structure. As the number of criteria increases, the size of the matrices also increases, and experts tend to be inconsistent. Moreover, the construction of the hierarchy can be influenced by the judgment and perception of the researchers, which could lead to an inadequate representation of the real problem.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152416620/s1, Figure S1: Wind speed map; Figure S2: Bathymetry map; Figure S3: Wave height map; Figure S4: Hurricane routes map; Figure S5: Electrical grid map; Figure S6: Submarine cable route map; Figure S7: Maritime route map; Figure S8: Airport map; Figure S9: Seaport map; Figure S10: Protected areas map; Figure S11: Migratory bird routes map; Figure S12: Military zones map; Figure S13: Touristic zones map; Figure S14: Fishing route map.

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Abbreviations

Abbreviation	Definition
FAHP	Fuzzy Analytic Hierarchy Process
AHP	Analytic Hierarchy Process
GIS	Geographic Information System
MCDM	Multi-Criteria Decision-Making
SRCs	Smart Renewable Cities
IRENA	International Renewable Energy Agency
NOAA	National Oceanic and Atmospheric Administration
FAO	Food and Agriculture Organization
CR	Consistency Ratio
RI	Random Consistency

Appendix A

Table A1. Profile of the experts consulted for implementing the FAHP method.

Country	Profile
India	Ph. D. in Applied Hydraulics and Mechanics. Civil Engineer. Areas of interest: wind resource assessment, renewable energy, soil moisture and hydrology applications.
Canada	Ph. D. in Aerospace Research. Mechanical Engineer, Master's in mechanical engineering (MIT). Areas of interest: numerical simulation, renewable energy, forecasting, computational fluid dynamics and aerodynamics.
Spain	Ph. D in Electrical Engineering. Areas of interest: power quality, electrical engineering, renewable energy technologies, wind energy, photovoltaic power plants and energy efficiency.
Morocco	Ph. D. in Geosciences and Environment. Areas of interest: GIS, renewable energy, environmental consulting in soil and risk management.
Mexico	Ph. D. in Electrical Engineering, Master of Science in Electrical Engineering, Bachelor of Electrical Engineering. Areas of interest: distributed generation systems with renewable energy sources and computer programming.
Brazil	Ph. D., Master's and Bachelor's in Geography. Areas of interest: cartography, socio-environmental impacts, the use of geotechnologies, geoinformation, ArcGIS and socio-environmental analysis of offshore wind projects.
Colombia	Ph. D. in Electrical and Electronic Engineering (c), Electronic Engineer. Areas of interest: wind energy, photovoltaic solar energy and control systems.
Colombia	Ph. D. in Energy Technology, Electronic Engineer, Master's in project management. Areas of interest: energy technology, renewable energy and photovoltaic systems.
Colombia	Ph. D. in Mechanical Engineering, Master's in engineering with a focus on Electronics and Computers, Electronic Engineer. Areas of interest: artificial intelligence, renewable energy and control systems.
Colombia	Electronic Engineer, Master's in engineering. Areas of interest: renewable energy in the Colombian Caribbean and photovoltaic solar energy.

Table A2. Information source for the sub-criteria.

Sub-Criteria	Data Map
Wind speed	IRENA. "International Renewable Energy Agency". (s.f.). https://globalatlas.irena.org/workspace (accessed on 18 September 2023).
Bathymetry	GEBCO. "Gridded Bathymetry Data Download". 2023. https://download.gebco.net/ (accessed on 18 September 2023).
Hurricane routes	NOAA. "National Oceanic and Atmospheric Administration". (s.f.). https://www.nhc.noaa.gov/data/tcr/index.php?season=2011&basin=atl (accessed on 18 September 2023).
Distance to the power grid	UPME-Unidad de Planeación Minero Energética. "Geoportal-SIMEC". 2019. http://sig.simec.gov.co/GeoPortal/Mapas/Mapas (accessed on 19 September 2023).
Submarine cable routes	Telegeography. "Submarine Cable Map". 2022. https://submarine-cable-map-2022.telegeography.com/ (accessed on 20 September 2023).
Distance to airports	ANI-Agencia Nacional de Infraestructura. "Aeropuertos Geográficos ANI". 2023. https://www.datos.gov.co/Transporte/Aeropuertos-Geogr-ficos-ANI/cqwh-jz5k/data (accessed on 20 September 2023).
Seaports	Datos Abiertos. "Tráfico Portuario Marítimo En Colombia". 2023. https://www.datos.gov.co/Transporte/Trafico-Portuario-Mar-timo-En-Colombia/5r3g-zv5z (accessed on 17 September 2023).

Table A2. *Cont.*

Sub-Criteria	Data Map
Protected areas	RUNAP-Registro Único Nacional de Áreas Protegidas. "Parques Nacionales Naturales De Colombia" 2023. https://runap.parquesnacionales.gov.co/cifras (accessed on 17 September 2023).
Military zones	Datos Abiertos. "Zonas y Distritos Militares Ejercito Nacional". 2023. https://www.datos.gov.co/Seguridad-y-Defensa/ZONAS-Y-DISTRITOS-MILITARES-EJERCITO-NACIONAL/jpus-ug29 (accessed on 19 September 2023).
Landscape protection	A proprietary map was created based on data compilation from multiple sources.
Fishing route	INVEMAR-Instituto de Investigaciones Marinas y Costeras. "Atlas Caladeros De Pesca". (s.f.). https://invemar.maps.arcgis.com/apps/mapviewer/index.html?layers=36625d90a71e4abca52ed6e55f6eecaf (accessed on 18 September 2023).
Wave height	SURFEAME. "Mapas de Olas: Altura, Dirección y Periodo (Swell)". (s.f.). https://surfeame.com/prevision/mapas/olas/ (accessed on 18 September 2023).
Maritime routes	Logihfrutic. "Rutas Internacionales Marítimas". https://logihfrutic.unibague.edu.co/rutas-internacionales-maritimas (s.f.). (accessed on 18 September 2023).
Bird migration routes	C. Shupeng et al., 2008 [45]

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