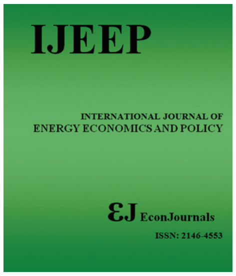

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2023, 13(6), 64-73.

An Analytic Hierarchy Process Based Approach for Evaluating Feasibility of Offshore Wind Farm on the Colombian Caribbean Coast

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Received: 15 June 2023 **Accepted:** 15 September 2023 **DOI:** https://doi.org/10.32479/ijeep.14621

ABSTRACT

Planning a wind power generation project is intricate, considering the number of variables to be careful in the acceptable zone selection for its siting. One of the difficulties of developing a wind farm is finding the most satisfactory location to build it; this can take years of feasibility studies. The main objective of this research is to use the Analytic Hierarchy Process (AHP) to prioritize a group of criteria and sub-criteria as decision-making support for the selection of suitable areas in which implementing wind energy projects in the Colombian Caribbean Sea. The criteria to be applied in this study were selected based on the most recurrently employed criteria in other research papers and the experience of the authors. Thus, a hierarchical structure with 4 criteria (technical, environmental, social, and economic) and 14 subcriteria was implemented. All criteria were prioritized using the methodology proposed by AHP, for which 10 experts with experience in offshore wind projects were consulted, through a form designed with a matrix structure. The results allowed prioritizing a set of criteria necessary for offshore energy planning projects, in which the criteria of Protected Area (19.62%), Wind Speed (13.84%) and Military Areas (9.79%) were the most relevant.

Keywords: Energy Planning, Analytic Hierarchy Process, Offshore Wind, Renewable Energy
JEL Classifications: D70, Q20, Q42, P181

1. INTRODUCTION

The use of renewable energies has expanded rapidly worldwide, of which wind energy has been the renewable source with the fastest rate of growth over the last decade, and projections indicate that this situation will continue in the following years. Countries like the United States, where the electricity demand rises every minute, are world leaders in wind power. Decreasing dependence on fossil fuels, particularly carbon, while renewable energy sources increase their contribution to the energy portfolio (Cerdá et al., 2012).

According to the Latin American Energy Organization (OLADE), Latin America and the Caribbean have great potential in electricity production, with renewable resources that exceed the expected demand for the year 2050. In the Global Wind Report presented in 2022, it was reported that the countries with bigger wind power installed potential by 2021 in Latin America: Brazil (21.5 GW), Mexico (7.2 GW), Argentina (3.2 GW), Chile (3.4 GW), Colombia (1.7 GW) and others LATAM countries (2.3 GW) (Global Wind Energy Council, 2022).

In Latin America, the development of wind power has been gaining impulse only during the last few years. There are some wind farms along the continent, particularly in countries such as Mexico, Brazil, Chile, Costa Rica, and Uruguay (Global Wind Energy Council, 2017). In the selection and identification of wind farms, the Analytic Hierarchy Process (AHP), is a relative measuring theory that provides the analytic tool to model the problem's complexity and process subjective and personal judgment from the individuals or a group in the decision-making (Andrea et al., n.d.). The AHP process categorizes subjective judgments inside a rigorous mathematical framework (using matrices), this way giving each an objective value with which it can be conducted in a decision-making process.

In practice, the AHP framework provides a problem decompression and structuring, to minimize the coherence of the subjective judgments, that generally are obtained from the experts in the study area (Osorio and Orejuela, 2008). AHP has been constantly used as a weight estimation technique in diverse application areas, such as in the sustainable development area, education, and waste recycling programs. In the energy sector research has been conducted to evaluate energy-saving technologies, planning of electric supply on remote rural zones, planning with renewable energies, microgrids, politics on favor of solar mobility and megaprojects of hydraulic energy, among others (Robles Algarín et al., 2017a).

Offshore wind energy is a relatively young industry and the first offshore wind farm in the world was established in 1991, in Vindeby in the Danish country (Breton and Moe, 2009). Since then, many offshore wind farms have been built in Europe (Latinopoulos and Kechagia, 2015; Ochieng et al., 2014; Vasileiou et al., 2017b; Willsteed et al., 2018), Asia (Kim et al., 2018; Kim et al., 2016; Mahdy and Bahaj, 2018a; Nezhad et al., 2021; Tegou et al., 2010; Wu et al., 2018) and American countries (Mekonnen and Gorsevski, 2015; Rodman and Meentemeyer, 2006; Villacreses et al., 2017; Vinhoza and Schaeffer, 2021a). In Colombia, despite having great potential, the development of offshore wind energy projects is still in the process of being developed, most existing studies have focused on assessing the region's wind potential, while economic, social, and environmental aspects have not yet been widely considered (Global Wind Energy Council (GWEC), 2022; Perez and Garcia-Rendon, 2021).

Colombia has an installed capacity of energy, distributed a 68.4% on hydraulic generation, the 13.3% with natural Gas, a 7.8% with liquid fuels, the 9.5% with carbon, and approximately a 1% with FNCER (wind, solar, and biomass) (Perez and Garcia-Rendon, 2021). This matrix composition makes the Colombian electric system vulnerable in scenarios such as the El Niño phenomenon, where the water resource tends to decrease, the backup is by thermoelectric generators, incurring high generation costs and a significant environmental impact (David et al., 2022). This scenario can be reduced with the diversification of the energy matrix, especially with a rise in the involvement of the NCRES, it is projected that these sources represent between 13% and 18% of the electrical system generation by 2031 (Restrepo-Trujillo et al., 2022; Reyes et al., 2022).

In the context of the ongoing energy transition towards renewable sources, offshore wind energy has become an increasingly viable and promising alternative in the production of clean and sustainable power (Rodrigues et al., 2015). Specifically, the Colombian Caribbean coast boasts superior wind and sea depth conditions and holds great potential for the implementation of offshore wind energy projects (Vera, 2019).

It is important to consider that decisions regarding offshore wind projects involve multiple criteria, such as technical, economic, environmental, and social feasibility. The Ministry of Mines and Energy launched a roadmap for offshore wind energy, which shows the general criteria and limitations of the Colombian Caribbean Sea (The Renewables Consulting Group, 2022). This roadmap does not socialize a systematic evaluation framework, which causes possible errors in decision-making. Given this situation, it is necessary to develop a multicriteria decision-making method to objectively evaluate the factors or criteria to be considered in determining the feasibility of a project.

The multi-criteria method to be used in this paper is based on the AHP approach. Also, a participatory approach was implemented involving multiple interest's parts, thus allowing a more complete and balanced evaluation of the offshore wind energy projects on the Colombian Caribbean coast.

2. AHP REVIEW

The Analytic Hierarchy Process (AHP), is being widely used for evaluating conflicting data, using a pair-wise comparison between the parameters under consideration. AHP is a mathematical approach that considers the group or individual's preferences in decision-making and may examine qualitative and quantitative aspects concurrently (Lin et al., 2008). In this method a hierarchy is performed in which the problem to solve is located at the top and at the base are the solution alternatives. At the intermediate levels are the criteria that are the basis of decision-making (Saaty, 1990).

The proposed AHP model to determine the importance of the criteria to find areas for the implementation of offshore wind energy is composed of the following steps described in Figure 1 (Santos et al., 2022).

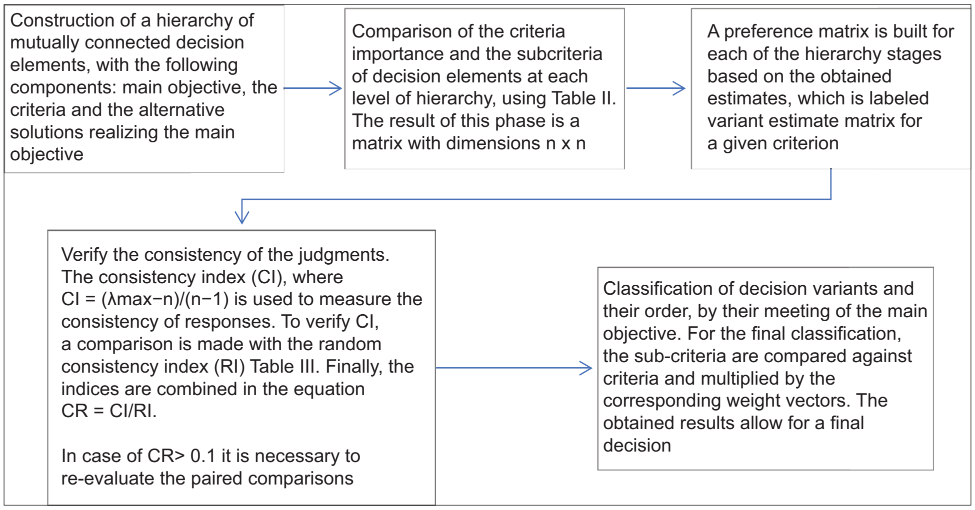
Table 1 shows the importance scale implemented in the AHP for the expert consultation process. Using this scale, the paired comparison matrices necessary to prioritize the criteria defined in this work are obtained. Table 2 describes the random consistency indices, defined by Saaty for matrices up to 10 × 10, which are necessary to calculate the consistency ratio.

3. POTENTIAL OF OFFSHORE WIND IN COLOMBIA

Renewable energy in Colombia has been on the rise in the last few years. In 2018, Colombia´s electricity portfolio coming from renewable energies was 50MW, which corresponded approximately to 1% of the total electricity; in 2019, the portfolio corresponded to 1.5% (or 180MW), and in 2020 it reached 1500MW (Unidad de Planeación Minero Energética-UPME, 2020). For 2022, it was expected to reach 10% of Colombia´s electricity portfolio, by reaching the 2500MW, which was not accomplished.

Because of the above, Colombia must intensify its efforts to increment renewable energies and develop non-conventional renewables to reach the planned energetic objectives (Cabello

Figure 1: Stages of the AHP



Construction of a hierarchy of mutually connected decision elements, with the following components: main objective, the criteria and the alternative solutions realizing the main objective

Comparison of the criteria importance and the subcriteria of decision elements at each level of hierarchy, using Table II. The result of this phase is a matrix with dimensions n x n

A preference matrix is built for each of the hierarchy stages based on the obtained estimates, which is labeled variant estimate matrix for a given criterion

Verify the consistency of the judgments. The consistency index (CI), where CI = (λmax−n)/(n−1) is used to measure the consistency of responses. To verify CI, a comparison is made with the random consistency index (RI) Table III. Finally, the indices are combined in the equation CR = CI/RI.

In case of CR> 0.1 it is necessary to re-evaluate the paired comparisons

Classification of decision variants and their order, by their meeting of the main objective. For the final classification, the sub-criteria are compared against criteria and multiplied by the corresponding weight vectors. The obtained results allow for a final decision

Table 1: Scale for importance (Saaty, 1990)

Linguistic scale	Value (a)
Equal importance	1
Moderate importance	3
Strong importance	5
Very strong importance	7
Extreme importance	9
Intermediate values between the two adjacent judgments	2, 4, 6, 8

Table 2: Random consistency index (RI) (Robles Algarín et al., 2017b)

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

et al., 2018). The Caribbean Sea has very good conditions to develop wind power because of the persistent trade winds from the northeast (Costoya et al., 2019). Other studies reported the potential of the offshore wind resource using reanalysis and satellite data (Guo et al., 2018; Rueda-Bayona et al., 2019); while other researchers have established this potential, using climate change scenarios and long-term wind energy tendencies (Zheng et al., 2017).

According to the IDEAM, the land wind power potential in Colombia has been studied all over the country, and in specialized literature exist several investigations at a local level (Fernando Álvarez et al., 2013; Jiménez and Diazgranados, 2012; Ordóñez et al., 2014). In offshore wind energy, one of the main advantages is that it is on the ocean, the wind speed is higher and less unstable due to the roughness of the sea surface, that's smaller than land (continental) surfaces. The principal disadvantages of offshore wind energy are the costs of construction and maintenance, which this type of system requires (Wen Cheng, 2002).

Colombia has a total offshore technical wind potential of approximately 110GW, which includes the implementation of fixed and floating wind farms (The Renewables Consulting Group (RCG), 2022). Being, the north coast of Colombia the area with the highest potential, due to the wind speeds which reach values higher than 10 m/s (Figure 2), making these areas to be technically desirable for wind energy production (Group World Bank and ESMAP, 2020).

Colombia has recently introduced the offshore wind energy development roadmap, where is proposed the production of up to 1GW of offshore wind energy for 2030, 3GW by 2040, and 9 GW by 2050 (The Renewables Consulting Group, 2022). This roadmap establishes the foundations for the implementation of offshore wind energy in Colombia, outlining the regulatory landscape for the social and environmental assessments, permits, licensing procedures, and the use of seabed (Global Wind Energy Council, 2022).

4. ESTABLISHING CRITERIA, SUB-CRITERIA, AND ALTERNATIVES

A bibliographic review of research related to evaluating the feasibility of Offshore Wind farms using multicriteria decision tools was performed to establish the criteria and sub-criteria. Solving the site selection issue for an offshore wind farm is a critical step and must be done considering many criteria, such as technical, environmental, social, and political. The criteria that will be applied in this study were selected based on the criteria previously applied with more frequency in other research projects and the international industry best practices. This way, a preliminary list of 14 sub-criteria was prepared, grouped into 4 categories (Figure 3):

4.1. Technical Criteria

4.1.1. Wind

Wind speed is an important factor to develop a wind farm in an economically viable area. The standard wind turbine requires a minimum speed between 3 and 3.5 m/s to function effectively (Zahid et al., 2021). On the contrary, wind speed higher than 15 m/s can cause damage to the turbine, and, besides they require the implementation of aerodynamic force regulation systems (Rafaat and Hussein, 2018). According to the authors Bahaj et al. (2020), Felipe and Guerrero (2020), Schallenberg-Rodríguez and García Montesdeoca (2018), a minimum annual wind speed of more than

Figure 2: Map of offshore wind technical potential (Group World bank and ESMAP, 2020)

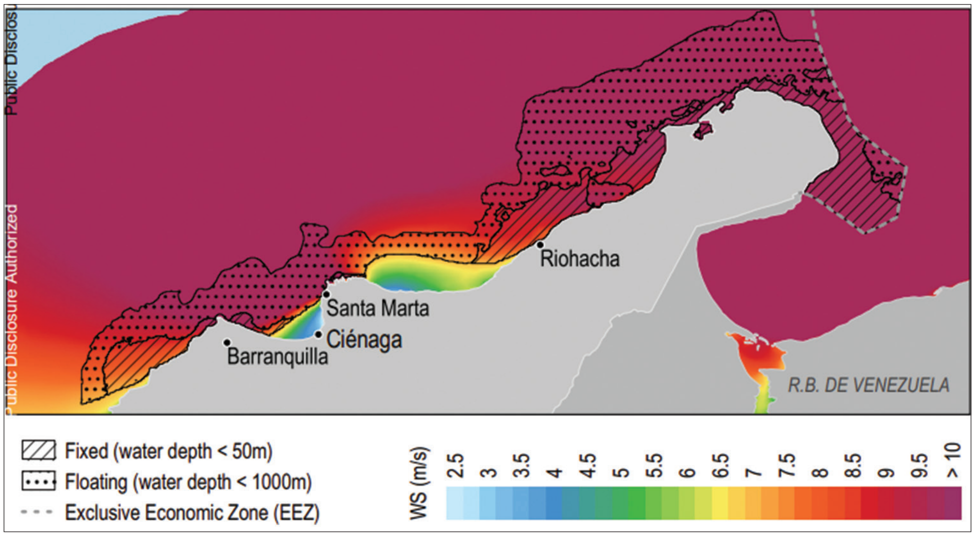
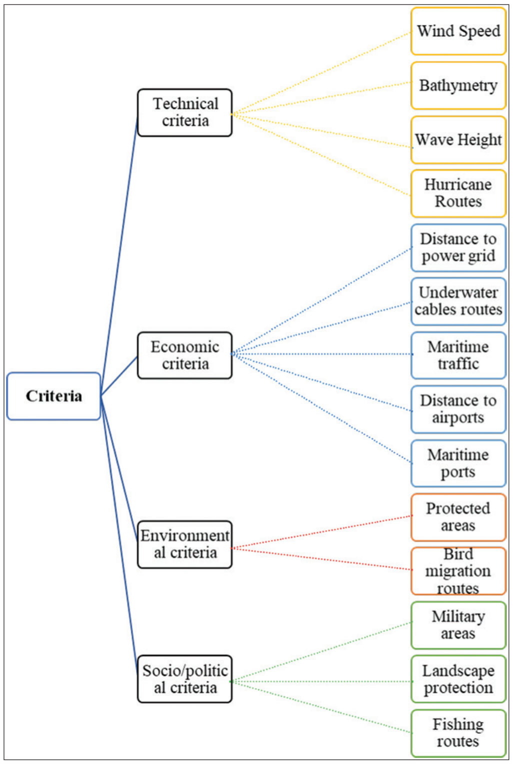


Figure 3: Criteria and sub-criteria



6 m/s is required for the optimal functioning of the installation of a wind farm.

The coastal-marine zone (CMZ) with greater wind potential is in the Caribbean region of Colombia with wind speeds up to 13 m/s (Arco De Mora et al., 2013). This potential is focused along the CMZ zones of the departments of Bolivar, Atlántico, Magdalena, La Guajira, which present speeds higher than 7 m/s, this being favorable for the development of offshore wind farms.

4.1.2. Wind bathymetry

Bathymetry is a crucial factor that determines the type and principal cost of the tower. The base technology of offshore wind turbines is affected by the water depth. Due to the continuous technological development in fixed and floating foundations, such as monopiles, jackets, tripods, floating and gravity-based (Deveci et al., 2020a).

The fixed turbine category can be used in water depths of about 50 m (Li et al., 2022), while floating wind turbines are implemented in depths oscillating between 50 m and 1000m (Program, 2019). Places, where depths are off those ranks, are excluded (higher than 1000 m) (Martinez and Iglesias, 2022). Due to geomorphology, the CMZ (coastal-marine zone) of the Colombian Caribbean Sea counts with depths of 50 m to almost 25 km of distance from the coast like it is the case of Barranquilla or 30 km from Galerazamba (Candel, 2014).

4.1.3. Wind wave height

According to the authors Fetanat and Khorasaninejad (2015); Gil-García et al. (2022); Sulaiman et al. (2013), the integrity of the offshore wind turbine will be negatively compromised with a wave height higher than 10 m. The authors in Thomas et al. (2011) conducted a climatological study of the significant height of swell (Hs) in the Colombian watershed (between 7° and 22° latitude north, and between 69° and 84° longitude west), showing estimated values between 4.17 m and 5.51 m.

4.1.4. Wind hurricane routes

Hurricanes are an important factor in the development of offshore wind energy projects. These natural phenomena implicate the life period of the wind farm according to the bearable maximum wind speeds by the aerogenerators. Nowadays, wind turbines must be designed for peak gusts of 250 km/h according to the engineering actual standards, which are equal to the speed of a category 4 hurricane. According to the NOAA, the Colombian Caribbean (excluding San Andres Island and Providence), has been categorized as having a low chance of tropical storm development and formation zone. The historic distribution percentages place the Atlantic zone, including the Caribbean Sea at 11% and the West Pacific zone at 39% (Ortíz Royero, 2007).

4.2. Wind Economic Criteria

4.2.1. Wind distance to the power grid

Generally, there are risks and costs for electric infrastructure construction for the connection of wind farms to the grid. The greater the distance between the transmission stations, the installation cost due to the price of the cable will be higher (Deveci et al., 2020b). The distance between the wind farm and the connection point with the grid must be minimal, because of this the closer the location it will be considered more adequate because the existing infrastructure will help reduce the costs of construction (Zahid et al., 2021). In the reviewed literature, the distances between electric infrastructure and offshore wind projects vary in rank between 1 km and 207 km (Aydin et al., 2010; Cullinane et al., 2022; Deveci et al., 2020a; Hansen et al., 2005).

4.2.2. Wind underwater cable routes

The underwater cable routes are selected as exclusion criteria because of the normative framework that protects these installations. A zone of buffering with 500 m around the submarine cables is established as an exclusion area to avoid possible maintenance problems and avoid damaging to the cables. Previous investigations stated that these areas are not deployment sites (Gavériaux et al., 2019; Mahdy and Bahaj, 2018b). The presence of this infrastructure can restrict the designated areas that are adequate for offshore wind farm development. The underwater cables can be easily damaged during the construction and maintenance process of wind farms. These activities can have drastic financial and social repercussions (Taoufik and Fekri, 2021).

4.2.3. Maritime routes

Offshore wind projects often implicate an additional risk according to navigation security, especially for areas with high boat traffic (Naus et al., 2021). For maritime routes, Candel (2014) recommends a buffering zone of 1km because of the collision risk. Another study recommends placing the turbines more than 3km away from zones with some communication medium (for example boat communication radios), because of the interference the turbines can cause to the electromagnetic waves (Aydin et al., 2010).

4.2.4. Distance to airports

Wind farms can be dangerous for aviation, due to their height these installations can get into conflict with low altitude flying planes, especially giving their visibility. These gigantic structures can also affect the performance of navigation and communication by the control tower (NASAG, 2012). A restriction to consider is selecting the location site of the aerogenerators in its proximity to airport areas for security and viability reasons (Aydin et al., 2010). According to Nguyen (2007), when selecting wind farms, an important consideration is the aviation areas that affect security and visibility. Nguyen mentioned that wind turbines must be at least 2500 m distance from the airport region (Zahid et al., 2021).

4.2.5. Maritime ports

The distance to the maritime ports can affect the maintenance and operation of offshore wind systems (Alkhalidi et al., 2023). This occurs because the ports are part of the supply chain that helps avoid the bottlenecks for the realization and maintenance of these projects (Adachi and Takagi, 2023). Because of this, it is considered desirable to count on a port near offshore wind farms. According to Vinhoza and Schaeffer (2021b), the maximum viable distance to the ports is 500 km, this value is given considering the types of turbines to be transported.

4.3. Environmental Criteria

4.3.1. Protected areas

Offshore wind projects can have negative effects on marine benthos, sea mammals or whales, fishermen, coral reefs and life coordination. This type of project must be planned in a way that no harm will come to marine life, to be considered reproduction breeding times for marine species (Deveci et al., 2020a). The protected marine areas correspond to zones of recognized natural value and ecology, where long-time viability and biodiversity maintenance are secure through national legislation. Consequently, deploying offshore wind systems in these areas is not feasible (Vasileiou et al., 2017a).

4.3.2. Bird migration routes

The effect on birds because of the installations of wind farms was deeply investigated in previous studies and emphasized insignificant impact along the operative faces (Astiaso Garcia et al., 2015). However, the birds can still physically impact/collide against the blades, towers, and wind gondolas or with any other related infrastructure (Marques et al., 2020; Moriguchi et al., 2019). A buffer distance of 1 km around the bird migration routes is considered a restriction zone in this study.

4.4. Socio/Political Criteria

4.4.1. Military areas

These marine zones are considered not suitable for the siting of offshore wind systems because these areas are used for the implementation of military periodic and/or special operations (Pahlke et al., 2007; Tercan et al., 2020; Vasileiou et al., 2017b).

4.4.2. Landscape protection

Touristic zones can be affected by the installation of wind farms. An important problem is that the visibility of the wind farms can reduce the touristic appeal of the affected areas (MINCIT-Ministerio de Comercio, 2021). According to a study conducted on the south Aegean (Greece), a minimum distance of 1.5 km is necessary for said places (Taoufik and Fekri, 2021). On the other hand, according to Chinese government politics, the minimum distance of the turbines from the coast must be more than 10 km (Wu et al., 2018).

4.4.3. Fishing routes

Sustainable fishing activities require space, such as developing and operating offshore wind farms, therefore, these areas have been excluded from the feasible sites (Candel, 2014; De Figueiredo Xavier et al., 2022). Fishing activities are directly affected by the offshore wind farms because it is prohibited for the fishermen to operate inside of these areas or are reluctant to fish inside these areas because of the concern about the security of the navigation and the inadequate space between the turbines for the safe deployment of the fishing (Qu et al., 2021). According to Candel (2014) a buffer zone of 1 km is recommended because of the risk of collision.

5. PRIORITIZATION PROCESS WITH AHP

In the process of prioritization of criteria and sub-criteria, a questionnaire was developed following the methodology proposed for the AHP, which was answered by 10 experts (Table 3).

For each expert, 4 matrices of comparison were elaborated and distributed as follows: Technical, economic, social/political, and environmental criteria. Each expert was assigned the same weight, and subsequently a process of aggregation of all the judgments was performed using the geometric mean. For the case of prioritization of the criteria, the opinions were compiled and standardized using global prioritization, assigning to each criterion the same level of importance (25% each).

6. RESULTS AND DISCUSSIONS

After processing the data obtained with the questionnaire applied to the experts, a consistency ratio of <10% was obtained for each of the matrices of each expert (Table 4). It can be seen that for the larger matrices, those associated with economic (5 × 5) and technical (4 × 4) criteria, the CR values are higher compared to the values obtained for the smaller matrices, associated with environmental (2 × 2) and social/political (3 × 3) criteria. In general, the larger the size of the matrix, the higher the probability of finding inconsistent experts.

The pairwise comparison matrices obtained, after the aggregation process using the geometric mean with the data of the 10 experts consulted, are shown in Tables 5-8. The methodology used is extended by the authors Robles Algarín et al. (2017b).

Once the criteria have been defined, the pair-wise analysis was conducted, meaning that for each criterion each one of the sub-criteria was compared with each other. For example, in the matrix shown in Table 7, the value of 3,647 indicates that PA is preferred over BMR, likewise, the value 0.274 corresponds to the inverse, which means, the comparison is made in both directions PA vs BMR and BMR versus PA, which explains why the diagonal corresponds to values of 1 since it reflects the sub-

Table 3: Profile of the experts consulted

Country	Profile
India	Civil Engineer. Ph.D. in Applied Mechanics and Hydraulics. Post-Doctoral Research Fellow in the Civil Engineering Department, Indian Institute of Technology Bombay. Focused on wind resource analysis, renewable energy, soil moisture, hydraulic application, Microwave Remote Sensing, and SIG. Active since 2012.
Canada	Mechanical Engineer, M.Sc. in Mechanical Engineering (MIT), Ph.D. (National Office of Aerospace Studies and Research), Professor in the Department of Engineering, University of Moncton. Focused on: Numerical simulation, Renewable energy, Forecasting, Computational fluid dynamics, and Aerodynamics. Active since 1981
Spain	Ph.D. in Electrical Engineering. Ph.D. Coordinator: Renewable Energies and Energy Efficiency, Department of Automatics, Electrical Engineering and Electronic Technology, Universidad Politécnica de Cartagena. Focused on: Power quality, electrical engineering, renewable energy technologies, electrical engineering, wind energy, photovoltaic power plants, and energy efficiency. Active since 1999.
Morocco	Ph.D. in Geosciences and Environment. Hassan II University. Professor, Ben M'Sik Faculty of Sciences. Focused on: GIS, Renewable Energies, Environmental Consultant, Soil, and Risk management.
Mexico	Ph.D. in Electrical Engineering. Master of Science in Electrical Engineering, Bachelor of Science in Electrical Engineering. Professor Universidad Autónoma de San Luis Potosí, Focused on Distributed generation systems with renewable energies, and computer programming.
Brazil	Ph.D., Master and Bachelor in Geography, Professor at EEEP Darcy Ribeiro - CENTEC/SEDUC-CE Researcher and Socio-environmental Consultant. Focus on: Cartography, socio-environmental impacts, use of geo technologies, Geoinformation, ArcGIS, and socio-environmental analysis of offshore wind projects.
Colombia	Professor, Faculty of Engineering, Electronic Engineering Program, Universidad del Magdalena, Colombia.
Colombia	Electronic Engineer, Master in project management, Ph.D. in Energy Technology. Professor Universidad Autónoma de Bucaramanga. Focused on: Energy Technology, Renewable Energies, and Photovoltaic Systems.
Colombia	Ph.D. in Mechanical Engineering, Master in Engineering, Electronics, and Computer Engineering. Electronic Engineer. Full Time Professor, Universidad Cooperativa de Colombia. Research Projects. Research Coordinator of the Faculty of Engineering, Santa Marta Campus.
Colombia	Electronic Engineer, Master in Engineering. Full-time professor, Universidad del Magdalena. Focused on renewable energies in the Colombian Caribbean, photovoltaic solar energy.

Table 4: Consistency ratio (CR) obtained for each expert

Experts	CR economic matrix (%)	CR technical matrix (%)	CR environmental matrix (%)	CR social/political matrix (%)
Expert #1	9.69	7.95	0.00	6.30
Expert #2	8.07	9.94	0.00	2.81
Expert #3	7.56	6.52	0.00	2.80
Expert #4	6.59	1.23	0.00	0.00
Expert #5	9.21	7.95	0.00	6.33
Expert #6	7.35	7.14	0.00	3.72
Expert #7	9.78	6.82	0.00	0.00
Expert #8	7.23	6.66	0.00	0.00
Expert #9	9.13	8.91	0.00	0.00
Expert #10	0.63	7.95	0.00	0.00

Table 5: Pairwise comparison matrix of economic criteria

var1/var2	DPG	UCR	MT	DFA	MP
DPG	1	2.088	2.106	3.105	2.106
UCR	0.479	1	1.184	2.176	1.136
MT	0.475	0.845	1	1.689	1.311
DFA	0.322	0.460	0.592	1	0.530
MP	0.475	0.880	0.763	1.885	1

Table 6: Pairwise comparison matrix of technical criteria

var1/var2	WS	B	WH	HR
WS	1	5.082	5.296	2.068
B	0.197	1	2.034	0.888
WH	0.189	0.492	1	0.695
HR	0.484	1.126	1.439	1

Table 7: Pairwise comparison matrix of environmental criteria

var1/var2	PA	BMR
PA	1	3.647
BMR	0.274	1

Table 8: Pairwise comparison matrix of social/political criteria

var1/var2	MA	LP	FR
MA	1	1.489	1.116
LP	0.672	1	1.025
FR	0.896	0.975	1

criterion comparison against itself. Later the normalized pairwise comparison matrix, the priority vector, and the CR were obtained (Tables 9-12).

It was possible to establish a multicriteria hierarchy for the selection of criteria, using AHP as a useful tool to prioritize criteria and sub-criteria, to aid the decision maker (Figure 4).

Figure 5 shows the general priorities. The protected areas, according to the expert's judgment are the most important variable, or with a heavier weight by the time of determining the feasibility of offshore wind projects on the Colombian Caribbean Sea, with a 19.62%. In second place, is wind speed with 13.84%. The last two spots with very similar percentages are distance from airports with 2.49% and wave height with 2.52%. These results are consistent with the roadmap for the deployment of offshore wind energy in Colombia given by the RCG (The Renewables Consulting Group, 2022), which takes into consideration these indicators for the choosing of feasible zones.

Considering, the inconsistency factor of each criterion evaluated: Technical (3.82%), economic (0.53%), socio/political (1.05%), and environmental (0%). The overall inconsistency rate was 1.35%, which is acceptable according to (Saaty, 1990). Considering that the experts gave their opinions with the verbal scale proposed by Saaty, the geometric mean was obtained by transforming each verbal judgment to its numerical equivalent, using the fundamental scale of Saaty. Thus, the findings of this research were accepted

Table 9: Normalized matrix of economic criteria

var1/var2	DPG	UCR	MT	DFA	MP	SUM	Priority vector (%)		
DPG	0.364	0.396	0.373	0.315	0.346	1.794	35.92	Lambda	5.02
UCR	0.174	0.190	0.210	0.221	0.187	0.981	19.61	CI	0.006
MT	0.173	0.160	0.177	0.171	0.216	0.897	17.94	CR	0.53%
DFA	0.117	0.087	0.105	0.101	0.087	0.498	9.94		
MP	0.173	0.167	0.135	0.191	0.164	0.830	16.59		
Total sum						5	100		

Table 10: Normalized matrix of technical criteria

var1/var2	WS	B	WH	HR	SUM	Priority vector (%)		
WS	0.535	0.660	0.542	0.445	2.182	55.38	Lambda	4.10
B	0.105	0.130	0.208	0.191	0.634	15.57	CI	0.034
WH	0.101	0.064	0.102	0.149	0.417	10.09	CR	3.82%
HR	0.259	0.146	0.147	0.215	0.767	18.97		
Total sum					4	100		

Table 11: Normalized matrix of environmental criteria

var1/var2	PA	BMR	SUM	Priority vector (%)		
PA	0.785	0.785	1.570	78.48	Lambda	2.00
BMR	0.215	0.215	0.430	21.52	CI	0.00
Total sum			2	100	CR	0%

Table 12: Normalized matrix of socio/political criteria

var1/var2	MA	LP	FR	SUM	Priority vector (%)		
MA	0.389	0.430	0.355	1.175	39.18	Lambda	3.01
LP	0.262	0.289	0.326	0.877	29.21	CI	0.005
FR	0.349	0.282	0.318	0.949	31.62	CR	1.05%
Total sum				3	100		

Figure 4: The hierarchy of decision criteria and relative weights

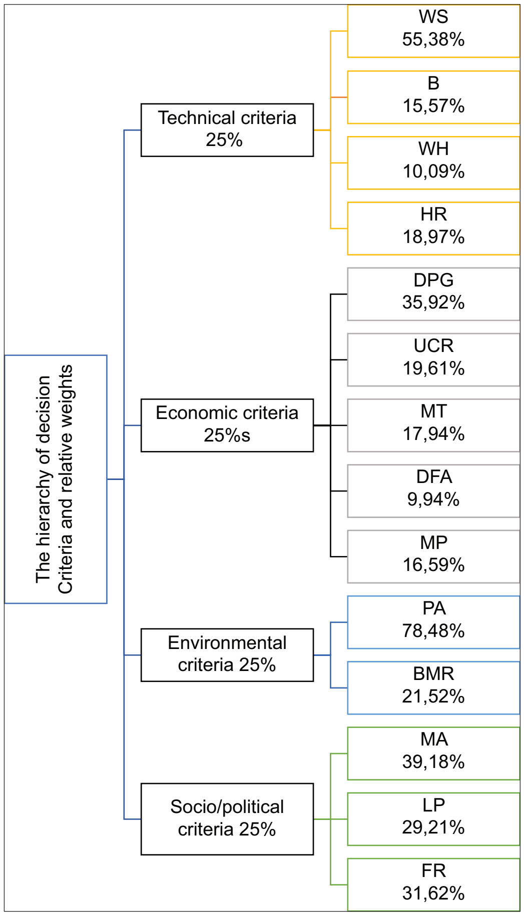
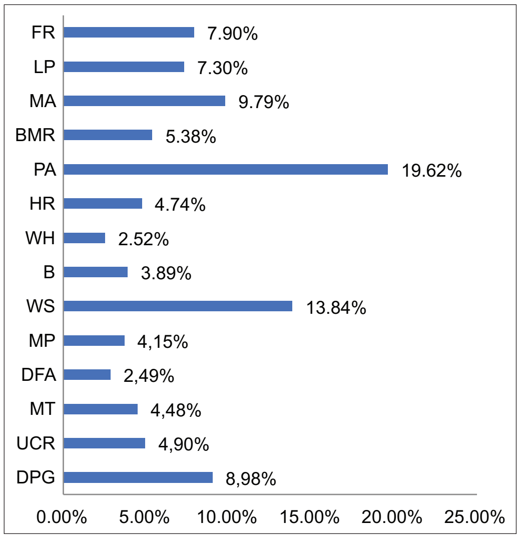


Figure 5: Absolute weights of criteria



and can be referred to as a decision-making model for selection criteria for evaluating the feasibility of offshore wind farms on the Colombian Caribbean Coast.

7. CONCLUSION

It can be concluded that the AHP is an effective method to prioritize criteria in energy planning processes. The results of this work are a contribution to the projects that seek to establish the suitable areas for the implementation of offshore wind projects in the Caribbean Sea in Colombia. Pairwise comparisons between criteria are more consistent to the extent that matrices of up to 3 × 3 are implemented, since in the case of larger matrices some experts tend to make mistakes, and the reciprocity axiom established in the AHP is not fulfilled. It can be noted that the 4 categories of criteria were adequate, which is evidenced in the level of importance obtained for each criterion, reflected in the percentages of the vectors of local and global priorities.

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