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Pre-feasibility assessment for identifying locations of new offshore wind projects in the Colombian Caribbean.

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ABSTRACT

The offshore wind energy is showing a growing interest because of the increment of global energy demand and the commitment to reduce the CO_2 emissions. The need to identify new wind offshore areas has motivated the development of methods where several quantitative and qualitative factors are considered. Due to the variety of the identified factors is necessary establishing a priority order to know when they could be analyzed. The priorization of the identified factors not only ease the planning-execution of the future projects, but also economize resources because the achievement cost from the prefeasibility to final decision is ascendant, what means that the initial factors require less economic resources to be met compared to the factors grouped in the following stages. Then, this research organized the main factors in three stages (pre-feasibility, feasibility and final decision) and developed a methodology to perform a pre-feasibility analysis for identifiying potential offshore areas considering technical-environmental features and the wind characteristics in the space, time and frequency domain. The Colombian Caribbean coast was selected as study case, and the results pointed three areas and 10 locations with high potential for developing offshore wind projects. The north and central zone of the Colombian Caribbean coast were identified as the most suitable areas with mean annual wind speed over 10 m/s with low magnitude and direction variability, two factors considered extremely important for the wind power generation.

Keywords

Wind energy;
Offshore wind turbines;
Colombian Caribbean;
k-means;
silhouette analysis.

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1. *Introduction*

The global increasing energy demand requires the increment of electricity generation capacity through low-carbon technologies such as offshore wind, which contribute to mitigate the effects of climate change because its cleaner production compared to fossil fuels [1]. The Colombia`s energy matrix is integrated by 70 % of hydroelectric plants and the remaining percentage correspond to thermoelectric and a few non-conventional energy projects [2]. However, the high dependence of hydropower to the rainfall regime and its vulnerability to the effects of ENSO in warm (El Niño) and cold (La Niña) phases [3,4], demands the diversification of the Colombian energy matrix.

During 2015 and 2016 occurred an unprecedented combination of El Niño, the warm phase of the Pacific Decadal Oscillation (PDO) and the warmest period of the planet [5]. As a result, the impact of these combined climate events in Colombia was identified by severe droughts that provoked a reduction of 20% of water reserves in dams and a rise of 4.5% of the electricity prices, what impacted a 0.6% of the gross domestic product [6]. That critical energy situation was reported by [7] who argued that the potential of the Colombian offshore wind energy could complement the hydropower during drought events. The authors classified as I (Strong wind) to Barranquilla and Santa Marta cities according to the wind energy classification of the

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Abbreviations

CAPEX:	capital expenditure
CCC:	Colombian Caribbean coast
CLLJ:	Caribbean low level jet
ECLAC:	Economic Commission for Latin America and the Caribbean
ENSO:	El Niño - Southern Oscillation
MPA:	Marine protected area
OPEX:	Operational expenditures
OWT:	Offshore wind turbine
OWF:	Offshore wind farm
PDO:	Pacific decadal oscillation
Ws:	Wind speed
Wd:	Water depth

International Electrotechnical Commission; these high values of winds in the studied areas show an option for complementing the energy matrix in Colombia [8].

Colombia must intensify its efforts not only to increment the conventional renewables, but also to develop non-conventionals to reach the planned energy goals [9]. The Caribbean Sea including Colombia's has very good conditions to develop offshore wind energy due to the persistent northeast trade winds [10–12]. Others studies reported the potential of the offshore wind resource using reanalisys data [7,13], multiple satellite data [14], projections using climate change scenarios [10] and long-term trends of the wind energy [15], the political and institutional barriers [16–18] and its contribution to the complementarity of the energy matrix [8,19].

The area classification of wind energy resources is necessary for identifying optimal turbine locations [20,21]. [22] recommended as first step at the macro level (regional scale), considering technical criteria as: wind resource, maximal depth, distance to coast, and constraints such as reserve and conservation areas. Secondly, the author suggests evaluating different solutions at the micro level (local) considering the technical feasibility and cost evaluation: capital expenditure and operating expenses (CAPEX-OPEX). Some approaches consider quantitative and qualitative features: buffer exclusion zones (protected areas, national parks, historical sites, shipping routes, ports, military zones), wind speed (Ws) threshold, slope, land uses, bathymetry, soil properties, distance to shore, among others. However, there is no consensus on the prioritization of specific criteria. [23] proposed six categories: climate, geographic, economic, location, political and socio-environmental. In 2019, the International Energy Agency (IEA) published a report pointing potential wind offshore areas worldwide, considering the distance to shore, water depth and exclusion regions (wind speed < 5 m/s), among others [24].

The reviewed literature pointed that pre-feasibility studies become important because these assessments reveal unexpected potential areas for offshore wind despite of not-having high Ws, nor infrastructure for supporting installation and operation activities. In the site-selection prevalence factors associated with climate, the environment and social-political constraints. Then, the wind climate analysis is considered essential for the pre-feasibility assessments because a high-variability of the resource carries a low persistence, and unexpected future negative trends of Ws generated by El Niño and PDO could affect the electricity generation.

The Ws is considered the most relevant factor for the wind energy sector, accounting about 90% of the contribution for the site-selection [23]. However, some authors have evaluated dispersion criteria such as wind stability [20] or wind volatility [25] which reflect the impact in terms of power fluctuation. [26] indicated that Barranquilla city area is better than La Guajira north area, because of their Weibull distribution of Ws, however, they did not consider that a high Ws variability affects significantly the suitability of a potential area.

According with the categories presented by [23], three factors have the highest percentage (70%) of relevance for the site-selection such as, 1- protected areas within the Socio-Environmental Category, 2-Ws in the Climate category and 3-water depth in the Geographic Category. However, there are other secondary three factors with a less percentage of contribution (30 %) which ease the site-selection. The first is the Distance to port/industrial facilities, where the increment of distance to port facilities demands more investments for the electric transmission from the offshore substations and more resources for transportation.

The second is the Environmental loads, where recurrent extreme environmental loads as hydrodynamic and aerodynamics forces affect the structural health what increase the maintenance-repair costs and interrupt the electricity generation. The third is the Bottom substrate, where unstable soils require further studies and complex geotechnical solutions. The Bottom substrate assessment will ease the determination of the pile depth, then, a characterization of the soil layer composition, hydrography (bathymetry) and turbine material properties is necessary [27]. [28] developed several phased approaches to offshore wind developments for the US considering the experience from the UK, [29] proposed a strategic planning for new offshore wind projects, and other studies provided economical and technical considerations for designing [30,31]. Various criteria for site-selection of new offshore areas were identified, but their priority order is not bounded by specific stages such as pre-feasibility, feasibiliy and final decision.The review showed that international studies established Ws < 5 m/s and distance to port as a restriction, hence, we shifted these factors into new values considering the recommendations of recent studies and wind turbine manufactures.

Considering the priority of Colombia in diversifying the energy matrix and its high offshore wind potential, is opportune the development of accessible evaluation tools for the stakeholders and decision-makers. Hence, this study proposes which criteria factor would be considered and when they could be analyzed and group them in three stages (prefeasibility, feasibiliy and final decision). Also, we developed a methodology to perform a pre-feasibility analysis for the site-selection considering the Colombian Caribbean coast (CCC) as study case. Within the methodology, three factors are considered (MPA, Ws, and Wd), where the Ws is analyzed through space, time and frequency methods. The results reveal technical information of new locations with high potential to develop offshore wind projects, not reported in the open access literature before.

2. *Data and Methods*

To identify best locations for offshore wind turbine (OWT) in the study area (Figure 1), were considered quantitative-qualitative factors and restrictions. A factor is a criterion that increases or decreases the suitability of candidate locations, while a restriction is a determining factor that allows or reject a candidate point because it did not fulfill a mandatory requirement [32].

This study gathered the recommendations retrieved from the literature review about the criteria and factors for site-selection and defined three main stages that could be present in the development of new offshore wind projects (Figure 2).

The scope of this research is limited to pre-feasibility and provides additional secondary information (literature survey) for a future second stage (feasibility). Hence, the description of the three main factors and the used data in this study are:

- Marine protected areas (MPA). In Colombia, the MPA are under administration of Sub-system of marine protected areas (SMPA), which provides the official cartography of the areas. This study considered the MPA as a restriction and it is defined by a Boolean value = 0 for the presence and 1 for the absence of MPA, on a buffer exclusion zone (5 km) around the candidate station.

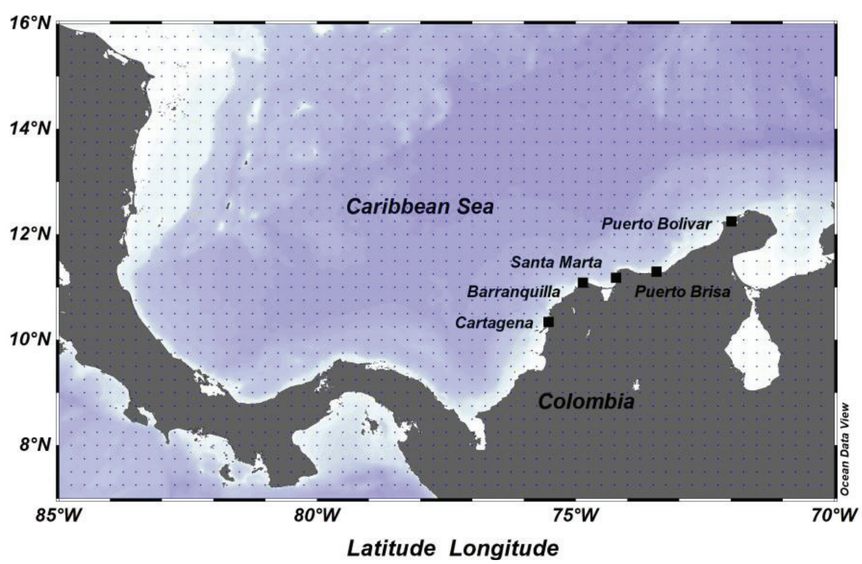

Figure 1: Study area: The CCC indicating the main ports.

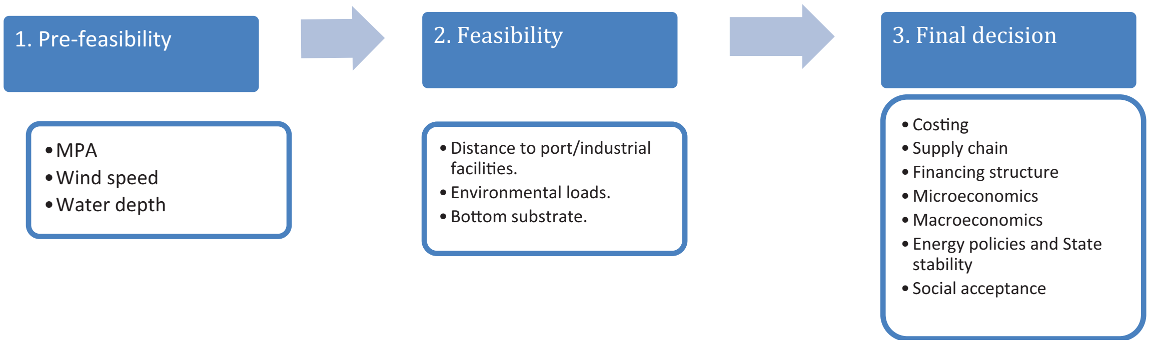

Figure 2: Stages of offshore wind projects and main criteria considered.

- Wind Speed (Ws). Ws below the 3 m/s cannot activate the turbine (Ws cut-in) [21,33,34], then, the lowest annual Ws mean values are verified before of rejecting candidate stations. The ERA5 Reanalysis wind data was used (1980-2019) for the time, space and frequency analysis (https://cds.climate.copernicus.eu/cdsapp#!/home). The nearest ERA5 wind data to the coast was selected to characterize the spatial and temporal distribution through Hovmöller diagrams and Clustering analysis (K-means) [35]. Because the K-means requires specifying the number of groups, a Silhouette analysis was performed to identify the distances among groups. Once the groups were identified, the wind variability analysis was done through a statistical toolbox of Matlab [36].
- Water Depth (Wd). Water depths over 50 m requires floating and specialized foundations increasing the CAPEX and OPEX of the project. In this study, the bathymetry data was obtained from the Colombian official nautical charts and the 50 m isobaths were evaluated to identify which stations were located < 50 m (Boolean value = 1) and which were over (Boolean value = 0).

The proposed methodology for performing the pre-feasibility is depicted in Figure 3

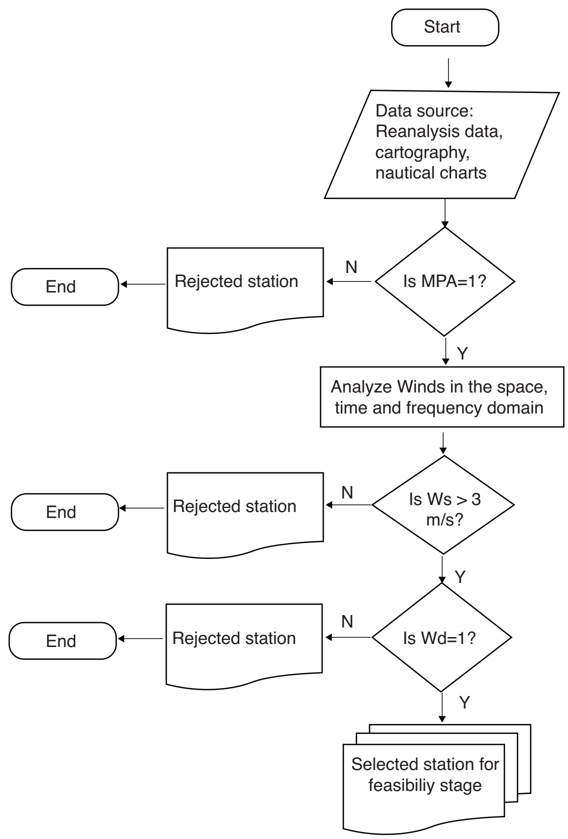

Figure 3: Methodology for the site-selection of offshore wind areas at pre-feasibility stage.

3. Results and Discussion

This section begins with the identification of MPA in the study area. Next, are described the Ws characteristics and the restrictions for installing offshore wind farm (OWF) considering the Wd criteria. The section ends with secondary information related to Distance to port/industrial facilities, environmental loads, Bottom substrate, thecnical-economical information and recommendations for future feasibility studies to promote the development of future OWF in the CCC.

3.1. Marine Protected Areas

In Colombia, the MPA regulation contribute to achieving the common conservation objectives in the marine

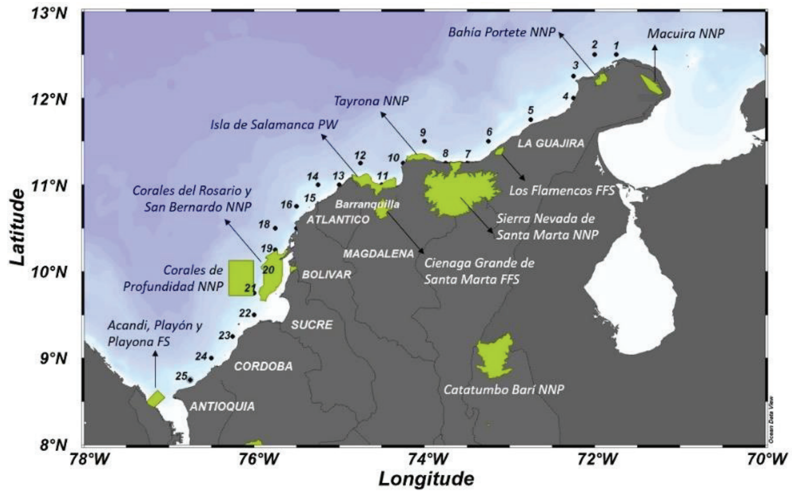

Figure 4: Marine Protected Areas in the study area (NNP: National Natural Park, FFS: Fauna and Flora Sanctuary, PW: Park Way, FS: Fauna Sanctuary)

and coastal territory. Currently, the MPA framework has 35 MPAs which 25 are in the Caribbean Sea with distinct categories [37]. Along the Caribbean coast, the (Figure 4): Bahía Portete, Los Flamencos, Sierra Nevada de Santa Marta (SNSM), Tayrona, Isla de Salamanca Park Way (ISPW), Corales del Rosario y San Bernardo (CRSB), Corales de Profundidad (CP) and Acandi, Playon y Playona. This study located 25 stations along the CCC for the assessment, and six stations were located within or nearby to a MPA, as a result, the stations 7, 8, 11, 19, 20 and 21 were discarded.

3.2. Wind speed

The Ws fields generated in this study agreed with other studies [38–40], showing a gradient from Northeast to Southwest (NE-SW) direction, depicting the highest values in the north area (Figure 5a) somehow, cross references of figure 5 added images within the paragraphs, please remove these images.

In the offshore areas of La Guajira and Magdalena (the northernmost area), the Ws exceeded 10 m/s, while in the SW area the wind was not over the 5 m/s. Although in the CCC presents high Ws for energy exploitation, this resource is not constant because of the high magnitude variability identified in front of the Magdalena and Atlántico (11-12 ºN and 74-75 ºW) (Figure 5b).

The north area (La Guajira) showed the lowest direction standard deviation, what is profitable for the electricity generation, contrary, the high standard deviation of wind direction in the central and south area will demand a recurrent use of control systems (turbine reorientation) increasing the maintenance costs and the energy consumption (Figure 5c).

The aforementioned wind direction variability agreed with the findings of [41], who through Reanalysis data identified that the higher dispersion in wind direction occurred at the 10.5° N.

The Hovmöller diagram (Figure 6) validates the mean annual Ws gradient (Figure 5.a) along the CCC; the results evidenced a Ws variation from north (maximum, 12.5 m/s) to south (minimum, 1 m/s). During the 2010 and 2011 was observed a significant decrement of Ws (Figure 6) generated by a strong ENSO - La Niña episode according to the report of Oceanic Niño Index of the NOAA Climate Prediction Center. This La Niña event in Colombia affected four millions of people, causing economic losses of approximatively US $7.8 billion, related to destruction of infrastructure, flooding of agricultural lands and payment of government subsidies [42].

The K-means revealed three main groups (Figure 7a), which the Group 1 (red bars) is compound by the northernmost stations (1, 2, 3 and 4 in front of Alta Guajira and 9 in front of Tayrona NNP). The annual cycle of Group 1 is characterized by two peaks (first maximum in July and the second in February), except for the station 9, which the maximum occurred in February and showed a poor cohesion with the Group 1 (Figure 7b). Similar to the findings of [11] and [40], the minimum Ws were presented in October. This is in this way due to the influence of the Caribbean Low Level Jet (CLLJ), with a semi-annual behavior with two maxima during

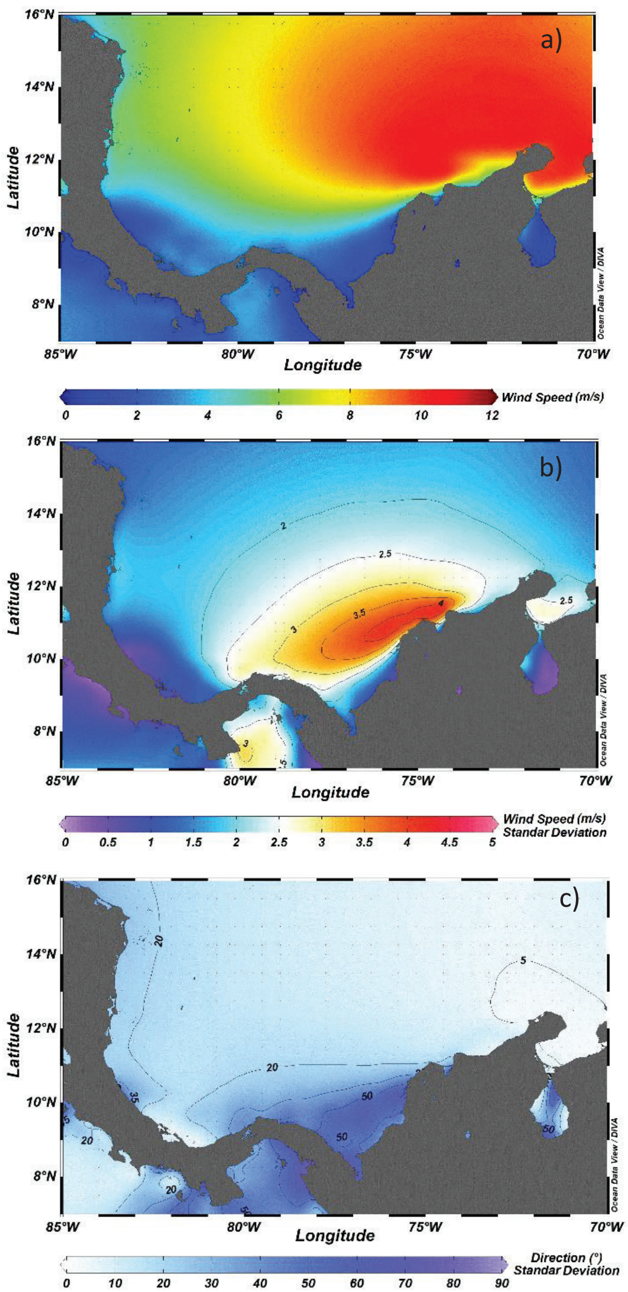

Figure 5: Mean annual values for the period 1980–2019 in the Colombian Caribbean: (a) Ws (m/s), (b) magnitude standard deviation (m/s), (c) direction standard deviation (°).

summer (July) and winter (January), and two minima in autumn and spring, showing velocities upper to 11 m/s during the windiest season.

The application of statistical methods as the Hovmöller diagram, K-means and Silhouette method seen in this study, provided detailed information of wind behaviour along the year and reveal spatial patterns that ease the

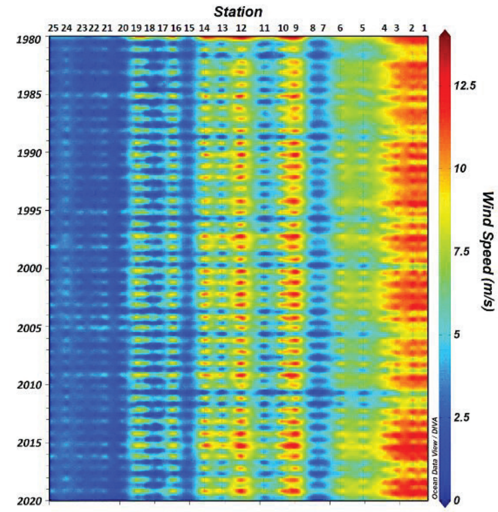

Figure 6: Hovmöller diagram of WS (m/s) for the 25 stations of the CCC.

planning of the new projects. [7] recommended OWT class III for the central and north area of the CCC, however, the applied methods of this study (Figure 7, Figure 8) revealed that in the north area and central area can be installed wind turbines class I and II respectively (e.g. turbine model V117-4.2 MW [43]). As a result, the change of wind turbines from class III to I-II increases the available power and reduces the total area of wind farms.

[26] Analized the annual produced energy (APE), the levelized cost of energy (LCOE), the net present value (NPV) with a Capacity Factor (CP) of 37 % of a theoretical OWF (360 MW) in Colombia. The farm is compound by 60 turbines of 6 MW, with 25 km of distance to shore (Barranquilla city) and 15-100 m of water depth. That study reported that not only the NPV was positive, but also the sensitivity analysis under a wide variety of conditions such as varying the discount rate, costs, and quantity of electricity generated. The OWT (class I) analyzed in that research agreed with this study in utilizing OWT higher than the class III recommended by [7].

The stations of Group 2 (green bars) are located in the central coastal zone (10, 11, 12, 13, 14 16 and 19) together with two stations in the northern zone (5 and 6) (Figure 7c). Same as Group 1, the annual cycle was bimodal, but the maximum occurred in February (Figure 7c). Like Group 1, the month with the lowest values is October (and September in some stations).The Station 12 presented the lowest silhouette value and showed the highest average magnitude as well as the highest dispersion. According with [44], the CLLJ is present throughout the year and varies in strength semiannually: peak magnitudes in July

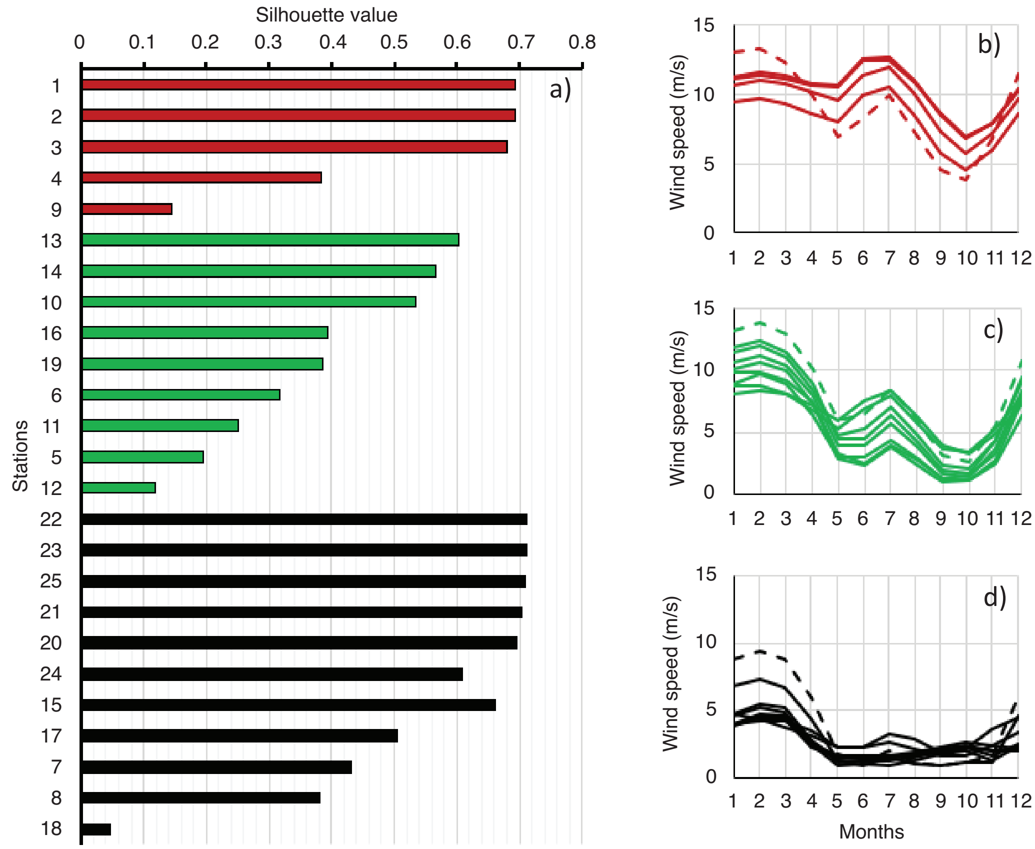

Figure 7: (a) Identified groups from the the K-means (in colors) and Silhouette method, (b) annual cycle for Group 1, (c) annual cycle for Group 2, (d) annual cycle for Group 3 of the period 1980-2019. The dotted line corresponds to the station with the lowest silhouette value for each group.

are related to the seasonal cycle of the North Atlantic subtropical high, and a second maximum in February caused by the heating in the northern area of South America.

The Group 3 (black bars) grouped the southern stations (15, 17, 18, 20, 21, 22, 23, 24, 25) and the two most coastal stations in the northern zone (7 and 8). This group has the lowest Ws of the study area and its annual cycle was monomodal, with the maximum in February and the lowest in May (Figure 7d). The months with the lowest Ws (May, September, October) must be considered for planning maintenance and repair activities of the OWT due to the lowest electricity generation. [40] delimited four wind regions in the Colombian basin: South (Uraba-Morrosquillo corner), West (San Andres Island), central (CLLJ) and North. Then, the Ws of Group 1 of this study corresponds to the North region reported by [40], and the stations of Group 3 would be compared to the south and central wind regions of that study.

The wind roses showed that Group 1 evidenced winds from the East-Northeast, the Group 2 winds from the Northeast and Group 3 showed predominance from North-northwest with some low-speed vectors from the south-southwest (Figure 8 a, b, c). It was observed that all the three groups of this study exhibited a predominance from the East similar to the regional level reported by other studies [40,41] and at the local level [7].

The Ws of Group 1 seen in the boxplot was not symmetric with a bias towards values below the median (10.10 m/s) and outlier data below the 4 m/s (Figure 8 d). The Ws distribution of Group 2 was more symmetric, close to the median (6.12 m/s) without outliers (Figure 8 e), and Group 3 showed a bias towards above the median (2.33 m/s) with no outliers (Figure 8f). In this sense, the highest statistical dispersion of Ws given by the interquartile range was found in the Group 2 (5.52 m/s),what could trigger recurrent voltage variations, while Group 1 and Group 3 showed similar ranges of 3.04 m/s and 2.49 m/s respectively (Figure 8 d, e, f).

Despite of [24] showed worldwide potential areas for new energy projects, it did not consider that Ws cut-in

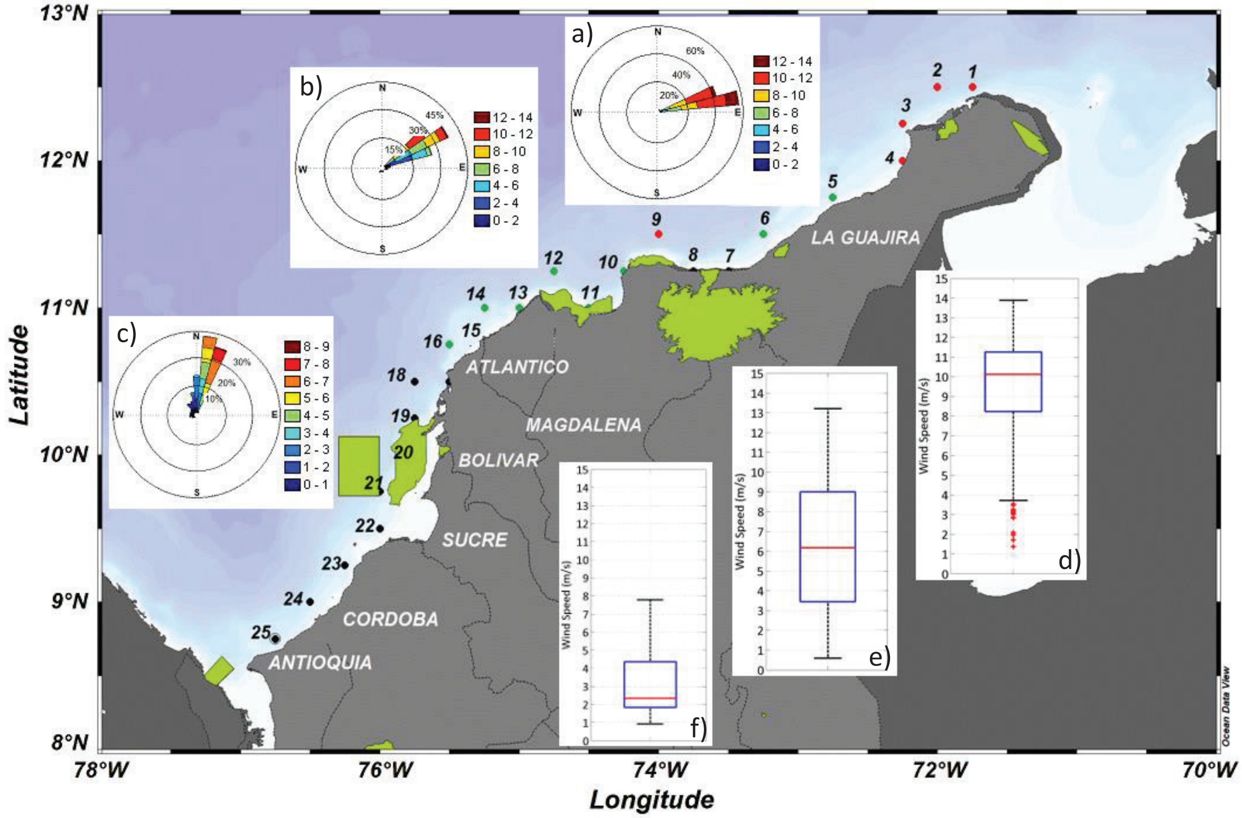

Figure 8: Wind features of Group 1 – red dots (a, d), Group 2 – green dots (b, e) and Group 3 – black dots (c, f) of the study area.

reported in the literature of OWT [33,34], onshore turbines [21] and manufacturers [43] is 3 m/s. As a result, the IEA report excluded zones around the world with Ws < 5 m/s, what provoked in Colombia the rejection of potential areas nearby to CCC such as the northmost zone (norht of La Guajira), the central area (Bolivar, Atlántico) and the south area (Córdoba).

3.3. Water depth

The CAPEX is manageable within water depths between 20 and 50 m [45], where the foundations installation represent a 73% of the total cost [46]. The Table 1 shows that 10 stations (3, 4, 13, 14, 10, 16, 6, 5, 24 and 17) are located below the 50 m isobath. At this stage, from the 25 stations of the study area, six were rejected (7, 8, 11, 19, 20 and 21) because they were located within or nearby a MPA, and four stations were discarded (15, 22, 23, 25) because their annual mean of Ws was not over the 3 m/s. Hence, this last pre-feasibility stage concluded that stations 3, 4, 5, 6, 10, 13, 14, 16, 17 and 24 should pass to a future feasibility assessment.

The Table 1 showed that there are two stations in Bolivar, which could provide offshore wind energy to Cartagena city considered the most touristic location in the CCC with and important commercial port. However, these stations belong to groups 2 and 3 which showed a high wind variability in the annual cycle (Figure 8 e, f), then, control positioning systems are recommended.The Magdalena and Atlántico area have three suitable locations for OWT (Table 1), which could reduce the high electricity cost and intermittent service that have affected the social wellness and economic development of Santa Marta and Barranquilla cities [47,48].

In La Guajira were identified four locations (Table 1) for new OWF, because of the high Ws, low variability and reduced environmental and technical restrictions, what agreed with other studies [7,49]. [50] showed that the northern area of La Guajira is the most suitable for developing wind energy projects, because its high mean Ws, is located far from highly populated urban areas and is away from protected natural areas. Considering that a high percentage of the indigenous population (*Wayuu*)

Table 1: Evaluation of the candidate stations for placing OWT.
Gray cells indicate that the station was not evaluated because a previous rejection.

Group	Station.	Department	MPA	Ws (m/s)	Water Depth (m)	Recommended for future feasibility assessments?
	1	La Guajira	1	10.37	0	No
	2	La Guajira	1	10.45	0	No
1	3	La Guajira	1	9.60	1	Yes
	4	La Guajira	1	8.25	1	Yes
	9	Magdalena	1	8.96	0	No
	13	Atlántico	1	6.06	1	Yes
	14	Atlántico	1	6.80	1	Yes
	10	Magdalena	1	6.91	1	Yes
	16	Bolívar	1	5.15	1	Yes
2	19	Bolívar	CRSB			No
	6	La Guajira	1	6.55	1	Yes
	11	Magdalena	ISPW			No
	5	La Guajira	1	6.63	1	Yes
	12	Magdalena	1	8.26	0	No
	22	Córdoba	1	2.46		No
	23	Córdoba	1	2.61		No
	25	Antioquia	1	2.53		No
	21	Bolívar	CP			No
	20	Bolívar	CRSB			No
3	24	Córdoba	1	3.21	1	Yes
	15	Atlántico	1	2.85		No
	17	Bolívar	1	3.13	1	Yes
	7	La Guajira	SNSM			No
	8	Magdalena	SNSM			No
	18	Bolívar	1	4.06	0	No

do not have access to electricity service [51], new projects such as OWT might provide the required energy that would promote their social and economic development. In places with deep-rooted cultural traditions, the development of small-scale and community-based projects could contribute to the improvement of living conditions, contributing to reductions in cost and environmental risk [52]. The tourism, which is an activity that has enormous potential and is constitutes as one of the main engines of the departmental economy, could attract green consumers, reduce costs and comply with national policies [53].

3.4. Remarks for future feasibility studies.

This section provides secondary information of the three main factors and recommendations for futures feasibility stages: Distance to port/industrial facilities, environmental loads and Bottom substrate. [54] reviewed the logistics capabilities of ports for supporting installation, operation and maintenance activities for the OWF. They used industry expert judgments and pointed that distance to port followed by the port's quay loadbearing are essential for selecting a location. Other secondary factors were reported by that study as follows:

- Port's depth.
- Quay length.
- Seabed suitability.
- Component handling equipment (Ro-Ro, Lo-Lo, heavy lifting equipment i.e. cranes).
- Distance from the key component suppliers.
- Distance from road networks.
- Distance from heliports.

- Storage space availability.
- Component manufacturing facility availability.
- Component laydown (staging) area availability.
- Workshop area (repairing of broken or faulty components).
- Office facilities.
- Potential for expansion.

The future feasibility studies for the Colombian ports must verify if the existent capabilities could be sufficient or expanded to attend a new demand of the offshore wind industry. A critical part of the offshore wind supply chain involves ports serving as an on-land base to support the installation as well as the operations and maintenance phases of the OWF [54]. [55] mentioned that the cuts of electricity production generated by failures must be solved quickly, but [32,56,57] considered ports facilities as a restriction due to maritime traffic would be interrupted. Then, this study agreed with [55] and recommends considering port facilities as a factor and not as a restriction, because OWF need a equipped-fast accessing port for facing technical problems and reestablishing the electricity production.

In 2018 the Economic Commission for Latin America and the Caribbean (ECLAC) commission reported that Colombian ports are ranked fourth in Latin America, due to the amount of goods that pass through them [58]. According with [59], the conversion of Colombian ports to sustainable (green) ports should ensure the contribution to sustainable development considering the economic, social, and environmental dimensions, and through the achievement of the Sustainable Development Goals. [60] reviewed the impact of major infrastructure projects on port choice decision in Colombia, and mentioned that Cartagena port is the most attractive for containerized cargo, what is in line with the required port facilities for handling containers, and Santa Marta port was considered less attractive for transport cargo but proper for handling bulk cargo. The port of Cartagena has an important capacity for receiving big cruise liners from worldwide, as well as massive vessels with general cargo [60].

Barranquilla port is in position 55 of the ECLAC ranking, which is located next to the mouth of Magdalena river and it is home of the most modern liquid bulk facilities in Colombia. In position 62 is Santa Marta, which handles multiple types of cargo from palm oil, fuels, mineral carbon as well as grain and containers [58]. La Guajira is in the 108 position of the ECLAC ranking, and has two mineral solid bulk ports known as Puerto Bolivar and Puerto Brisa (Figure 1). Puerto Bolívar is focused to export coal and its availability to support OWF would be limited. Puerto Brisa port in 2021 received 10 onshore turbines of 2 MW [61], what revealed its potential of this port for providing services to the future OWF.

The environmental loads factor comprises the influence of the ocean waves, earthquakes, wind, tidal, and currents over the OWF [62–64]. In the CCC there are studies about ocean waves, e.g. [65] describes mean and extreme wave behavior and its alterations during ENSO phases, while [66] revealed the influence of ENSO on the significant wave heights and peak period. Other studies have considered the environmental loads for marine energy exploitation [67,68], as well as their evaluation for offshore applications [69]. Some studies are related to wave climate [64], sea state modelling [70], and information of hydrodynamic forces and structural dynamic analysis for offshore structure designing [71–73], however, understanding the effects of the environmental loads over OWF requires more research.

The open access information for Bottom substrate factor is scarce. [74] mentioned that La Guajira is characterized by a wide platform compound by carbonate-rich sedimentation, with facies predominantly organic (biogenic sands), in contrast the area of Magdalena department has a narrow platform whose sedimentation is mostly terrigenous muddy. Then, because of that strait platform the Wd > 50 m causing the rejection of station 9 (Table 1). The Atlántico and Bolivar also exhibits a narrow platform with a high detrital sediment (muddy to sandy-muddy) due to the Magdalena river discharge and mud diapirism. Considering that mud diapirism affects the soils stability of offshore foundations, the future offshore wind projects in the central area of the CCC (Atlántico, Bolivar) will require specialized geotechnical studies. The Cordoba was the only department of the south area of the Colombia Caribbean coast that passed the three stages of the feasibility assessment, and the sea floor of this zone is characterized by lithobioclastic muddy sand due to the discharges of Sinú river [74].

4. Conclusions

This research performed a literature review and found various studies aimed to identifiying new offshore wind areas considering different factors or restrictions. Among the variety of identified factors, it was not observed a priority order to know when they should be met, nor their classification in traditional stages of designing-execution projects. Then, this study analyzed these factors and organized them within three main stages (pre-feasibility, feasibility and final decision) to suggest when they could be performed. The survey pointed that MPA, Ws and Wd are considered the most important factors for identifying new offshore wind areas at a pre-feasibility stage. Other secondary factors were identified in this research, and we recommend to considered them for future feasibility and final decision stages.

From the three main factors (MPA, Ws, Wd) this work developed a methodology for the site-selection of offshore wind areas at pre-feasibility stage, and selected the Colombian Caribbean Coast as study case. The results pointed that 10 stations are potential offshore wind areas and are candidates for future feasibility assessments. The prefeasible 10 locations are distributed along the CCC: four locations are in La Guajira (north), five in the central area (Magdalena, Atlántico, Bolivar), and one in the south region (Cordoba).

This study proposes a wind speed factor = 3 m/s and to consider the proximity to ports as a factor and not as a restriction, to avoid rejecting potential areas as was observed in the literature review. Also, we recommend a time, space and frequency analysis to characterize the wind resource through Hovmöller diagrams and Clustering analysis (K-means - Silhouette methods). These methods eased a detailed regionalization of the wind resource alongside the Colombian Caribbean Coast, and allowed considering offshore wind turbines class I and II when previous studies suggested less powered turbines (Class III).

The reviewed information of the secondary three main factors for futures feasibility stages (Distance to port/industrial facilities, environmental loads and Bottom substrate), revealed that Cartagena, Santa Marta and Puerto Brisa ports could support the future offshore wind projects because their capabilities and distance to the pre-feasible 10 locations, however, future feasibility studies are needed to analyze possibilites of enhancement-expansion of these ports. The environmental loads reported in the literature evidenced that future wind farms are not under extreme hydrodynamic and aerodyanmic forces, nor dangerous seismic activiy, however, some diapirism activity in the central region of the study area should be analyzed in the future feasibility assesments. The open acces information of bottom substrate is scarce, but the study area reported narrowed oceanic platforms and sediments compound by sands and mud.

Future feasibility assesments may validate the results of this study and will reveal if the 10 selected locations in this study would be candidates for developing new OWF, then, as future research it is recommended new studies related to tehcnical factors (Distance to port/industrial facilities,environmental loads,bottom substrate) and technical-economical factors such as annual behaviour of CP, APE, LCOE, and NPV. Also, additional studies about social, environmental and economic factors will provide information for reaching final decisions of the stake holders to perform new offshore projects in the recommended locations.

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