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ABSTRACT

Mexico is an attractive candidate for offshore wind energy development due to its geographical location with extensive coasts in the Pacific Ocean and Mexico's Gulf. Although potential offshore wind areas have been geographically assessed, an evaluation of the seasonal variations of the capacity factors has not been considered for the feasibility of the locations. This research identifies potential zones for offshore wind development in the Gulf of Mexico, implementing geographical restrictions such as the Economic Exclusive Zone, distance from the coast, protected areas, bathymetry, and capacity factor seasonality. Wind speeds were obtained from 39 years of reanalyses historical data and two reference wind turbines of 5 and 10 MW were included in the analysis. Three potential areas were identified from the results: the northeast Tamaulipas, the western Campeche, and the northern Yucatan. Monthly mean capacity factors above 45% were estimated from October to June, with the maximum values near 60% between March and April. Conversely, minimum values were observed from July to September but consistently higher than 30%. The analyzed zones show suitable technical conditions for offshore wind development. Further analysis is needed to validate the wind speed conditions, in addition to the evaluation of economic factors, the study of extreme weather conditions like tropical cyclones as well as characteristics in the intertropical region.

Introduction

Until 2020, the global energy generation by renewable sources was 29%, where wind energy was the second highest contributor to the energy mix (REN21, 2020). In Mexico, during 2020, the installed capacity of onshore wind energy was 8127 MW, representing 28.7% of the national renewable energy contribution (IRENA, n.d.). To achieve the country's clean energy goals of at least 41% by 2035 (SENER, 2021), both onshore and offshore wind developments are needed in order to make a significant contribution to the Mexican renewable installed capacity.

Most of the operating wind farms in Mexico have been installed at the Tehuantepec isthmus region, which is considered one of the areas with the highest wind resource in the American continent (IMP, 2017). Offshore wind developments are almost non-existent in the country but they are considered a potential future market for the offshore wind sector (Global Wind Energy, 2020). Furthermore, offshore wind farms offer important advantages compared to onshore facilities as they are subject to a higher and steadier wind resource in larger available areas.

Existing studies have evaluated the offshore wind potential in Mexico. Bosch et al. (2018) estimated the global offshore wind energy potential using a methodology based on Geospatial Information Systems (GIS) for 157 countries. The study used data from the Global Wind Atlas in combination with reanalysis MERRA2 datasets which provided multiple meteorological variables. The spatial restrictions considered were the Economic Exclusive Zone, protected areas, bathymetry, submarine cables, and landing stations. Different wind turbines were evaluated according to the International Electrotechnical Commission (IEC) wind class and considering each location's annual average wind speeds. The study found a global offshore wind capacity potential of 85.6 TW and a total generation of 329,600 TWh/year. For Mexico, the estimated annual energy production is near 4000 TWh/year. Using a similar methodology with the reanalysis model ERA5, the International Energy Agency estimated a generation of 5705 TWh/year for the country (IEA, 2020).

Haces-Fernandez et al. (2018) presented an assessment study to supply electricity from wind and waves to offshore oil platforms in the Gulf of Mexico. The assessment used three hourly data from WaveWatch III, a

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numerical framework for wind-wave modeling, with available data from 1979 until 2015, a one-sixth per one-sixth degree resolution and diverse GIS. Using a commercial wind turbine of 3 MW, the regions with the highest wind power output were identified in the northwestern part of the Gulf, the western Yucatan Peninsula coast, and the Florida strait, with capacity factors (CFs) above 20–30% all year round.

Researchers from the National Renewable Energy Laboratory (NREL) in US developed a study to quantify the technical and economic potential of offshore wind energy for each state of the USA in the Gulf of Mexico (Musial et al., 2020). They used two databases to estimate the annual mean wind speeds at 100 and 150 m height; data from the AWS Truepower system from 0 to 80 km (50 miles) from shore and data from the numerical weather prediction model, Weather and Research Forecasting (WRF), for higher distances. The data resolution was 2 km per 2 km and it was downscaled to 200 m. The potential zones were delimited by average wind speeds above 7 m/s, water depths lower than 1000 m and available area for commercial development among others. The Levelized Cost of Energy (LCOE) was calculated for six potential sites. The results were reported in terms of the economic activity generated by developing a 600 MW offshore wind plant, including created jobs and contribution to the gross domestic product.

The literature review reveals opportunities to continue analyzing the offshore wind power resource in Mexico. Bosch et al. (2018) lack the delimitation of specific zones for offshore wind development. The results described by Haces-Fernandez et al. (2018) take as priority the oil platforms in the Gulf of Mexico, on the north coast of Tamaulipas and north coast of Tabasco, therefore limiting results to these specific locations. In this paper, a methodology is proposed based on previous work (Al-Nassar et al., 2019; Ranthodsang et al., 2020; Mattar & Guzmán-Ibarra, 2017; Castro-santos et al., 2020) which uses ERA5 and MERRA2 reanalyses datasets to study the offshore wind resource. In addition, two academic wind turbines with nominal power of 5 and 10 MW respectively are selected to estimate the power production and capacity factors from a seasonal and geographical perspective. GIS are implemented to define the spatial and power production restrictions. Finally, we delimit potential zones for the development of offshore wind energy in the Gulf of Mexico, giving a next step in the research field.

This paper is structured as follows. Section 2, Section 3 and Section 4 describes the study area and presents the data and methodology used, including technology selection and the spatial and technical restrictions. Section 0 shows the analysis and results for the wind resource availability, capacity factors, delimitation of potential areas, and inter-annual variability. Finally, Section 0 presents the conclusions.

Data and methodology

The methodology consists in applying the superimposition of geographical and power production restrictions in order to identify specific potential zones for offshore wind power development. Once the potential zones are identified, a seasonal analysis of the CFs is presented for chosen points in these specific areas.

Study area

The study area is limited to the sea in the Gulf of Mexico, between the longitudes from −100°0′0″ to −80°0′0″ W and latitudes from 17°0′0″ to 33°0′0″ N as shown by the red box in Fig. 1. The analysis of the wind resource includes the complete area of the Gulf, delimited by the states of Tamaulipas (TS), Veracruz (VZ), Tabasco (TB), Campeche (CH), Yucatán (YC), and Quintana Roo (QR). The area of analysis is restricted to Mexico's Economic Exclusive Zones, and includes the territorial seas that correspond to the United States of America (USA) and Cuba.

Reanalyses data sets

The wind speed time series used in this study are obtained from the reanalyses data sets ERA5 (Hersbach et al., 2020) and MERRA2 (Gelaro et al., 2017), developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Aeronautics and Space Administration (NASA), respectively. The data from reanalysis models is obtained through data assimilation, which combines physical models with meteorological observations during an extended period of time. For both reanalyses, information is available for a time period over 30 years (Hersbach et al., 2020; Gelaro et al., 2017).

The two reanalyses data sets were used to compare the potential zones with the highest wind speeds. Both data sets have an hourly output, but different vertical and horizontal resolutions. As shown in Table 1, ERA5 offers a higher horizontal resolution, near 30 km, than MERRA2 with 50 km. It is worth to mention that reanalysis data are constantly updated, MERRA2 provides data up to three months and ERA5 up to five days before the current date.

Wind turbines

Two reference wind turbines of 5 and 10 MW are proposed to estimate the power production and CFs; their nominal power represents current and near future technologies for offshore power production (Global Wind Energy, 2020). Detailed technical information of the

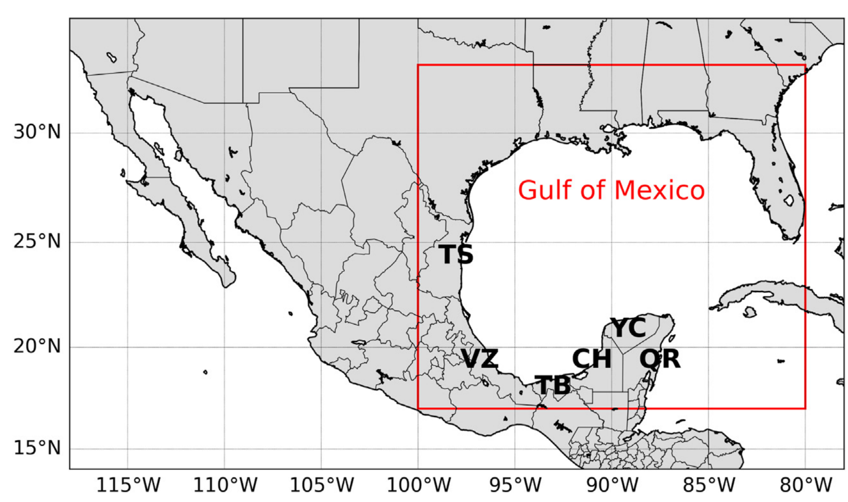


Fig. 1. Study area located in the Gulf of Mexico, between the longitudes from −100°0′0″ to −80°0′0″ W and the latitudes from 17°0′0″ to 33°0′0″ N. Delimited by the state's coats of Tamaulipas (TS), Veracruz (VZ), Tabasco (TB), Campeche (CH), Yucatán (YC), and Quintana Roo (QR).

Table 1
Characteristics of the reanalysis data sets used for the wind resource assessment (Hersbach et al., 2020; Gelaro et al., 2017).

<table>
<tr><th></th><th>MERRA2</th><th>ERA5</th></tr>
<tr><td>Developer</td><td>NASA</td><td>ECMWF</td></tr>
<tr><td>Data availability</td><td>1980-01-01</td><td>1979-01-01</td></tr>
<tr><td>Spatial coverage</td><td colspan="2">Global</td></tr>
<tr><td>Temporal resolution</td><td colspan="2">Hourly</td></tr>
<tr><td>Spatial resolution</td><td>50 km</td><td>30 km</td></tr>
<tr><td>Vertical coverage</td><td>2, 10, 50 m</td><td>10, 100 m</td></tr>
</table>

Table 2
Properties of the NREL's 5 MW and the DTU's 10 MW wind turbines (Jonkman et al., 2009; Bak et al., 2013).

<table>
<tr><th></th><th>NREL</th><th>DTU</th></tr>
<tr><td>Cut-in wind speed</td><td>3 m/s</td><td>4 m/s</td></tr>
<tr><td>Rated wind speed</td><td colspan="2">11.4 m/s</td></tr>
<tr><td>Cut-out wind speed</td><td colspan="2">25 m/s</td></tr>
<tr><td>Hub Height</td><td>90 m</td><td>119 m</td></tr>
<tr><td>Rated Power</td><td>5000 kW</td><td>10,640 kW</td></tr>
</table>

wind turbines is provided by the National Renewable Energy Laboratory (Jonkman et al., 2009) and the Technical University of Denmark (Bak et al., 2013) respectively. The design of the selected turbines was based on commercial technology and optimized using numerical tools (Bak et al., 2013).

The power curve characteristics of each turbine are displayed in Fig. 2. Besides the nominal rated power, both turbines have similar operating wind speeds except for the cut-in wind speed as observed in Table 2. The NREL wind turbine's cut-in speed is 3 m/s, and for the DTU turbine it is 4 m/s. The rated and cut-out wind speeds for both turbines are 11.4 m/s and 25 m/s respectively. Thus, the turbines are expected to reach similar CFs for the same wind speed conditions.

The wind turbine's power curve is defined as follows: the power produced is zero if the wind velocity at hub height is below the cut-in wind speed threshold; between the cut-in velocity and the rated wind velocity, the power increases until it reaches nominal power, a constant power production is maintained until the cut-out wind velocity is achieved, where the power becomes zero.

It is important to mention that in practice, power curves have to be derived from 10 min-averaged power and wind speeds following international standards. However, the power curves as shown in Fig. 2 are derived from theoretical studies for academic purposes. Therefore, such power curves are considered to be valid as well to be used with the hourly averaged values of the available reanalysis data sets used in this study. A similar approach has been used in literature regarding offshore wind power assessment at different global and regional locations (Al-Nassar et al., 2019; Ranthodsang et al., 2020; Mattar & Guzmán-Ibarra, 2017; Castro-santos et al., 2020). On the other hand, different average times for the wind resource assessment will result in differences in the estimated energy, as shown by Rodriguez-Hernandez et al. (2016), mostly in small wind turbines where usually 1 min or 10 min averages are used.

Geographical restrictions

This section describes the following restrictions considered in the study: bathymetry, protected areas, distance from shore and space availability within the Economic Exclusive Zone for Mexico. These restrictions were selected considering technical requirements and data availability.

Bathymetry refers to the distance from the ocean's surface to the seabed. This defines mostly the suitable support structure type for the offshore wind turbines (Oh et al., 2018; Sánchez et al., 2019). This study considers the bathymetry until 50 m water depth, where bottom-fixed foundations are commonly installed (Sánchez et al., 2019). The bathymetry information was obtained from the General Bathymetric Chart of the Oceans (GEBCO), which is a global model for ocean and land with a spatial resolution of 15 arc sec (~463 m) (GEBCO, 2021).

Natural protected areas are essential to preserving the existent biodiversity in Mexico. Marine protected areas along the Mexican coast in the Gulf of Mexico are also considered as a geographical restriction for the feasibility analysis. The protected locations were identified with data obtained from the International Union for Conservation of Nature (I. U. for Conservation of Nature, n.d.). The states of Veracruz (VZ) and Campeche (CH) have two protected areas in each state; in Tamaulipas (TS), there are three; five in Yucatan (YC) and ten in Quintana Roo (QR). The list of these protected areas is displayed in Table 3 and its locations are shown in Fig. 3.

The last geographical restriction considered is the distance to shore. According to the Renewable Power Generation Costs by IRENA (n.d.), most of the offshore wind projects installed during the 2001–2018 period, were located up to 40 km from the coast, with a maximum distance

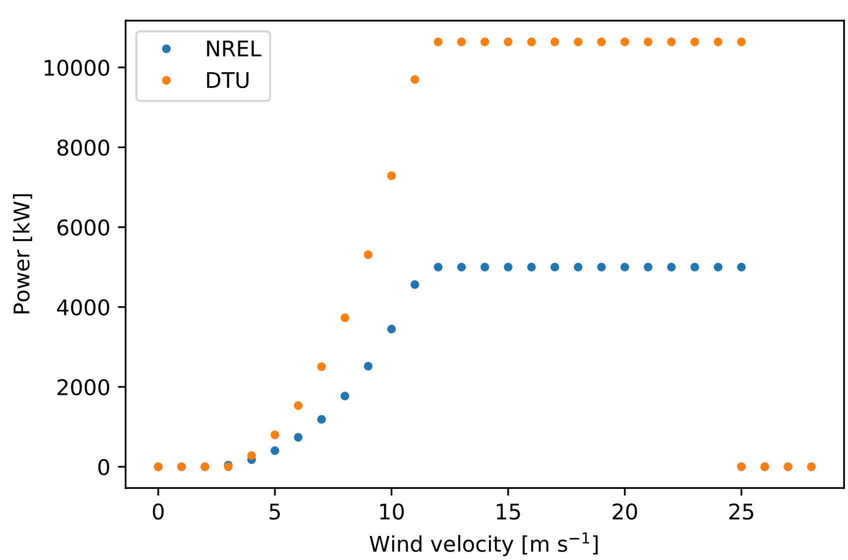


Fig. 2. Power curves of the NREL's 5 MW and the DTU's 10 MW wind turbines. Both turbines present similar operating wind speeds: rated wind speed at 11.4 m/s and cut-out wind speed at 25 m/s (Jonkman et al., 2009; Bak et al., 2013).

of 90 km. For this work, the distance from the coast is considered a constraint. A maximum distance of 44.44 km was selected according to recent world projects development as well as from data of Mexican territorial waters and its contiguous zone (INEGI, n.d.). The latter is defined as the distance from the shore up to 22.22 and 44.44 km (12 and 24 nautical miles) respectively.

Power production zones

Wind velocities from the reanalyses ERA5 and MERRA2 data sets are used to estimate the mean wind speeds and CFs in order to define potential development zones. The selected period for analysis dates from the 1st of January 1980, to the 31st of December 2018, corresponding with both models' available information of 39 years. ERA5 includes horizontal wind components $U = (u_x, u_y)$ at 10 and 100 m height, and MERRA2 at 2, 10, and 50 m.

The empirical power-law vertical profile is used to adjust the wind velocities of reanalyses data to the required hub heights of the wind turbines according to Eq. (1) (Touma, 1977; Sumair et al., 2021). This expression does not account for the influence of atmospheric stability, however due to the lack of specific in situ measurements, it is assumed the power-law expression provides a simple and practical approach to adjust the wind speeds to the required hub height from the 100 m reference.

$$U(z) = U(z_r)\left(\frac{z}{z_r}\right)^{\alpha} \tag{1}$$

where U_{zr} is the wind velocity to extrapolate at the reference height z_r and, U_z is the velocity to be estimated at the height z. The wind speed from the reanalyses is obtained from the reference height z_r=10 m components and extrapolated to the heights z=90 m and z=119 m, hub heights of the NREL and DTU wind turbines, respectively. A value of 0.11 was used for the exponent α according to empirical data and estimations given in (Hsu et al., 1994), based on 30 samples of anemometers at different heights in the Gulf of Mexico and off the Chesapeake Bay, Virginia.

The annual energy produced by the wind turbines, E_w, is calculated by evaluating each point of the grid at every temporal step for the 39 years in the adjusted power curves of the wind turbines following Eq. (2) (Manwell et al., 2006):

Table 3
Protected areas in the Gulf of Mexico with data obtained from the World Database on Protected Areas (UNEP-WCMC, IUCN, n.d.).

State	Protected area
Tamaulipas (TS)	Laguna Madre
	Delta del Río Bravo
	Playa de Rancho Nuevo
Veracruz (VZ)	Laguna de Tamiahua
	Sistema Arrecifal Veracruzano
Campeche (CH)	Laguna de Términos
	Los Petenes
Yucatan (YC)	Ría Celestún
	Ciénagas y Manglares de la Costa Norte de Yucatan
	Reserva Estatal de Dzilam
	Reserva Río Lagartos
	Arrecife Alacranes
Quintana Roo (QR)	Tiburón Ballena
	Parque Nacional Isla Contoy
	Caribe Mexicano Profundo
	Banco Chinchorro
	Sian Ka'an
	Manglares y Humedales del Norte de Isla Cozumel
	Parque Nacional Arrecife de Cozumel
	Parque Nacional Arrecifes de Xcalak
	Manglares de Nichupté
	Tulum

$$E_w = \sum_{i=1}^{N} P_w(\mathrm{U_i})(\Delta t) \tag{2}$$

where P_w is a fitted function for the power curve of the turbine, U_i are the mean wind speeds at hub height, Δt the time interval which is 1 h for the reanalyses used and, N is the numbers of hours in each year.

The CF is defined as the ratio between the average power produced and the rated power of the wind turbine or the wind farm during a period of time (Masters, 2004). The CFs are calculated for the NREL and DTU wind turbines according to Eq. (3), as the ratio between the total energy produced E_w during a certain time period of power production, and the total energy produced assuming operation at nominal power of the turbine, P_{rated} in the same time period, typically expressed as the number of operation hours N.

$$CF = \frac{E_w}{P_{rated}N} \tag{3}$$

It is important to mention that although the CF is not a measure of the technology efficiency by itself, it provides an indicator for the proper matching between the wind resource at the location and the selected turbine. For existing offshore wind developments, a range of CF values between 33% and 47% was reported by IRENA for installations in 2019 (IRENA, n.d.). A minimum value of 30% for the CF was used in this study as a criteria to identify potential zones based on their wind power production. In next section, the power production and geographical restrictions are analyzed, the latter are summarized in Table 4.

After analyzing the restrictions and considering the zones with high power production, the potential areas are delimited by the maps' superposition. Finally, smaller areas are delimited within the potential zones where a bilinear interpolation is implemented (Cannon et al., 2015) to estimate the local time series and analyze the CFs' seasonal variability.

Results and discussion

Wind speeds and capacity factors

The average wind speeds for 39 years (1980–2018) obtained from ERA5 are shown in Fig. 4a. The maximum average values are identified in both models between 8 and 9 m/ s in the same two areas: at the northwest of the Gulf, north of the TS state coast and at the northwest of the YC Peninsula.

In both reanalyses, the differences between the 39-year averages of wind speeds at 90 m and 119 m are <0.5 m/s. However, ERA5 results shows larger areas with the same maximum values. Conversely, minimal wind speeds are near 5 m/ s, which are presented along the coast of the states of VZ, TB, CH, YC, and QR. The identification of these areas in both reanalyses is consistent with the results reported by both Haces-Fernandez et al. (2018), and the Global Wind Atlas (Davis et al., 2019) which use different numerical tools.

In Fig. 4b the CFs calculated over 39 years for the DTU turbine at 119 m are displayed. Zones with the highest CFs, between 50% and 55%, are located in the same zones with high wind velocities. These regions are located at the Gulf of Mexico's Northwest, near the TS coast, and the northwest of the YC Peninsula. Conversely, minimum CF values, between 10% and 20%, are observed along the coasts of VZ and TB. Similar results were obtained at 90 m and consistent with the results from MERRA2 reanalysis data at both heights. The estimation of the CFs is calculated assuming full availability of the offshore wind turbine. The CFs are presented only for DTU's wind turbine due to similar results between the 5 and 10 MW technologies, where the differences in cut-in wind speeds and hub heights have a negligible effect in the CFs obtained.

The CF regional variability is analyzed by presenting the seasonal means of the DTU wind turbine along the period analyzed as shown in Fig. 5. Blue zones in the map are assigned to CF values equal or above

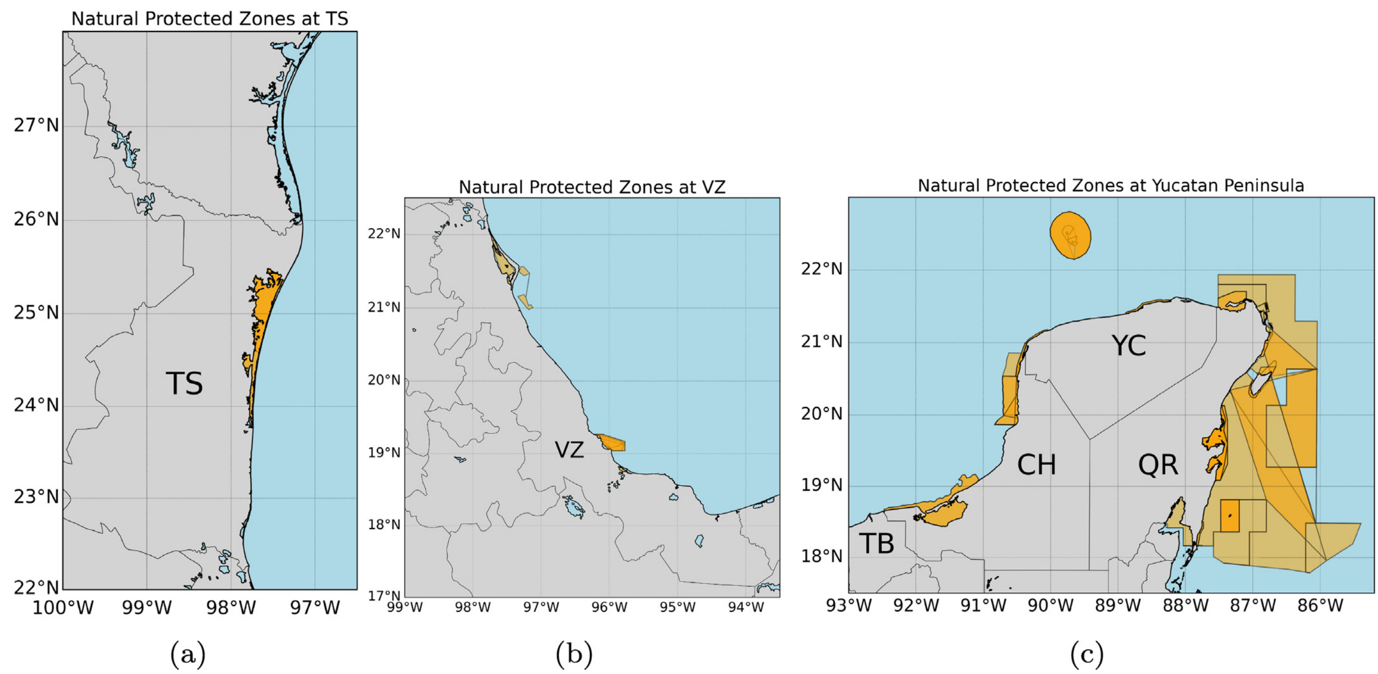


Fig. 3. Protected areas in the states of a) Tamaulipas (TS), b) Veracruz (VZ) and c) Yucatan Peninsula which includes the states of Campeche (CH), Yucatan (YC) and Quintana Roo (QR).

55%. CFs in the potential zones show important differences throughout the seasons of an average year. For the TS state, an average maximum CF above 55% is observed in winter (in the months from December to January), while for the YC state this is observed in spring (in the months from March to May). Although maximums are seasonal alternated, CF values are well above 50%. In Autumn (in the months from September to November), the average CFs in these regions reach values of 40% for the TS and YC peninsula, this last region with considerably smaller areas than the TS state. In the summer season (in the months from June to August), white areas which represent a CF equal or below 20%, are remarkably abundant the entire Gulf of Mexico. TS state, and the YC peninsula, are the only regions with an average CF near 30%. An important characteristic to mention is that these white zones are present consistently throughout the year along the VZ coasts.

Since the CFs are obtained from the reanalysis models, it is necessary to validate the data with real measurements to avoid bias errors as presented in the work of (Gualtieri, 2021; Samal, 2021). For the Mexican case, onshore applications have shown that reanalyses typically underestimates the wind speeds (Morales-Ruvalcaba et al., 2020). Assuming that for offshore conditions this is also the case, it would be possible to reach higher wind velocities in the ocean and therefore higher CFs when compared to onshore locations, which could increase the number of potential areas.

Delimitation of potential zones

In this section, the potential zones are delimited by the superposition of area restrictions as shown in Fig. 6. The bathymetry is delimited by a red line which represents the maximum depth of 50 m; the two black dashed lines depict the distances from the coast at 22.22 and 44.44 m; the natural restricted areas are represented by yellow polygons, and the limit of the EEZ is represented by the black line across the Gulf of Mexico. Therefore, three potential zones, A, B, and C are identified from this analysis stage.

Zone A, located on the TS coast, has no protected areas off the coast, and the bathymetry delimits a small region at the north, up to 44 km from the coast. On the VZ coast, the viable area is reduced to 22 km due to the water depth, as shown by the red line in Fig. 6. The east coast of TB, the western region of the CH coast in zone B and the YC coast in zone C, have the suitable conditions for offshore wind development except for the southeast CH where protected zones are present.

The coast of Veracruz and the west of Tabasco are excluded areas due to water depths >50 m, where non-conventional support structures or even floating structures would be necessary. The north coast of CH (between zones B and C) and the entire coast of QR are also excluded because there are protected areas on those coasts.

In general, the VZ coast presents the lower average CF values in combination with the smaller areas with 50 m depth; this suggests that although high wind speeds are observed in the Gulf of Mexico, the VZ state has limited conditions for large offshore wind development. It is essential to highlight the offshore regions of CH and YC states, at its north-west and west direction respectively, where a large area is feasible for bottom founded structures in addition to the largest CF values, however with higher distances from the coast than the world's average. These results suggests that further detailed area analysis is required where economic factors must be considered including the electric transmission lines and CFs minimal values.

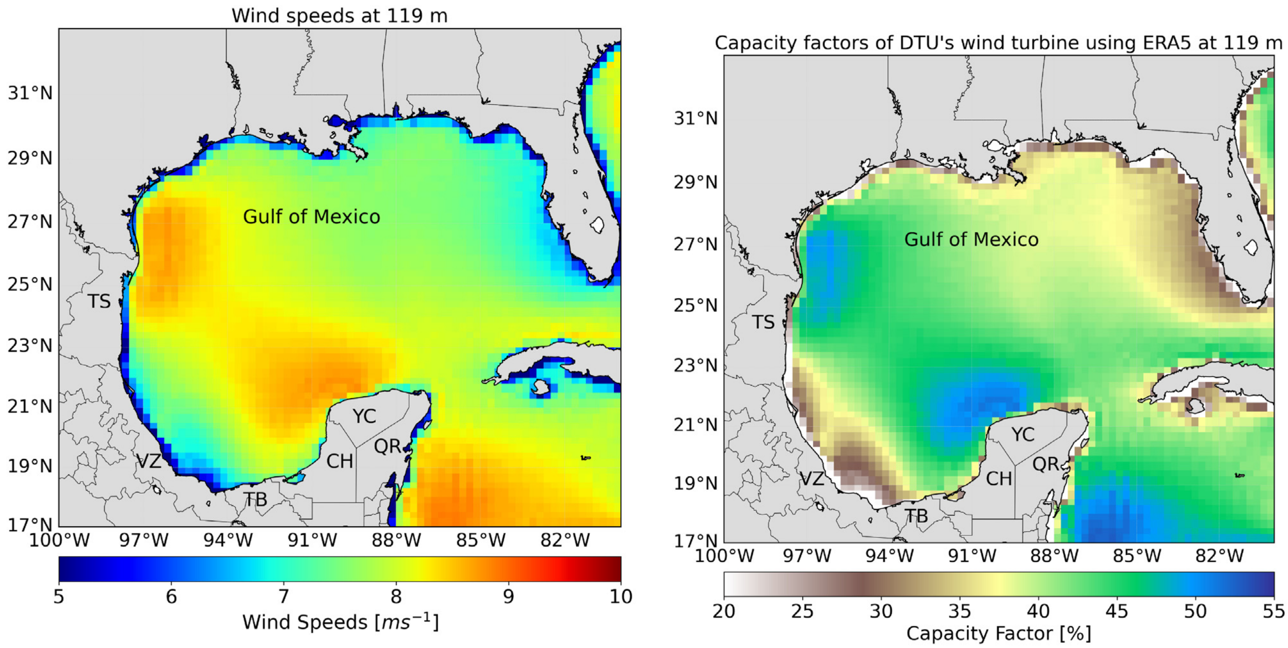
Fig. 7a and b show the superposition of the restrictions together with the CFs above 30% obtained from ERA5. In order to have a better description of near shore areas, the results from ERA 5 were used due to the higher resolution when compared to MERRA2. Four specific locations; P1, P2, P3 and P4, are proposed in these potential regions to analyze their CF variability throughout the year.

Table 4
Technical and spatial restrictions considered in this study.

Type	Restriction
Bathymetry	Maximum 50 m
Protected zones	Must be avoided
Economic exclusive zone	Inside the EEZ for Mexico
Capacity factor	Above 30%
Distance from coast	Maximum of 44.44 km

Local capacity factors seasonality

Smaller areas are delimited within the potential power production zones and geographical restrictions. Four representative points in these



(a) ERA5 average wind speeds at 119 m for 39 years of data

(b) Average capacity factors for 39 years of data

Fig. 4. Maximum average wind speeds at 119 m height (a) and CFs values (b) are located at the north of TS and the northwest of the YC Peninsula. The minimal values are observed along the coast, mainly at the coasts of VZ and TB.

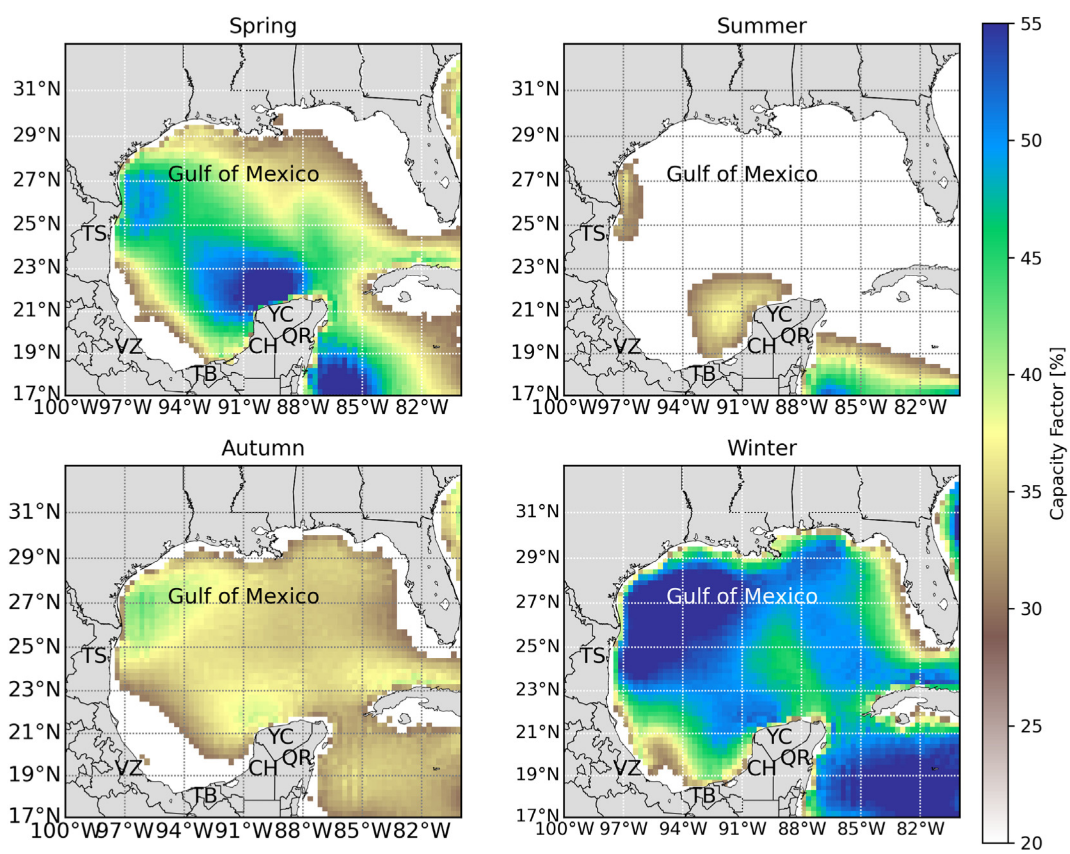


Fig. 5. Mean CF's for the 10 MW DTU wind turbine at 119 m height. Blue zones represent CF values equal or above 55%. The seasons are divided as follows: Spring from March to May, Summer from June to August, Autumn from September to November and, Winter from December to February. This maximum threshold is seasonally alternated by two regions: TS state in winter and the YC peninsula in spring. These two regions show CF values above 20% all year round. Summer is the season with most CFs' values equal or below 20%, shown in white and always present in the VZ state coasts.

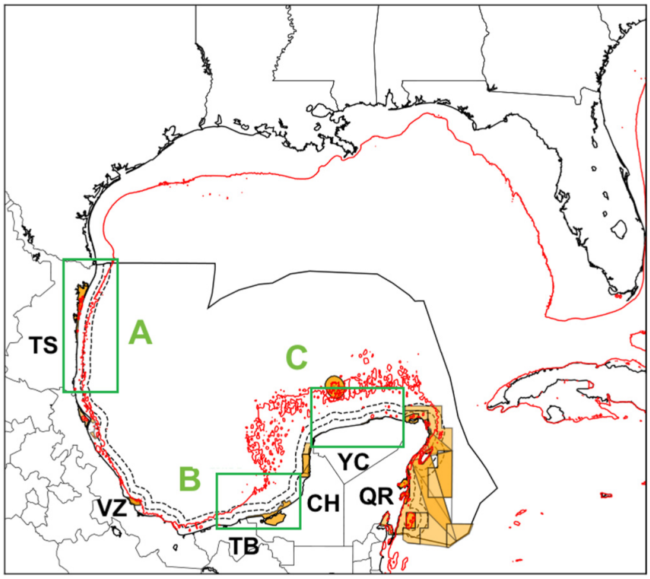


Fig. 6. The areas selected as potential are those which satisfied the analyzed restriction. Three areas are identified: the northeast TS (A), the western CH (B), and the north YC (C).

areas with CFs values above 35% are used to interpolate the wind speeds and calculate the respective CF's time series. For the Yucatan Peninsula, composed by CH, YC, and QR states, three specific locations are selected: P1 in the north of YC; and P2 and P3 in the coasts of CH, shown in Fig. 7a; and the last point P3 at the north-east of Tamaulipas, shown in Fig. 7b.

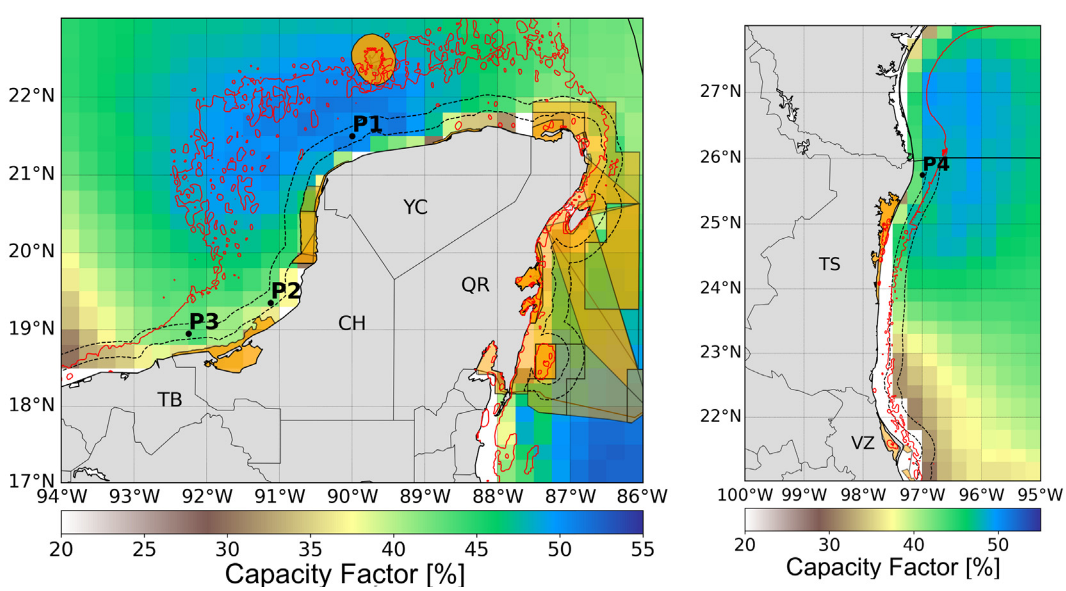
Monthly average CFs for the 39 years are estimated for the four points selected. Due to similarities in the power curves of the NREL and DTU's wind turbines as well as minor variations in the wind speeds observed at their respective hub heights, the resulting CFs are consistent for both wind turbines. Therefore, only the results for the DTU's wind turbine are discussed. Results show similar tendencies along the year among P1, P2, and P3. Therefore to describe the CF variability, only P1, and P4 are shown. In Fig. 8, the boxplots represent the distribution of the monthly average capacity factors during the 39 years. The top and bottom edges of the boxes indicate the 25th and 75th percentiles, while the top and bottom lines are the extreme values excluding data points considered as outliers. CF's boxplots are presented for P1 and P4, the continuous lines link the monthly averages to identify annual trends. P1, P2, and P3 present an harmonic-like behavior with the maximum, CF of 60% in the months of March and April as well as a minimum value of 30% in August or September. It is important to mention that during three months of the year, from July to September, the CF values are between 30% and 45%, while for the remaining months the CF's values are above 45%.

Among the four cases, P1 has the highest values, while CH the lower CFs. P2 presents similar maximum values of 50% from December to April and a minimum value of 25% in September. P4 in TS state presents constant mean monthly values above 45% throughout the year except for July, August, and September. A minimum of 34% CF is observed in August.

The previous results show the distribution of the CFs along the months. The shortest boxplots mean than the distribution of CFs on those months show small yearly deviations. In terms of production, it is possible to estimate a historical range of minimum and maximum annual energy yields since the values of the capacity factors have been determined by the temporal series of 39 years.

Two annual trends are identified, one of high power production, from October to June and one of low power production, from July to September. In four cases, the highest values of the CFs are presented between March and April, and the lowest between August and September. The lower seasons can be used for operation and maintenance to minimize losses in the associated costs. The rest of the analyzed points show similar behavior, probably due to their location in the Gulf of Mexico.

The points outside the boxplots, i.e. the data identified as outliers, represent atypical values in the distributions that only happened once in a given year. Higher outliers can be associated with several hourly periods of sustained high wind speeds but within the range of the cut-in and cut-out speeds of the wind turbines' power curve. On the other hand, lower outliers could be produced by higher wind speeds than the cut-out speeds or lower velocities than the cut-in speeds that lead to zero power production. The atypical CFs are minimal and could be associated with seasonal events that affect the local winds such as hurricanes or tropical cyclones. Besides the effect of these atypical wind speeds regarded in the power curves, these extreme events are not considered in the operation of the turbines.



(a) Potential zones in Yucatan Peninsula. (b) Potential zones in Tamaulipas.

Fig. 7. Three potential areas with CFs above 35% are identified as feasible for offshore development in the Gulf of Mexico, in Yucatan Peninsula: at the north of YC (P1), west of CH (P2) and north of Ciudad del Carmen (P3) and one area is located at the east of TS (P4). The maximum CF of 50% is presented in Yucatan while a minimum CF of 35% is shown in Campeche.

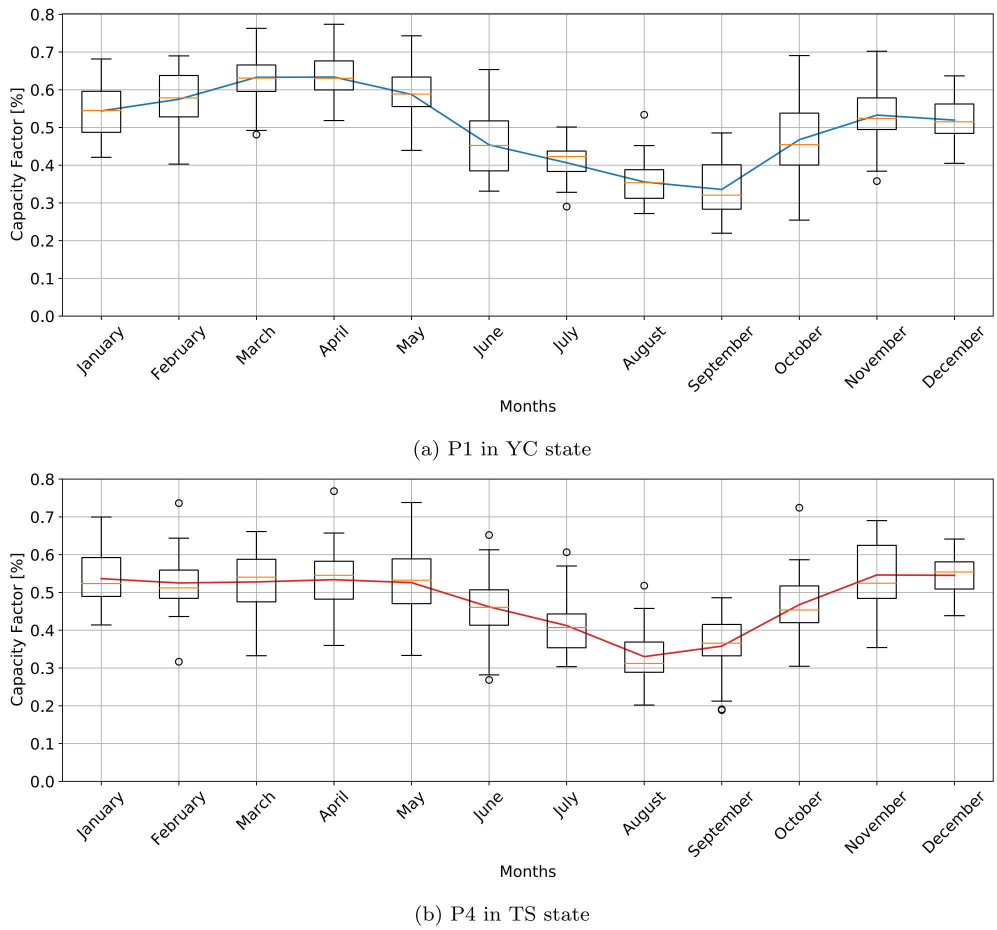


Fig. 8. Average capacity factors evaluated with the DTU's wind turbine for 39 years. P1 and P4 locations, in YC and TS states, are the sites with maximum CFs between 40 and 55% over the years. P2 and P3 in PC state present the minimum values between 30 and 45%.

Conclusions

A methodology was presented to identify potential zones for offshore wind energy development in the Gulf of Mexico. The approach used wind data from ERA5 and MERRA2 reanalyses in combination with GIS tools to account for spatial restrictions such as bathymetry, distance from the coast, natural protected areas and power production using two reference wind turbines of 5 and 10 MW. In the identified zones, four points were selected to interpolate wind speed's time series and to analyze CF variability. As a result, two areas were found with CF values above 30%, located at the northeast of Tamaulipas (TS) state coast and northwest of the Yucatan (YC) Peninsula. In these zones, the average wind speeds over 39 years from reanalyses data were found to be between 8 and 9 m/s, with annual mean CFs between 50 and 55% for the selected 5 and 10 MW wind turbines. Four points within the YC, CH, and TS state areas were selected to interpolate local wind speeds, estimate CF, and analyze their monthly variability. In the four cases studied, two annual trends were identified: high power production, from October to June, and low power production, from July to September. In four cases, the highest values of the CFs are presented between March and April, and the lowest between August and September. Results suggest the presence of areas with high offshore wind potential in the Gulf of Mexico, with CFs above 45% throughout the year except for July, August and September. Although results are promising in terms of power production, specific economic factors were not assessed. Further experimental validation and analysis regarding the effects of tropical cyclones over offshore wind turbines are necessary to continue analyzing Mexico's offshore wind development.

Credit authorship contribution statement

D. A. Canul-Reyes: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing. **O. Rodríguez-Hernández**: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Review. **A. Jarquin-Laguna**: Conceptualization, Formal analysis, Methodology, Supervision, Validation, Review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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