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Feasibility study of offshore wind energy in the Gulf of Mexico

TESIS
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Dedicatoria

”Wit beyond measure is man’s greatest treasure.”
—Rowena Ravenclaw

A mi familia, mis padres Edith y Felix, y mi hermano Gerardo; quienes sin su apoyo y cariño durante toda mi vida, este trabajo no sería posible.

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Abstract

In the last years, the new offshore wind energy projects have been increasing globally, and due to the development of technology, the costs have decreased. In comparison with onshore, offshore wind resources are higher and steadier, allowing them to generate more energy from wind turbines. Also, the availability of larger areas can avoid social issues related to the use of land. Some studies have been realized in Mexico to estimate the potential offshore wind, but none of them have evaluated the feasibility of offshore wind projects in specific potential zones.

Mexico is located between three oceans: the Gulf of Mexico at the east, the Caribbean sea at the southeast, and the Pacific Ocean at the west. This study is delimited to the Gulf of Mexico. A feasibility study is realized in two stages: first, the wind resource is estimated using 39 years data from the reanalyses models MERRA2 and ERA5 (1980-2019), then, the capacity factors are calculated for two reference turbines the NREL's 5 MW wind turbine and the DTU's 10 MW.

In the second stage the potential zones are delimited by the superposition of the maps based in the following technical and spatial restrictions: Economic Exclusive Zone (EEZ) of Mexico, maximal distance from the coast of 40 km, exclusion of protected areas, bathymetry below 50 m, accessibility due waves, and capacity factor above 30%. Considering these conditions, two potential areas are delimited: the northwest of the Gulf of Mexico and northwest of the Yucatan Peninsula.

From those results, four potential are identified: three in the northwest of the Yucatan Peninsula (Yucatan, Campeche and Ciudad del Carmen) and one in the east Tamaulipas. For each zone, monthly and annual energy production and capacity factors are obtained, and study cases of a 1 GW wind farm are performed in each area. Considering losses of 10% due to wakes, a wind farm located in Yucatan could supply 79.45% of the Peninsular electricity zone and one located in Tamaulipas 18.35% of the Northeast zone.

Although the effectiveness of the reanalyses models has been demonstrated in the literature, for onshore and offshore applications, this study is limited to the validation of the reanalysis data sets with real measurements.

This work its the first approach for offshore wind energy development in Mexico, the results here presented shows its technical feasibility in the Gulf of Mexico.

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Chapter 1

Introduction

In this introductory chapter, the motivation to develop this work is given in the context of renewable energies to mitigate climate change. Likewise, the objectives and the thesis outline are delimited.

1.1 Motivation

Since 1997, with the Kyoto protocol, most of the countries participate in international agreements whose objectives are to reduce the emissions of greenhouse gasses to mitigate climate change. Current efforts are focused on accomplishing the Paris Agreement and the 2030 Agenda for Sustainable Development. The constant growth of the electrical demand has derived in energy matrix diversification through economic support and, as a consequence, the decrease in the cost of these cleaner technologies. In this context, the use of renewable energies has increased in the last years.

Until 2018, the global generation by renewable energy was over 26%, being the wind energy the second source of greater contribution to the energy mix, a total of 591 GW [1]. In 2019, the total installed capacity increased 10% compared to 2018, 54.2 GW onshore and 6.1 GW from offshore, being the best year with more capacity installed for the global offshore industry [2].

At the end of 2019, there was a total of 29.1 GW offshore installed capacity (fig. 1.1), 75.2% located in Europe, 24.7% in the Asian-Pacific region, and 0.1% in North America [2]. The leader countries in offshore installed capacity are United Kingdom, Germany, China, Denmark, and Belgium [3].

In Mexico, the installed capacity of onshore wind energy is only 6591 MW, representing 25.7% of the renewable energy contribution [5]. Most of it is installed at the Tehuantepec isthmus region, which is considered one of the best areas with a high wind resource in America [6]. Oaxaca, Yucatan, and Tamaulipas are the most abundant

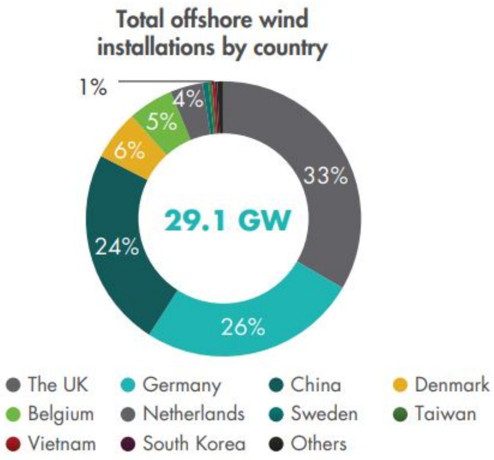


Figure 1.1: Total offshore wind installations by country. The top five countries are the UK, Germany, China, Denmark, and Belgium. By region, 75.2% is installed in Europe, 24.7% in the Asian-Pacific, and 0.1% in North America. Image obtained from [4].

wind resources in the country [6]. The offshore wind facilities are non-existent in the country but are considered a potential future market for offshore wind [2].

More wind turbines must be installed to make a more significant contribution of wind energy to the Mexican and global energy mix. The trend on the design of new machines is to create larger turbines and increase its rated power capacity; this requires higher and more stable wind regimes [5]. The offshore wind farms represent an alternative to the facilities on land, in the ocean, the wind resource is steadier, and there are larger areas available. Also, the installations on the sea can avoid social problems related to land use, as in the case of Oaxaca, where the society was not satisfied with the government's decisions, mainly due to the low costs associated with terrain.

Sanchez et al. [7] describe the next advantages of offshore wind farms:

- The wind resource is higher at sea than on land and nearby coasts.
- The visual and acoustic impact is lower than wind farms on land.
- The lower surface roughness in the sea favors the use of lower tower heights.
- Possibility of integration with ocean renewable energies.
- More constant and stable energy generated.
- The social issues related to the acquisition of land are reduced.

Some studies have determined the offshore wind potential in Mexico. The review of these studies is presented next.

Bosch, Staffell, and Hawkes [8] estimated the global offshore wind energy potential using a methodology based on Geospatial Information Systems (GIS) for 157 countries. They used the reanalysis model MERRA-2 data sets that provide multiple meteorological variables and the Global Wind Atlas. The constraints considered were the Economic Exclusive Zone, protected areas, bathymetry, submarine cables, and landing stations. Different wind turbines were evaluated in accord with the IEC wind class, considering the annual average wind speeds in each location. The study found a total offshore wind capacity potential of 85.6 TWh 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 [3] estimates a generation of 5705 TWh/year for the country.

Haces-Fernandez, Li, and Ramirez [9] developed an assessment study to supply electricity from wind and waves to offshore oil platforms in the Gulf of Mexico. They used data from the WaveWatch III system and diverse GIS. Using a Vestas V90 of 3MW, the regions with the highest wind power output were the northwestern Gulf, the western Yucatan Peninsula coast, and the Florida strait, with a capacity factor above 20-30% for all months of the year.

The National Renewable Energy Laboratory [10] 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. The potential zones were delimited by average wind speeds above 7 m/s, water depths less than 1000 m, available area for commercial development, among others. For six potential sites the Levelized Cost of Energy was calculated for each one. The results were reported in terms of the economic activity generated by the development of a 600 MW offshore wind plant, including the jobs that can be created and the gross domestic product.

The work developed by Bosch, Staffell, and Hawkes [8] is a global study and does not delimit specific areas for offshore wind development, also, given that the wind data are cut into seasonal bins, an analysis of the variations in capacity factors cannot be performed. The results described by Haces-Fernandez, Li, and Ramirez [9] take as a priority oil platforms in the Gulf of Mexico located on the north coast of Tamaulipas and north coast of Tabasco, and are presented as a sensitivity analysis considering the distance of those platforms. In this thesis, it is proposed to delimit potential zones to harness offshore wind energy in the Gulf of Mexico, being the main objective to estimate the energy that can be produced in those zones.

A methodology based on previous works in other countries is developed to reach the objectives. Data for reanalysis models are used to estimate the wind resource, which allow a long-term global analysis. Additionally, data from GIS is used for spatial restrictions. These constraints are selected accord to the requirements of the offshore technology and are related to the sea depth, the distance from the coast, and the preservation of nature.

This work and its results represent opportunities for offshore wind energy development in Mexico, a technology that has not been exploited yet in the country. Wind farms located in the ocean not only can benefit the states in the Gulf of Mexico coast, but they also open new research lines, reduce the emissions of greenhouse gasses, have economic impacts on the electric sector, and generate new jobs.

1.2 Objective

To estimate the offshore wind energy that can be produced in the potential zones in the Gulf of Mexico.

1.2.1 Specific Objectives

- To identify the zones with high wind resource.
- To delimit potential zones where spatial and natural constraints are valid.
- To estimate the annual energy that can be produced on the potential zones

1.3 Thesis Outline

This thesis is structured in four chapters. In this chapter, the background of offshore wind energy, the basic concepts, and the objective of this work were presented. Chapter 2 presents the literature review, a description of the offshore wind technology, and the conceptual framework related to wind energy. 3 describes the data and methodology used in this thesis. Chapter 4 discusses the results and chapter 5 closes with the conclusions and future work.

Chapter 2

Literature Review

Once the motivation and objectives of this thesis have been given in the previous chapter, a review of the wind resource in the Gulf of Mexico is presented below, and the theoretical concepts related to offshore wind energy necessary to delimit the potential zones.

2.1 Wind Resource

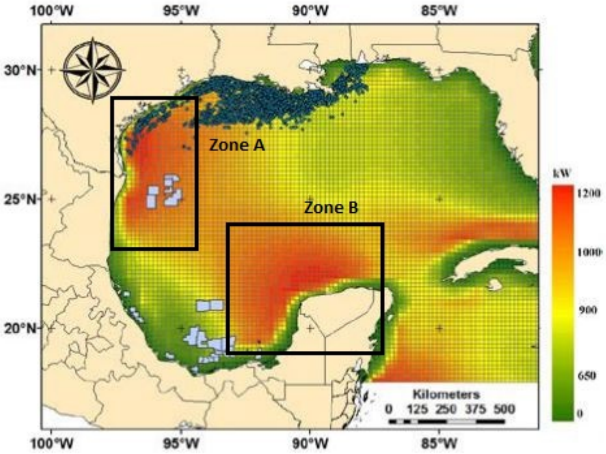
The analysis of wind resources presented in previous works has identified potential zones that suggest an opportunity for the development of wind energy in the Mexican coasts. This section summarizes the review of these studies, which were carried out using different reanalyses models.

Haces-Fernandez, Li, and Ramirez [9] identified three zones at the Gulf of Mexico with high wind power production using the WaveWatch III model: the northwestern Gulf, the western Yucatan Peninsula coast, and the Florida strait.

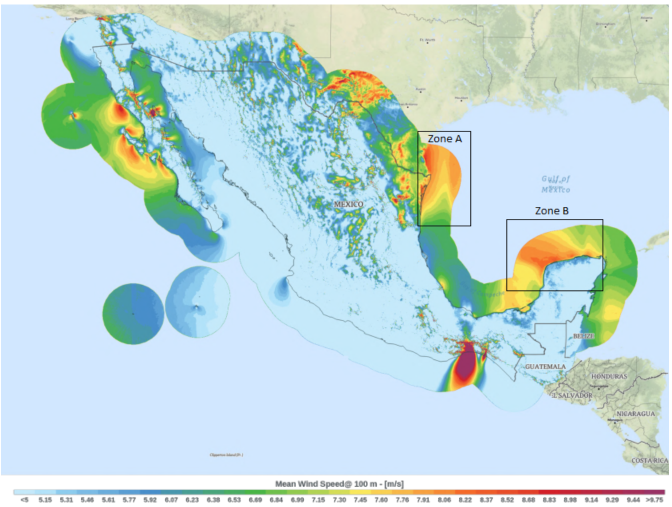
The Global Wind Atlas, developed by the Technical University of Denmark (DTU), estimates the global wind resource using data from the reanalysis model ERA5 and downscaling the data from 30 km to a 250 m grid [11]. The downscaling process uses the reanalysis data (large scale, 20-200 km) as an input for mesoscale model (medium scale, 1-20 km), and finally in a microscale model (small scale, 0.1-1 km). This last stage considers high-resolution topography and land use to predict the local wind climates.

The Global Wind Atlas only shows information up to 200 km from the shorelines. The numerical information from the atlas is only available for the average wind speeds between 2008 and 2017. The spatial resolution is better in comparison with the obtained directly from ERA5, but the temporal resolution does not allow an analysis of the wind dynamics. In figure 2.1b the wind resource at 100 m height, only for Mexico, is shown. The zones with the highest mean wind speeds are located at the east of the

Tamaulipas coast, and the northwest of the Yucatan Peninsula.



(a) Yearly average wind power generation by a 3 MW wind turbine over 36 years (1979-2015) at 80 m height using data from the WaveWatch III model. Map obtained from [9].



(b) Average wind speed at 100 m over the 2008-2017 period. The max average wind speeds in the potential zones (A and B) are between 7.5 and 8.5 ms^{-1}. Data from the Global Wind Atlas for Mexico up to 200 km from the shorelines. Map obtained from [11].

Figure 2.1: Zones with high wind resource at the Gulf of Mexico identified from previous works. Both works have identified potential zones in the same locations: at the east of the Tamaulipas coast (zone A), and the northwest of the Yucatan Peninsula (zone B).

Both of the previous works have identified potential zones in the same locations.

These results will be compared with those obtained by the reanalyses models MERRA2 and ERA5 over 39 years (1980-2018) as a product of this research.

2.2 Offshore Wind Technology

A wind turbine is a mechanical device used to convert wind energy into electricity, using the aerodynamic force in the blades to produce a torque in a generator to generate electricity. The most common design of modern wind turbines is with the horizontal axis (fig. 2.2, its principal components are [12]:

- The rotor, blades, and the supporting hub.
- The drive train, including the rotating parts of the wind turbine.
- The nacelle and mainframe, including wind turbine housing, bedplate, and the yaw system.
- The tower and the foundation.
- The machine controls.
- The balance of the electrical system, including cables, switchgear, transformers, and possibly electronic power converters.

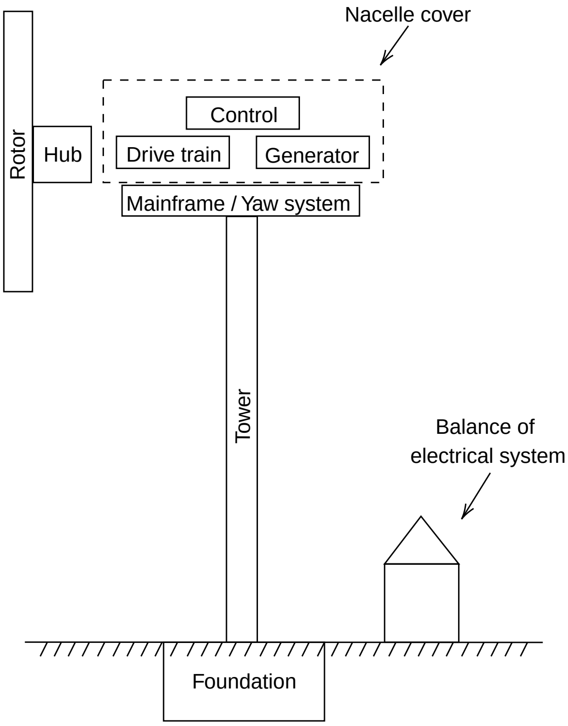


Figure 2.2: Schematic diagram of a wind turbine with its principal components. Adapted from [12].

The foundations for wind turbines at the ocean are different from those used on land, mainly due to the seabed water depths and soil conditions. The adequate selection of the foundation for an offshore wind turbine is one of the main parameters for its installation, due to the structure which must support the wind turbine, absorb aerodynamics and hydrodynamic forces, loads from the wind and waves; and provide a safe and stable base [7, 13].

Most of the existing offshore wind turbines are installed with fixed-bottom foundations, which are briefly described in table 2.1, these foundations work for water depths below 50 m.

Type	**Description**	**Water depth**
Gravity base	The support structures are standing directly on the seabed due to their self-weight	Less than 10 m
Monopile	Typically it is composed of a single steel tube pile of a diameter of 3 to 8 m	Between 20 and 40 m
Tripod	Composed of three steel pipe piles arranged in an equilateral triangle	From 10 to 35 m
Jacket	Space frame structure assembled from steel tubular members	From 5 to 50 m

Table 2.1: Description of the fixed-bottom offshore wind turbines foundations. Adapted from [14].

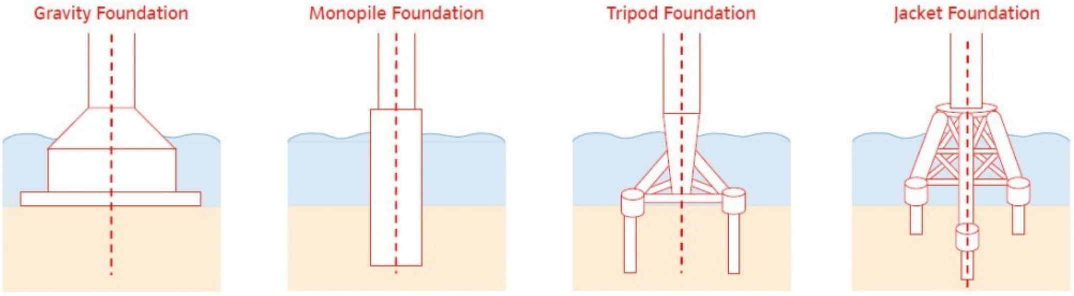


Figure 2.3: Schematic diagrams of the fixed-bottom offshore wind turbines foundations. Range of water depth application: gravity, less than 10 m; monopile, between 20 and 40 m; tripod, from 10 to 35 m; jacket, between 5 to 50 m. Image obtained from [15].

The wind turbine foundation costs increase with depth and represent between the 19% and 36% of the total cost [13]. For depths higher than 50 m, the fixed-bottom foundations are not economically viable due more material is required, and it is necessary to use floating structures, which is a technology still under research.

The designs of floating structures are based on the development of the floating oil and gas platforms, there are three basic types [14]: tension leg platforms (TLPs), semi-submersibles, and spars (fig 2.4). At the end of 2019, 65.7 MW was installed using this technology: 32 MW in the UK, 19 MW in Japan, 10.4 MW in Portugal, 2.3 MW in Norway, and 2 MW in France [2]. The importance of the research of floating structures is to fully harvest the offshore wind potential since 80% of the world's resource lies in waters deeper than 60m [2].

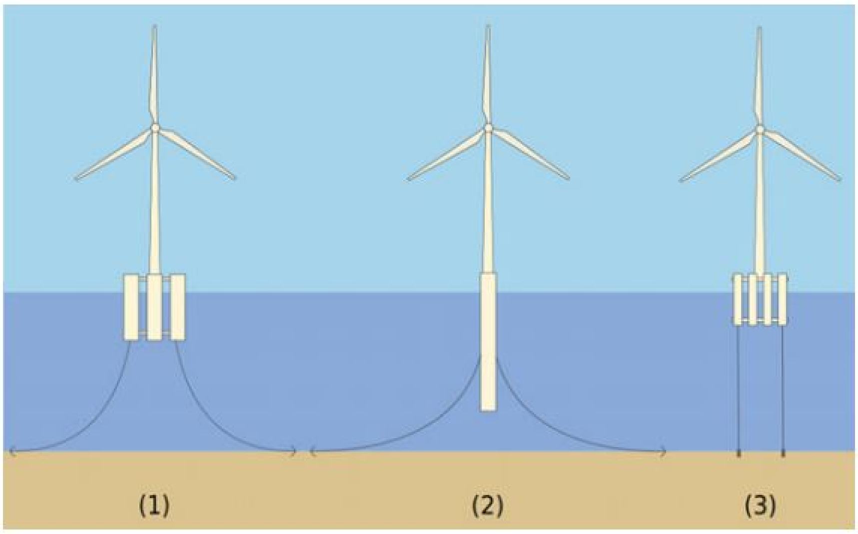


Figure 2.4: Designs of floating structures. (1) Semi-submersible platform (2) Spar buoy (3) Tension leg platform (TLP). Image obtained from [16].

The trend in technology is to make bigger turbines (fig. 2.5) to reduce the Levelized Cost of energy, increasing the annual energy produced by unity [2]. In 2000 the average offshore wind turbine size was 1.5 MW, in 2018 was 6.5 MW, it is expected to reach 10-12 MW by 2025 [2].

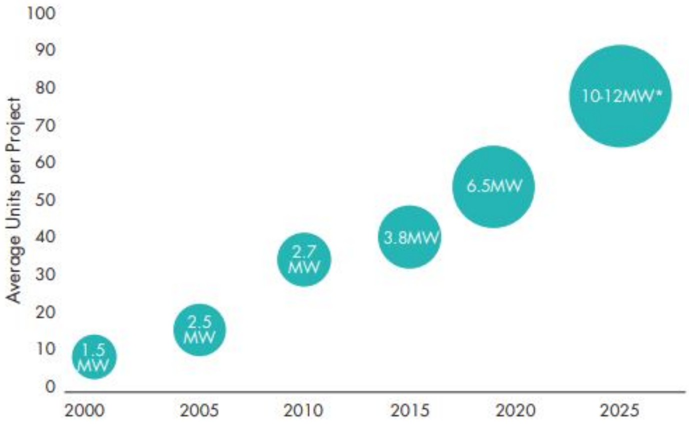


Figure 2.5: Evolution of offshore wind turbine and project size. In 2000 the average offshore wind turbine size was 1.5 MW, in 2018 was 6.5 MW, it is expected to reach 10-12 MW by 2025. Image obtained from [2].

One of the disadvantages of the new offshore wind facilities is the non-existence of electrical infrastructure near the location [7]. The cost of the connection to the electrical grid increases as the distance to the coast increases due to the required equipment to transmit the energy generated [17] (offshore substations, subsea cables, protection equipment, among others).

It is preferable to locate the wind turbines as far as possible to take advantage of higher wind speeds and to avoid the visual impact on the landscape and the coast [7]. However, longer distances from the shore are associated with more transmission losses and also with greater depths to the seabed. The criteria to select the adequate location for a wind turbine must be in terms of the most convenient and cost-efficient relation between lower depth and distance to the coast [7].

According to the Renewable Power Generation Costs in 2018 by IRENA [5], most of the new offshore wind projects considered in that report during 2001-2018 were installed up to 40 km from the coast, but also, there were some projects installed between 40 and 90 km far from the shoreline (see figure 2.6).

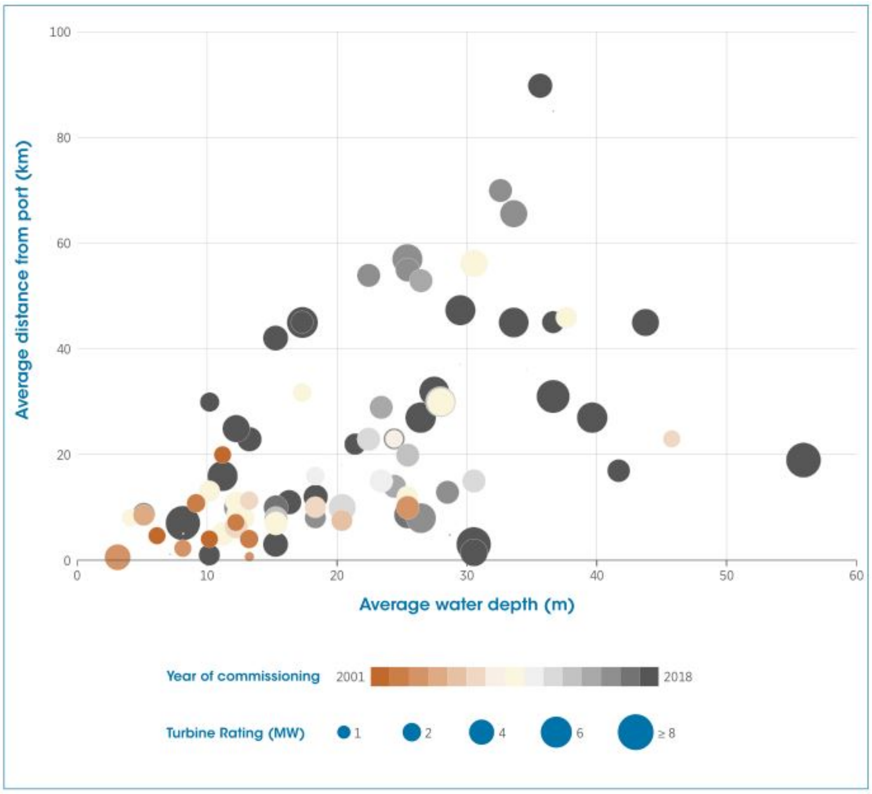


Figure 2.6: Distance from the coast of new offshore wind projects during 2011-2018. Most of the projects are located up to 40 km from the coast. Image obtained from [5]

Based on the information described in this section, a maximum depth of 50 m and a distance to the coast up to 40 km are considered restrictions for this study.

2.3 Conceptual framework

The necessary concepts for the development of the methodology and discussion of the results are presented in this section.

2.3.1 Power Curve

One of the most important parameters of a wind turbine is its power curve, which is a function of velocities and represents the relationship between the wind speeds at the cube height and the energy production. In figure 2.7 a typical power curve is presented, three particular speeds are identified:

- Cut-in wind speed: the turbine starts to produce power.
- Rated wind speed: the turbine produces its nominal power.
- Cut-out wind speed: above this value, the turbine stops producing power and shuts down.

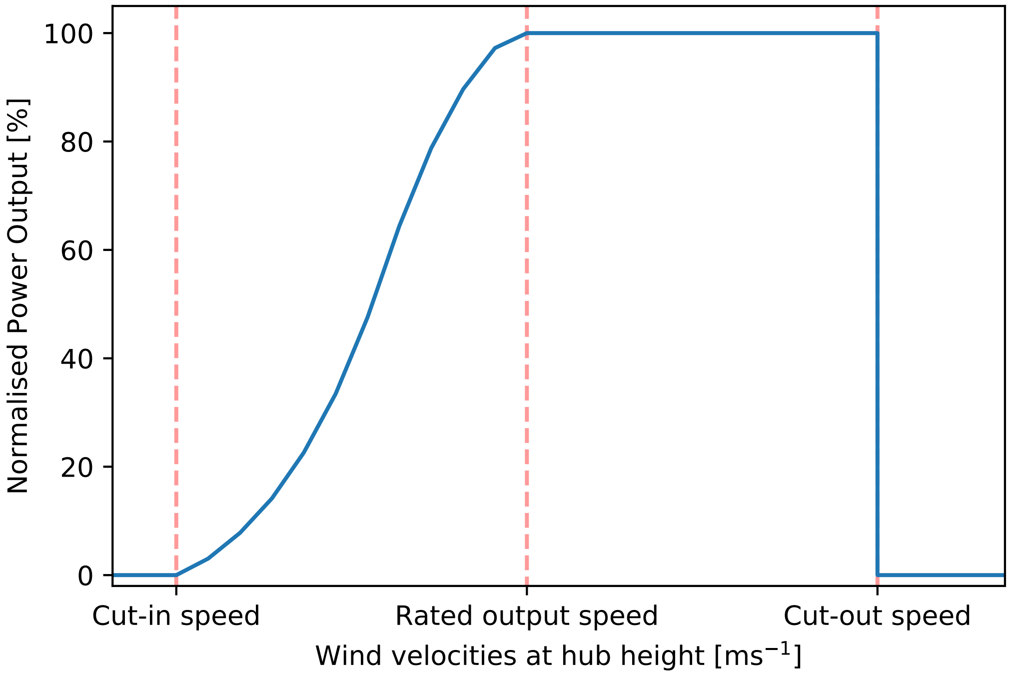


Figure 2.7: Power curve for a typical wind turbine. Three particular speeds are identified: cut-in, rated and cut-out, where the turbine starts to produce power, reach its nominal power and stops producing power, respectively.

The power curve is provided by the manufacturer and can be used to estimate the energy produced by the machine by modeling the curve with a mathematical function and evaluating the wind speeds in that function. This is an idealized estimation since the curves are generated in test fields with controlled atmospheric conditions and do not consider the losses that may exist [18].

2.3.2 Athmospheric Boundary Layer

To assess the power production from a wind turbine using its power curve it is preferable to have the wind velocity at its hub height. However, when the data is not available at that height, it is recommendable extrapolate to calculate the required wind speed and improve the power production estimation.

The vertical distribution of the wind speed on the ocean is influenced by the momentum flux of the waves and currents, the wind loads on ships and marine structures as oil platforms [19].

There are two models widely used in the literature to model the vertical profile [12]:

- Logarithmic profile.
- Power-law profile.

The logarithmic profile it has its origins in boundary layer flow in fluid mechanics and atmospheric research. It is based on a combination of theoretical and empirical research.

The power-law profile is a simplified model for the vertical wind speed profile that can be used to extrapolate the wind data, it is defined as [12]:

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{2.1}$$

where $U(z)$ is the wind speed at height z, $U(z_r)$ is the reference velocity at height z_r, and α is the power-law exponent. This coefficient is a function of the atmospheric stability in the layer which α is determined and the underlying surface characteristics [19]. Since the α exponent is an empirical relation, S. A. Hsu [19] estimated the value of 0.11 ± 0.03 for the sea, based on 30 samples of anemometers at different heights in the Gulf of Mexico and off the Chesapeake Bay, Virginia. For this work, the value of 0.11 for α is used.

2.3.3 Annual Energy Produced

The annual energy produced (AEP) from a wind turbine is the amount of electrical energy generated by the machine over a period of time. Using the temporal series of the wind velocities, the AEP is calculated as the sum of the velocities evaluated on the power curve function $P(U)$ of the turbine during 8760 hours for a typical year:

$$AEP = \sum_{t=1}^{N} P(U)\triangle t \tag{2.2}$$

This estimation does not consider looses that may exist as in transmission cables, wakes effects in the case of wind farms, neither does consider seasons of maintenance where the turbine stops.

2.3.4 Capacity Factor

A complementary parameter to the AEP is the capacity factor (CF), which is the ratio between the real power output and the nominal power that can be produced by a wind turbine during a period of time:

$$CF = \frac{AEP}{(\text{Nominal power})(\text{Time})} \tag{2.3}$$

The capacity factor is used to evaluate the performance of a wind turbine or a wind farm in a specific location. A capacity factor of 100% means that the wind turbine produces the maximal power during a specific period of time, this is an idealized supposition due to the natural variations of the wind. In Europe, in 2019 the average capacity factor was 38% for offshore projects and 24% for onshore [20].

In this chapter, previous works on wind resources in the Gulf of Mexico and the characteristics of offshore wind technology were presented. The conceptual framework of the methodology was delimited, which is presented in the next chapter.

Chapter 3

Methodology and Data

In the previous chapter, the background and theoretical framework were presented. In this chapter, the methodology and data used in this thesis are described.

3.1 Study Area

Mexico is located between three oceans: the Gulf of Mexico at the east, the Caribbean sea at the southeast, and the Pacific Ocean at the west.

For this work, 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 for the latitudes from 17°0'0" to 33°0'0" N. Initially, the analysis for the wind resource includes the complete area of the Gulf, including the territorial seas correspond to USA and Cuba and then, restricted only to the Economic Exclusive Zone of Mexico (see Fig 3.1).

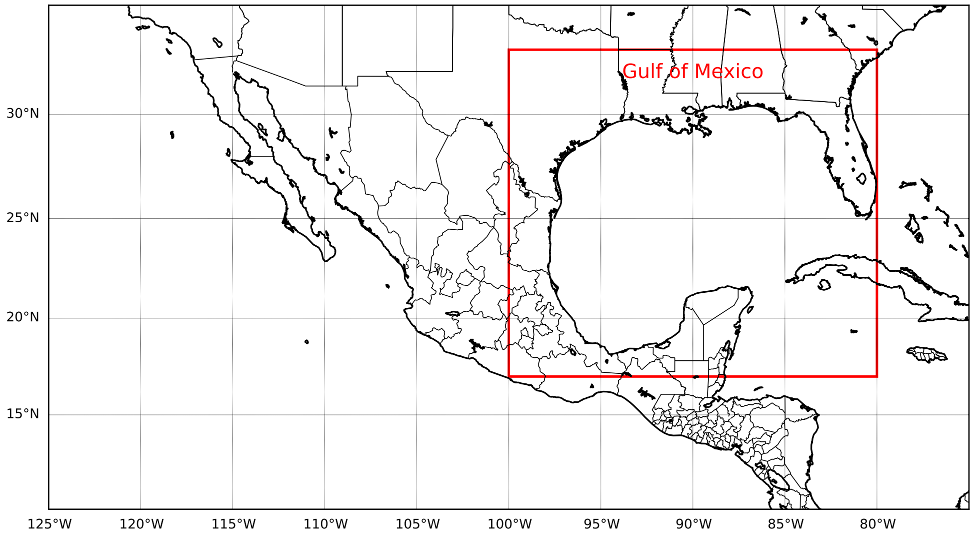


Figure 3.1: Study Area. The study area is limited to the Gulf of Mexico, between the longitudes from -100°0'0" to -80°0'0" W and for the latitudes from 17°0'0" to 33°0'0" N.

3.2 Reanalyses Models

In the resource assessment analysis, it is recommendable to use at least one year of wind speed data with a 10 minute time resolution. If more information is available the estimation of the energy produced is better. For offshore observations, data can be obtained from buoys, satellites, or ships. However, the disadvantages of these measurements are that the buoys and ships offer observations in specific sites, and satellite observations are for different areas at specific times. Given that the objective of this work is to estimate the wind resource in an area and also, to evaluate the changes in the energy production over time, it is proposed to use reanalyses data sets that provide a long-term analysis tool.

Genaro et al [21] define reanalysis as "the process whereby an unchanging data assimilation system is used to provide a consistent reprocessing of meteorological observations, typically spanning an extended segment of the historical data record". This is, data assimilation and physical models are combine with real observations to create the reanalysis.

The outputs of these models are gridded data sets for a broad range of variables [21]. The variables are mainly related to weather and atmospheric information as to wind speeds, precipitation, radiation, clouds, temperature, and pressure.

Dee [22] describes some advantages of the use of reanalysis:

- Global data sets, consistent spatial and temporal resolution over 3 or more decades, hundreds of variables available, model resolution, and biases have steadily improved.
- Reanalysis incorporate millions of observations into a stable data assimilation system that would be nearly impossible for an individual to collect and analyze separately, enabling a number of climate processes to be studied.
- Reanalyses data sets are relatively straightforward to handle from a processing standpoint (although file sizes can be very large).

Reanalyses models are obtained from a forecasting process and should not substitute real observations. The use of two reanalyses is proposed to compare the potential zones with the highest wind speeds that can be estimated by them:

- Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA2) [21].
- ECMWF ReAnalysis version 5 (ERA5) [23].

The characteristics of these models are described in table 3.1.

	MERRA2	**ERA5**
Developed	NASA	ECMWF
Available since	1980-01-01	1979-01-01
Spatial coverage	Global	
Temporal resolution	Hourly	
Spatial resolution	50 km	30 km
Vertical coverage	2, 10, 50 m	10, 100 m

Table 3.1: Characteristics of the reanalysis models.

Both models keep updated, MERRA2 provides data up to three months ago, and ERA5 up to five days ago. For this work, the temporal coverage is from 1980-01-01 to 2018-31-12 (39 years).

3.3 Selection of technology

The characterization of the wind speeds and the selection of an adequate wind turbine are some of the most important factors to develop a wind resource assessment. A turbine must be selected considering the mean wind speed at a specific site. In this study, multiple sites are evaluated to delimit potential zones, for this, two theoretical wind turbines are proposed:

- The 5 MW Reference Wind Turbine by the National Renewable Energy Laboratory [24].
- The 10 MW Reference Wind Turbine by the Technical University of Denmark [25].

The proposed turbines were designed to optimize the performance of the turbines using numerical tools and iterating over its designs [25]. The decision for its use was made considering that the trend in the wind turbine size is to reach 10-12 MW by 2025 as mentioned in section 2.2 therefore, the results will show the potential areas to explore towards future development.

The properties of both turbines are presented in table 3.2 and the power curves in figure 3.2. The curves of the turbines are similar being the main difference that the cut-in wind speed of the DTU's turbine is at 4 m/s and the NREL's at 3 m/s, due to this, it is expected to obtain similar results in terms of capacity factors but not in terms of energy produced.

	NREL	**DTU**
Cut-in wind speed	3 ms^{-1}	4 ms^{-1}
Rated wind speed	11.4 ms^{-1}	
Cut-out wind speed	25 ms^{-1}	
Hub Height	90 m	119 m
Rated Power	5000 W	10640 W

Table 3.2: Properties of the NREL's 5 MW wind turbine and the DTU's 10 MW.

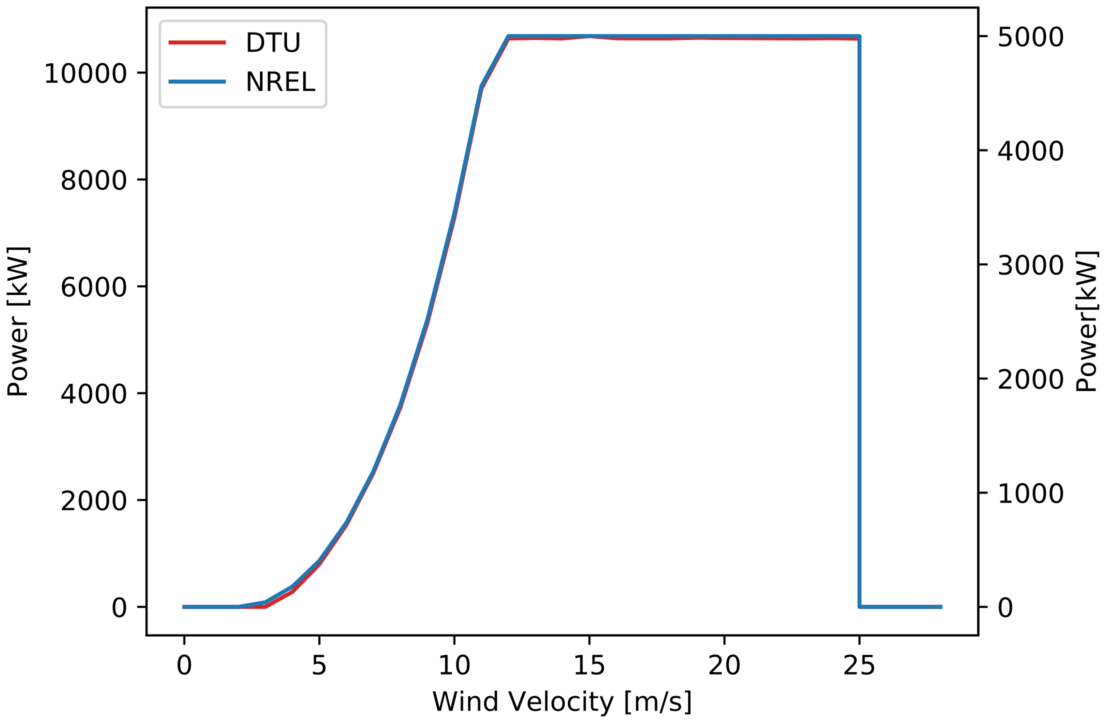


Figure 3.2: Power curves of the NREL's 5 MW wind turbine and the DTU's 10 MW. Both wind turbines present similar power curves: rated wind speed at 11.4 m/s, and cut-out wind speed at 25 m/s. The main difference is the cut-in speed, for the NREL's wind turbine is 3 m/s, and for the DTU's is 4 m/s.

3.4 Technical and Spatial Restrictions

The marine spatial planning process considers technical, economic, environmental, and ecological aspects, among others. Planning information can be obtained and manipulated from Geographic Information Systems (GIS) and other kinds of databases. In this section, the technical and spatial restrictions considered for this work are described: bathymetry, protected areas, and distance to the coast.

It is important to consider that although the wind resource is analyzed for the entire area of the Gulf of Mexico, this study is carried out to harness the wind resource in Mexico, this is, inside the Economic Exclusive Zone (EEZ), which is the area that extends to 370.4 km (200 nautical miles) counted from the continental and insular coastline [26]. The EEZ of Mexico is shown in figure 3.3.

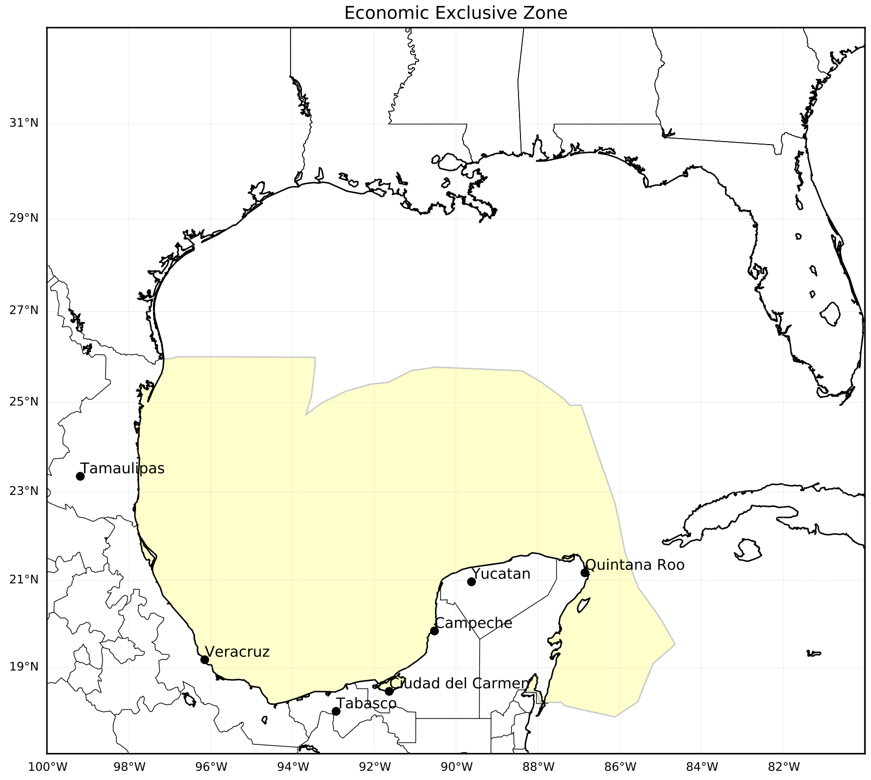


Figure 3.3: Economic Exclusive Zone (EEZ) of Mexico (yellow area). It is the area that extends to 370.4 km (200 nautical miles) counted from the continental and insular coastline. The states along the Mexican coast in the Gulf of Mexico are Tamaulipas, Veracruz, Tabasco, Campeche, Yucatan, and Quintana Roo.

3.4.1 Bathymetry

For this study, only the feasibility for fixed-bottom foundations is considered, this is, the depth to the seabed must be up to 50 m. The NOAA defines the bathymetry as “the ocean’s depth relative to sea level” [27]. The data set for the bathymetry is obtained from the General Bathymetric Chart of the Oceans (GEBCO)[28], which is a global model for ocean and land with a spatial resolution of 15 arc seconds ($\sim$ 463 m).

The bathymetry for the Gulf of Mexico is presented in figure 3.4. Along the southern coast of Tamaulipas, the entire coast of Veracruz, and the west coast of Tabasco the area with bathymetry below 50 m is almost non-existent, the depths are above 300 m. In contrast, potential zones may be observed in a very small area at the northeast of Tamaulipas, near Texas, and a large area in the Yucatan Peninsula along the east coast of Tabasco, the Campeche coast and Yucatan.

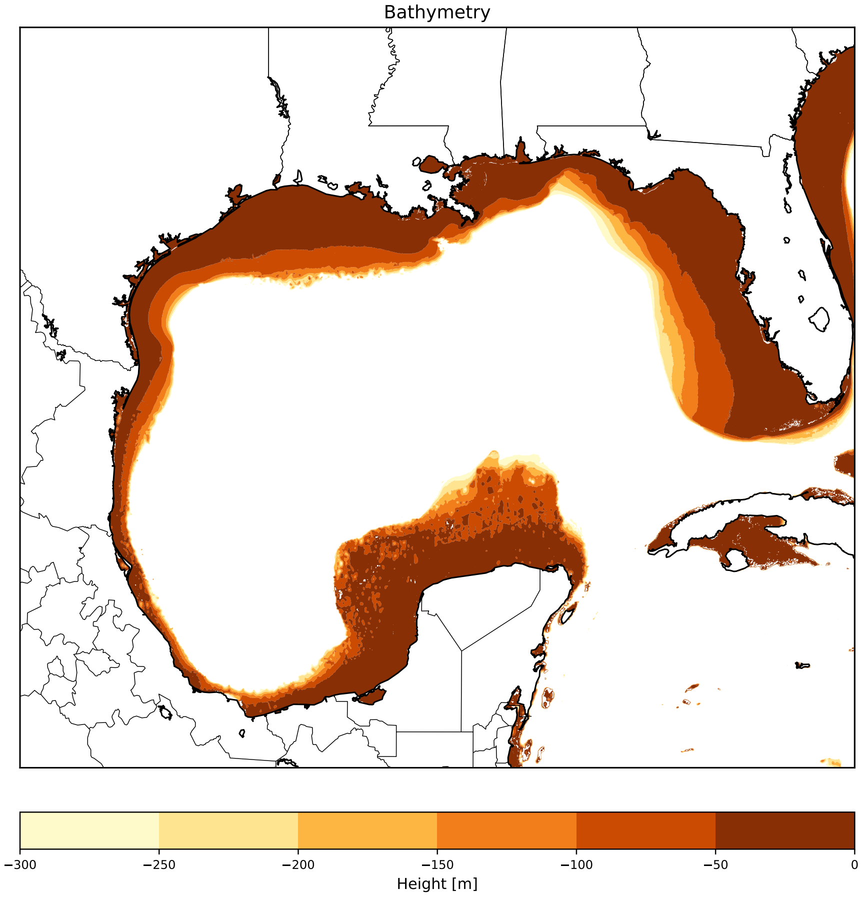


Figure 3.4: Bathymetry for the Gulf of Mexico, lighter colors are deeper areas. Two areas with depths under 50 m (dark brown) are identified: a small area at the east of Tamaulipas and a large area along the east coast of Tabasco and the entire coast of Yucatan and Campeche. Along the southern coast of Tamaulipas, the entire coast of Veracruz, and the west coast of Tabasco the area with bathymetry below 50 m is almost non-existent, the depths are above 300 m.

3.4.2 Protected Areas

Due to the great biodiversity in Mexico, it is important to conserve the Protected Areas which are defined by the International Union for Conservation of Nature [29] as "a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values".

For this work, only the Marine Protected Areas along the Mexican coast in the Gulf Mexico are considered as a restriction for the feasibility analysis. These areas are listed in table 3.3 and shown in figure 3.5. In each state, Veracruz, and Campeche, there are two areas; in Tamaulipas, there are three, five in Yucatan and ten in Quintana Roo.

State	**Protected** Area
Tamaulipas	Laguna Madre Delta del Río Bravo Playa de Rancho Nuevo
Veracruz	Laguna de Tamiahua Sistema Arrecifal Veracruzano
Campeche	Laguna de Términos Los Petenes
Yucatan	Ría Celestún Ciénagas y Manglares de la Costa Norte de Yucatan Reserva Estatal de Dzilam Reserva Río Lagartos Arrecife Alacranes
Quintana Roo	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

Table 3.3: Protected Areas in the Gulf of Mexico.

From figure 3.5, the protected areas at Quintana Roo cover the marine surface at the east of the Yucatan Peninsula. Excluding the Quintana Roo coast and the north coast of Campeche, the other protected areas do not represent a restriction for the installation of wind turbines due to its proximity to the coast.

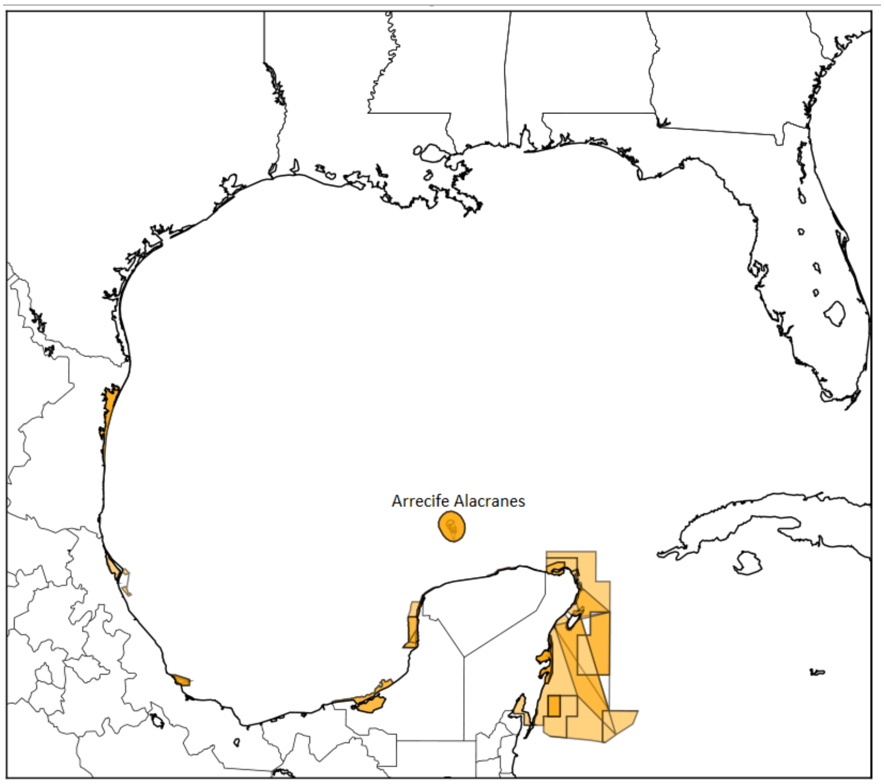


Figure 3.5: Protected areas in the Gulf of Mexico (yellow areas). Except for the Quintana Roo coast and the north coast of Campeche, the other protected areas do not represent a restriction for the installation of wind turbines due to its proximity to the coast.

3.4.3 Distance from the coast

The data of territorial waters of Mexico and its contiguous zone are used to delimit the distance to the coast, (see fig. 3.6), which are defined as the distance from the shore up to 22.22 and 44.44 km (12 and 24 nautical miles), respectively [30].

For this project, the distance from the coast is considered as a constraint, the maximal distance to install wind turbines is up to 44.44 km, this distance is comparable with the new projects reported by IRENA mentioned in section 2.2.

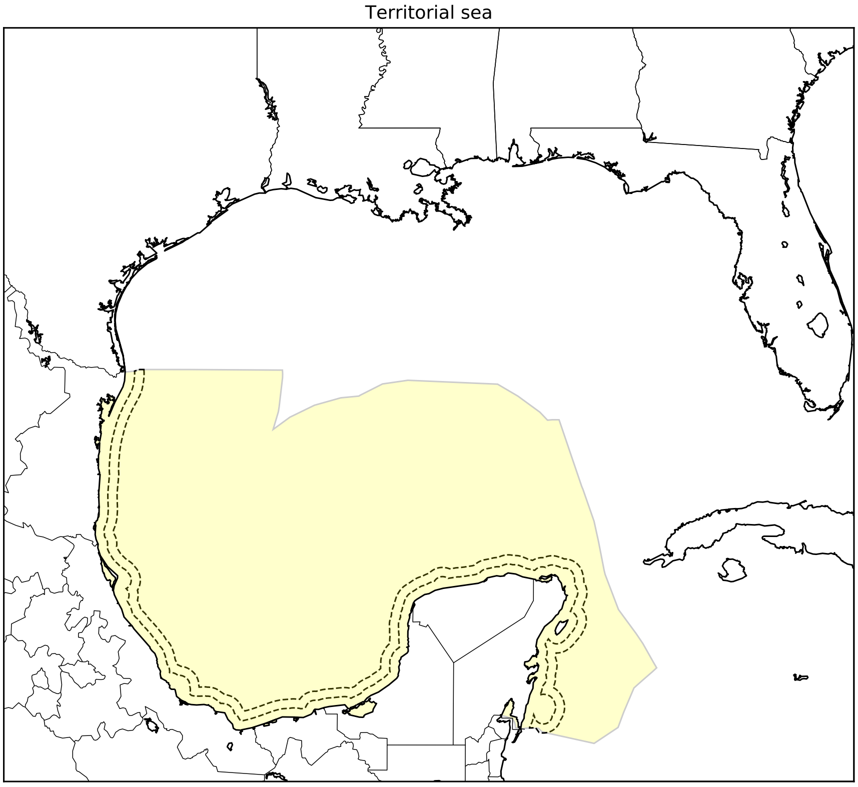


Figure 3.6: Distance to coast. The dashed lines represent 22.22 and 44.44 km (12 and 24 nautic miles) from the coast; the yellow area is the EEZ for Mexico. The constraint considered in this work is to delimit a potential zone up to 44.44 km far from the coast.

3.4.4 Waves

During the planning of offshore wind farms, accessibility to the facilities must be guaranteed for their installation and for carrying out operation and maintenance (O&M) tasks. The main issue to consider is the waves due to the location in the sea. Higher waves do not allow access to ships and then O&M may not take place and this affects energy production and therefore increased Levelized Costs of energy as longer non-operating periods would be necessary [31].

Due to the above, the waves are considered also as a natural restriction, wave heights over 1.5 m impede workboats access [31]. To determine if the waves restrict access to the zones previously determined (Yucatán, Campeche, Ciudad del Carmen, Tamaulipas), the probability of obtaining those heights is calculated.

The accessibility is defined as "the proportion of the time a turbine can be safely accessed from a particular vessel" [32]. If the significant wave height is greater than 1.5 m for 40% of the time (cumulative probability), means there is 60% accessibility [32].

To quantify the wave heights, it is used the significant wave height, which statistically is calculated as the average height of the highest one-third of the waves experienced over time [33].

For each zone, the probability of obtaining the wave heights is calculated using data from ERA5 as follows:

- For the 39 years of available information, the data is interpolated at each point.
- The maximum and minimum values for the significant height are obtained.
- The values of the variable are divided into intervals.
- Each event that occurred during the temporal coverage is counted in its respective interval.
- The sum on each interval is divided by the total events to obtain the probability of occurrence.
- The cumulative probability is calculated by the sum of each interval with the previous one.

The Dutch Offshore Wind Energy Converter is a reference wind farm located in the North Sea, where accessibility is 71% considering wave heights of up to 1.5 m [34]. This will be used as a reference to compare accessibility for specific potential areas in Mexico.

3.5 Methodology

The wind velocities data are obtained from the reanalyses models ERA5 and MERRA2 (section 3.2). The temporal period is selected considering the available data from both models, which is from 1980-01-01 to 2018-12-31 (39 years). ERA5 has a vertical coverage at 10 and 100 m height; MERRA2 at 2, 10, and 50 m.

In the first stage, the wind resource is calculated. The horizontal and vertical components of the wind speed are extracted at 10 m height (U_{10} and V_{10}) to compare the potential areas that could be identified by both models. For each point of the grids and each temporal step (hourly), the wind speeds at 10 m are calculated by the equation:

$$WS_{10} = \sqrt{{U_{10}}^2 + {V_{10}}^2} \tag{3.1}$$

and then, interpolated with the power-law (section 2.3.2) as follows:

$$U(z) = U(z_r)\left(\frac{z}{z_r}\right)^{0.11} \tag{3.2}$$

with $z_r = 10$, $z = 90$ and $z = 119$, respectively hub heights of the NREL and DTU wind turbines.

Once the wind resource is obtained, are determined the capacity factors for the NREL and DTU wind turbines. The power curves are adjusted with a polynomial function and directly evaluated for each point of the grids and each temporal step (for the 39 years there is a total of 341880 hours) and divided by the total time and the nominal power of each turbine to get the capacity factors. Considering that the capacity factors are related to wind speeds, is expected to identify the same areas with the highest wind speeds and capacity factors. The capacity factor could be a restriction considering uniquely the areas with capacity factors above 30% [35].

In the next stage, the technical and natural restrictions are analyzed, these are summarized in table 3.4.

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

Table 3.4: Technical and spatial restrictions.

After the analysis of the constraints and also considering the zones with high wind speeds, the potential areas are delimited by the superposition of the maps generated. The last restriction to consider is the waves, so a wave analysis is carried out in each area to calculate the probability of high waves which is related to the accessibility for operation and maintenance.

Finally, smaller areas are delimited within the potential zones. In each one, a point is taken as a reference to calculate the annual energy produced and the capacity factors. With these data, the temporal analysis of the CF is carried out and the energy that each one could supply to the electrical network is estimated to know the percentage of contribution to the grid.

The methodology for this thesis described in this chapter is summarized in figure 3.7.

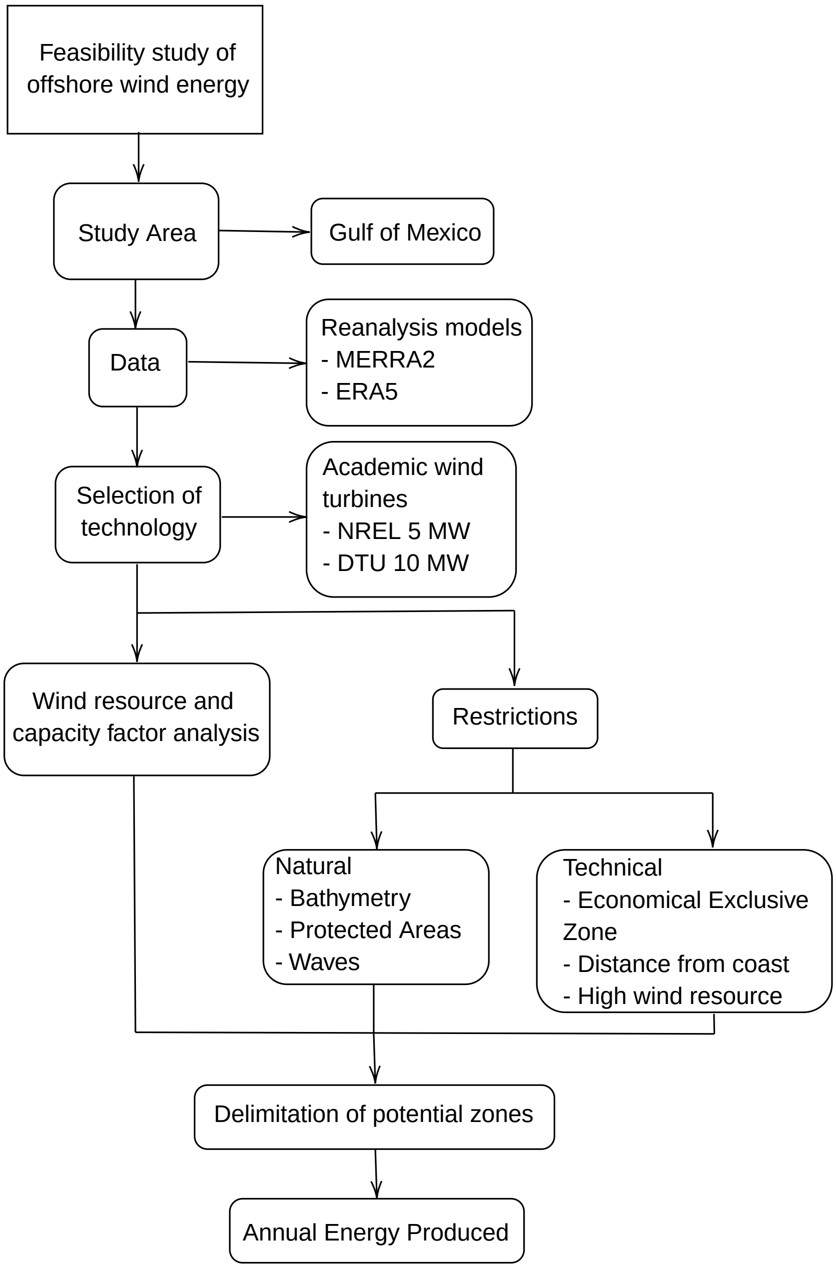


Figure 3.7: Methodology

In the next chapter, the results for the methodology are discussed.

Chapter 4

Results and Discussion

In this chapter, the results of the methodology described in the previous chapter are discussed. First, the analysis of wind speeds and capacity factors are presented to identify areas with high wind resources, then the restrictions to delimit potential zones are analyzed. Finally, for each selected area, a monthly capacity factor analysis is performed to estimate the contribution to the electricity grid.

4.1 Wind Resource Analysis

Wind speeds are calculated for the Gulf of Mexico at 90 and 119 m, hub heights of the NREL and DTU wind turbines respectively, the average wind speeds for the 39 years are shown in figure 4.1. The max average values are identified in both models between 9 and 10 ms^{-1} in the same two areas: at the northwest of the Gulf (at the north of the Tamaulipas coast) and the northwest of the Yucatan Peninsula. The differences between the wind speeds at different heights are minimal, and also between models, however, ERA5 shows bigger areas with the same maximum values. The minimal wind speeds (5 ms^{-1}) are presented along the coast of Veracruz, Tabasco, Campeche, Yucatan, and Quintana Roo. The identification of these areas are consistent with those reported by Haces-Fernandez, Li, and Ramirez [9] and in the Global Wind Atlas [11], using different numerical tools.

In link[1] the annual average wind speeds at 119 m for each year from 1980 to 2018 are presented for both models. For all years, the annual variations are minimal due to the stability of the wind resources in the ocean, presenting maximal and minimum values in the zones mentioned before. Interannual variability may be associated with meteorological phenomena like hurricanes, cold surges, El Niño, and La Niña. This phenomenon can occur periodically and can affect the power production, by increasing

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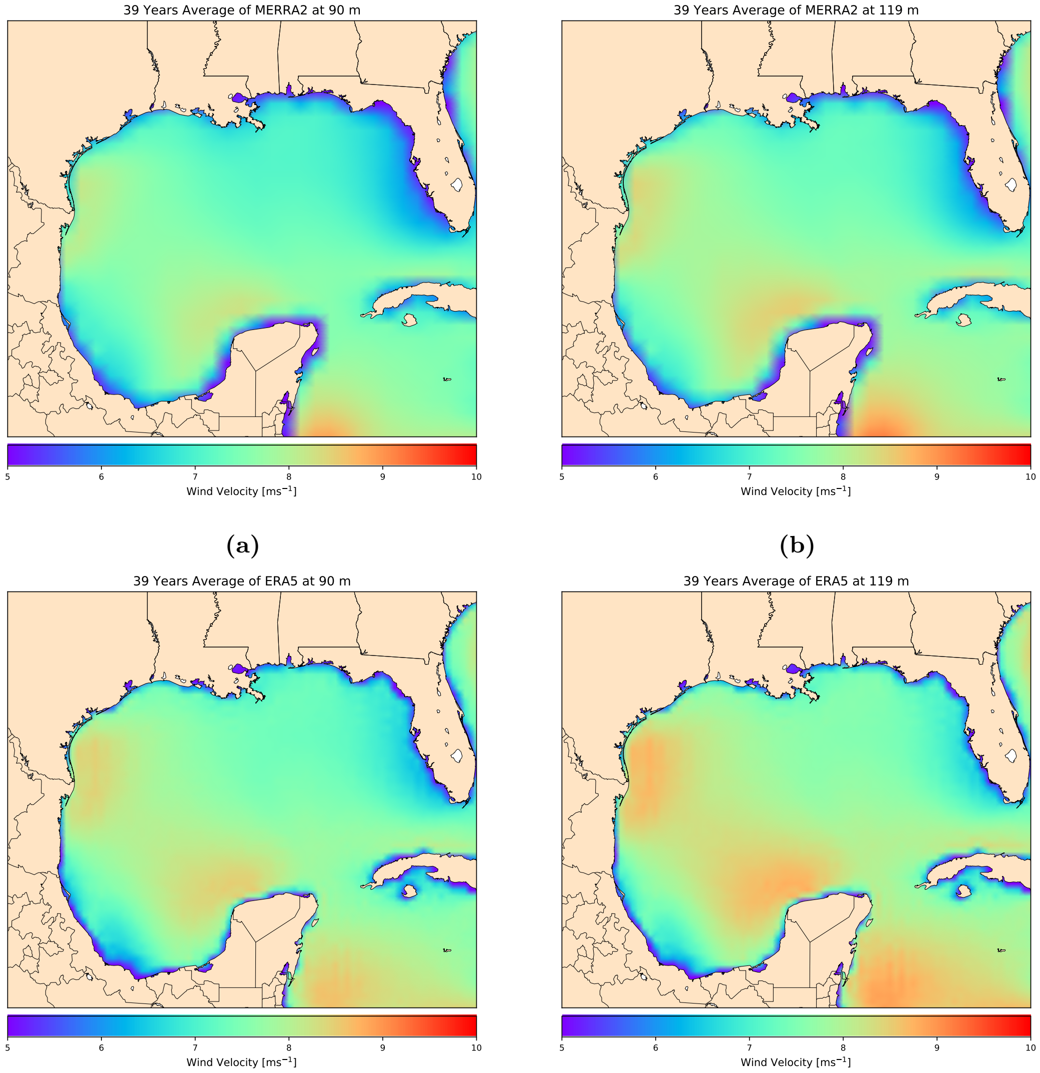
[1] `https://drive.google.com/drive/folders/1VvNskdptzDKFxt062QG8raImLLdrajk6?usp=sharing`

it o decreasing it.



(a) **(b)**

(c) **(d)**

Figure 4.1: The wind resource in the Gulf of Mexico. The wind velocities differences between heights (comparing (a) with (b) and (c) with (d)) are minimal and also between models (comparing (a) with (c) and (b) with (d)), however, ERA5 shows bigger areas with the max average values, between 9 and 10 ms^{-1}, at the northwest of the Gulf and at the northwest of Yucatan Peninsula (orange zones). The minimal values are along the Mexican coast (purple zones).

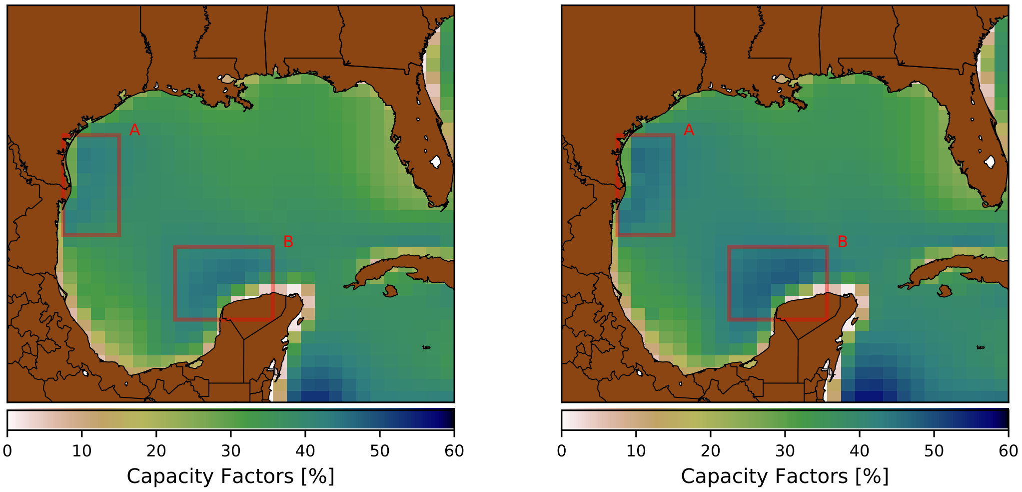
Once the wind speeds are obtained, the capacity factors (CFs) are calculated. It is important to consider the assumption of 100% availability.This is, the wind turbine is producing energy all the time, and there are no seasons when the turbine stops to perform operation and maintenance tasks.

Due to the similarity of the power curves, it is expected to have similar behaviors in the capacity factors. In figure 4.2 the capacity factors for 39 years (not an average) are shown. Capacity factors are related to wind speed intensity, zones with the highest capacity factors, between 50 and 55%, are located in the same zones with high wind velocities. These regions identified are the northwest of the Gulf (near to Tamaulipas coast) and the northwest of Yucatan Peninsula. The minimum values of CFs, between 10% and 20%, are along the coast.

As mentioned above, it was expected to obtain similar values for the capacity factors, but not the same in terms of energy produced because the nominal power of the NREL's 5 MW turbine is half that the nominal power of the DTU turbine. The annual max values for capacity factors and annual energy mean produced are presented in table 4.1.

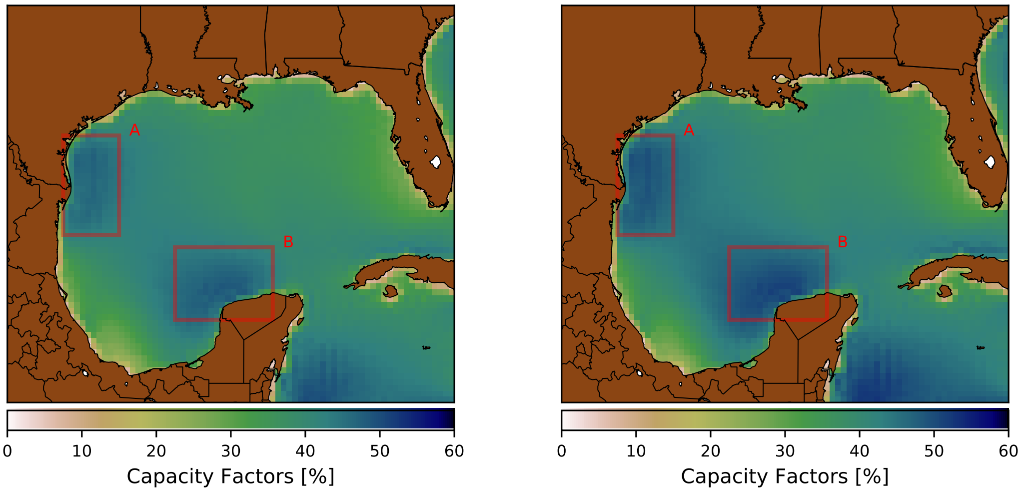
	MERRA 2	**ERA 5**
NREL	23.28 GWh	22.26 GWh
	52.90 %	50.79 %
DTU	52.12 GWh	49.81 GWh
	55.87 %	53.40 %

Table 4.1: Max values of capacity factors and annual mean energy produced for 39 years in the Gulf of Mexico. The maximum values are similar in terms of capacity factors since the power curves are similar. The max annual energy produced by the NREL's 5 MW turbine is half that the DTU's 10 MW, due to its nominal powers.



(a) MERRA2, NREL wind turbine

(b) MERRA2, DTU wind turbine



(c) ERA5, NREL wind turbine

(d) ERA5, DTU wind turbine

Figure 4.2: Capacity factors for DTU and NREL wind turbines for 39 years. Due to the similarity of the power curves, the CFs values are similar. The zones with the highest CFs, between 50 to 55% are the same with high wind velocities (blue zones): the northwest of the Gulf (zone A) and the northwest of the Yucatan Peninsula (zone B). In terms of CF, ERA5 shows bigger areas in comparison with MERRA2. The minimum values of CFs, between 10% and 20%, are along the coast (light brown zones).

From the previous results, the potential areas observed are reproduced by previous studies and guide the delimitation of the work. These areas must be analyzed to determine the technical feasibility of offshore wind turbines.

4.2 Delimitation of Potential Zones

In section 3.4 each restriction was described individually, in this section, the potential zones are delimited by the superposition of the maps of the natural and technical constraints. In table 3.4 the restrictions from chapter 3.4 are summarized.

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

[

Technical and spatial restrictions.]**Table 4.1:** Technical and spatial restrictions. The constraints were selected taking into account the requirements of the technology. The current work is the first to consider all the constraints described in the table.

Figure 4.3 shows the superposition of the constraints considered for this work. Only the viability for offshore wind in Mexican territory is analyzed, so the areas must be inside the Economic Exclusive Zone of Mexico (between the shoreline and the continuous black line). The area between the shoreline and the red line is the one with bathymetry below 50 m, the area beyond the red line is excluded. The dashed lines represent a distance from the coast of 22.22 and 44.44 km (12 and 24 nautical miles). The yellow zones are protected areas and must be avoided.

The coast of Veracruz and the west of Tabasco are excluded areas because the depth of the sea is greater than 50 m and floating structures would be necessary. Fixed bottom structures are not viable in these areas. The north coast of Campeche and the entire coast of Quintana Roo are also excluded because there are protected areas on those coasts.

In the north of Tamaulipas (zone A in figure 4.3), there are no protected areas off the coast, the bathymetry delimits a small area up to 44 km from the coast. On the south coast, the viable area is reduced to 22 km due to the depth of the sea.

The east coast of Tabasco, the western region of the Campeche coast (zone B in figure 4.3), and the Yucatan coast (zone C) have the necessary conditions for offshore wind technology except for Ciudad del Carmen where it is a protected zone.

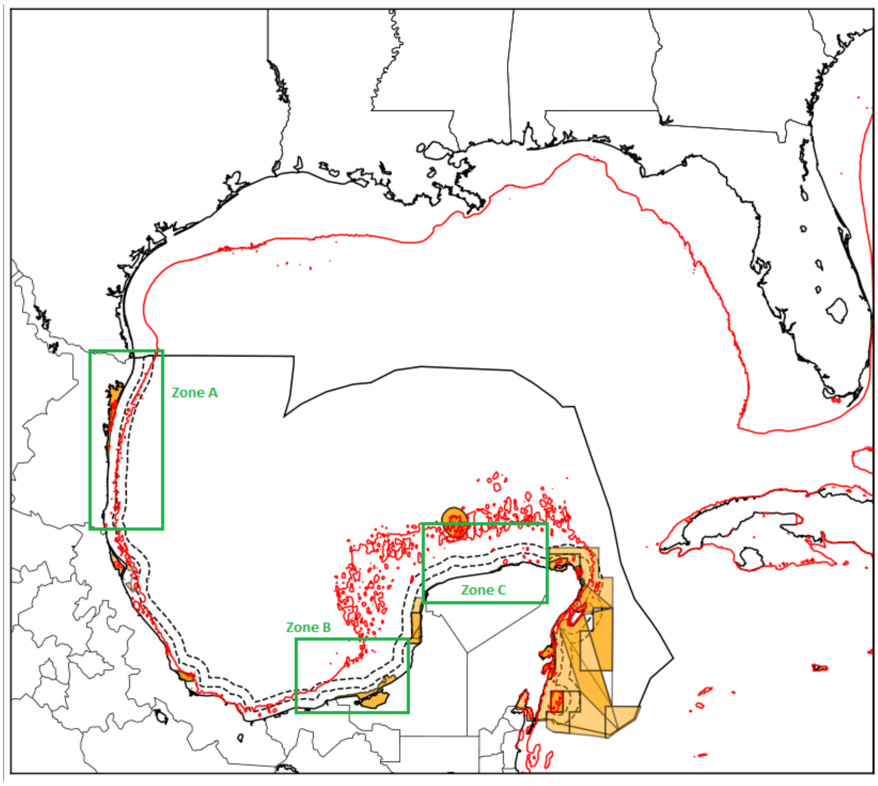


Figure 4.3: Restrictions in the Gulf of Mexico. Red line: Bathymetry below 50 m. Continuous black line: EEZ. Dashed lines: 12 and 24 nautic miles from the coast. Yellow zones: Protected areas. On the Tamaulipas coast (zone A), eastern Tabasco, the western region of the Campeche coast (zone B), and the Yucatan coast (zone C), the conditions are viable to install wind turbines

The capacity factor is also considered a restriction, only areas with values higher than 30% can be selected as potential. Since the capacity factors are obtained from the reanalysis models, it is necessary to verify the data with real measurements to avoid bias errors as in the case of onshore applications where ERA5 typically underestimates wind speeds. This means that it is possible to reach higher speed values in the ocean and therefore higher capacity factors, which can increase the size of potential areas.

In the previous section was concluded that in terms of the capacity factor the NREL and DTU wind turbines are similar, henceforth only the DTU's 10 MW turbine will be considered, due to its nominal power is in the range (10-12 MW) of the future offshore technology.

Figure 4.5 shows the same restrictions than figure 4.3 but now the capacity factors are included. In both models, southern Tamaulipas and Veracruz coast do not present capacity factors above 30%, these areas are excluded considering also that the bathymetry is greater than 50 m.

Both ERA5 and MERRA2 models have reproduced similar results, identifying the same potential areas. ERA5 has a higher spatial resolution than MERRA2, thus more data is available and allows better visualization of the zones near to the coast. Therefore, only the ERA5 model will be used for further discussions.

Two potential zones are selected not only by the technical viability of the restrictions but also by present high wind speeds identified by both reanalysis models previously discussed in section 4.1. These zones are located in the east of Tamaulipas and the northwest of the Yucatan Peninsula (fig. 4.6). In each zone, Yucatan Peninsula and the east of Tamaulipas, it is possible to identify specific areas where can be installed bottom-fixed offshore wind turbines.

For Yucatan Peninsula, three specific areas are selected: the north of Yucatan, the west of Campeche, and the north of Ciudad del Carmen; and one area is located at the east of Tamaulipas (fig. 4.6). In these areas, the total CFs are above 35%. Considering the size of the ERA5 grid ($\sim$ 900 km^2 each square) it is possible to estimate the area of each zone:

- Yucatan (P1): $\sim$ 10800 km^2
- Campeche (P2): $\sim$ 4500 km^2
- Ciudad del Carmen (P3): $\sim$ 6300 km^2
- Tamaulipas (P4): $\sim$ 3600 km^2

The state of Morelos has a land area of 4950 km^2. In comparison, the available area in Tamaulipas is smaller than Morelos, the area in Campeche is almost the same, and in Ciudad del Carmen and Yucatan it is larger, more than double for the latter. These available areas may increase if the ERA5 reanalysis model is underestimating the wind speed data.

The inclusion of renewable energy generation in the development of port activity represents an opportunity to increase economic activity, as is the case of the ports of Tampico and Altamira located in Tamaulipas, and the port of Progreso in Yucatan, all of them within the potential areas detected. In Ciudad del Carmen, the infrastructure and the experience of the oil platforms are an advantage for the new offshore wind farms.

For each specific area, a waves analysis is carried out to determine the probability of obtain high waves. Higher waves can be an impediment for the installation of offshore wind facilities due that the access to them can restrict operation and maintenance tasks. Wave heights over 1.5 m impede workboats access [31].

The cumulative probabilities of the wave heights are shown in figure 4.4. The results for Yucatan, Campeche, and Ciudad del Carmen are similar. The probabilities at these sites of obtaining wave heights greater than 1.5 m are less than 10%, which represents more than 90% accessibility. In the case of Tamaulipas, the accessibility is near 80%. In all cases, the probability of obtaining waves above 2.5 m is less than 5 % and above 3 m is unlikely.

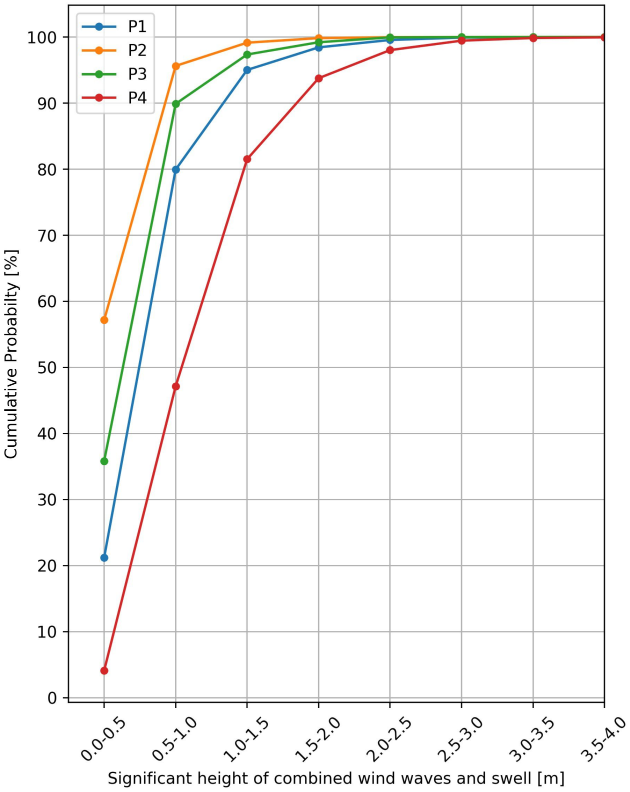
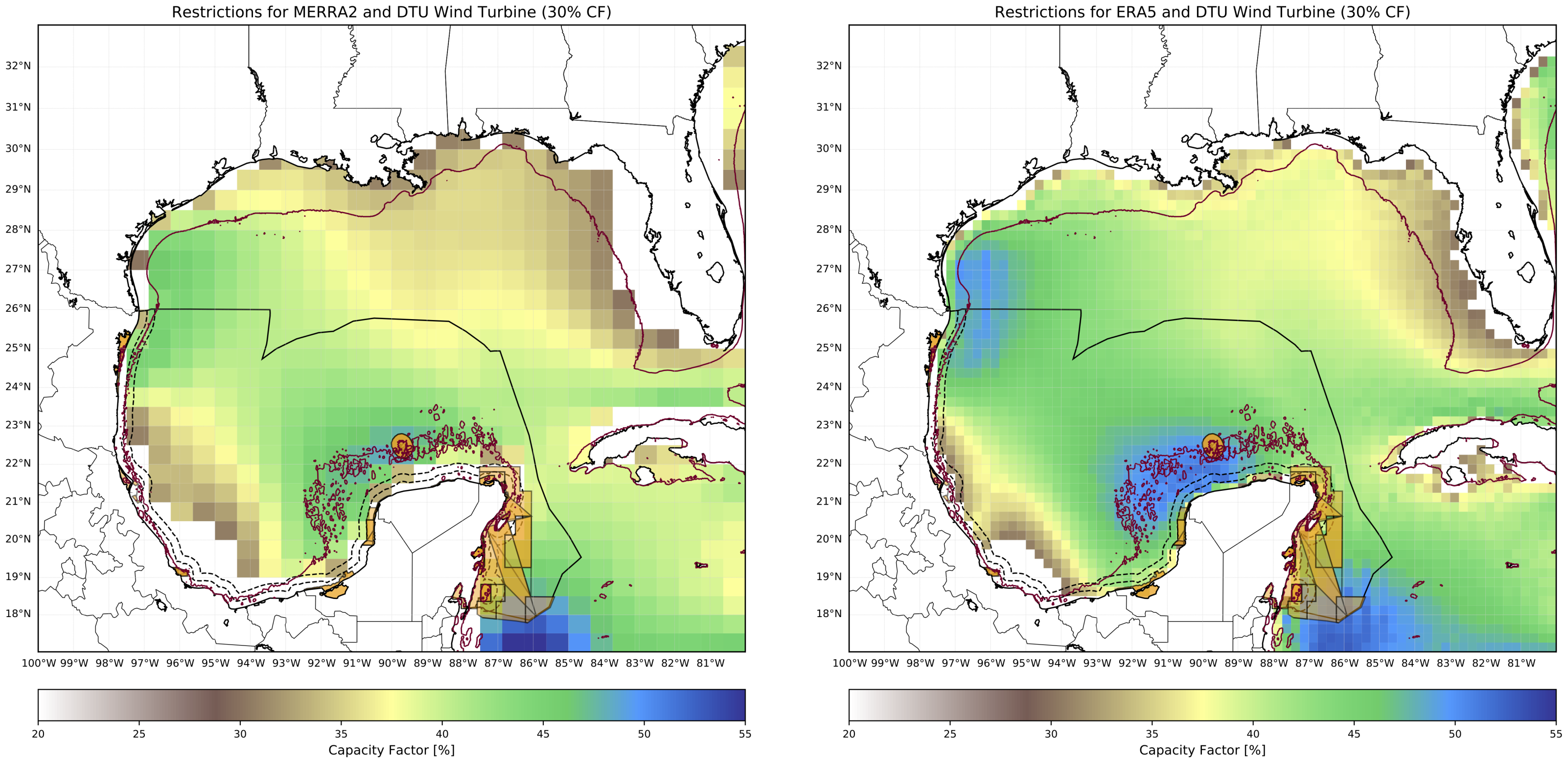


Figure 4.4: Cumulative probabilities of the waves significant height. P1: Yucatan. P2: Campeche. P3: Ciudad del Carmen. P4: Tamaulipas. The probabilities at Yucatan, Campeche and Ciudad del Carmen of obtain wave heights greater than 1.5 m are less than 10%, which represents more than 90% accessibility. In the case of Tamaulipas, the accessibility is near 80%.

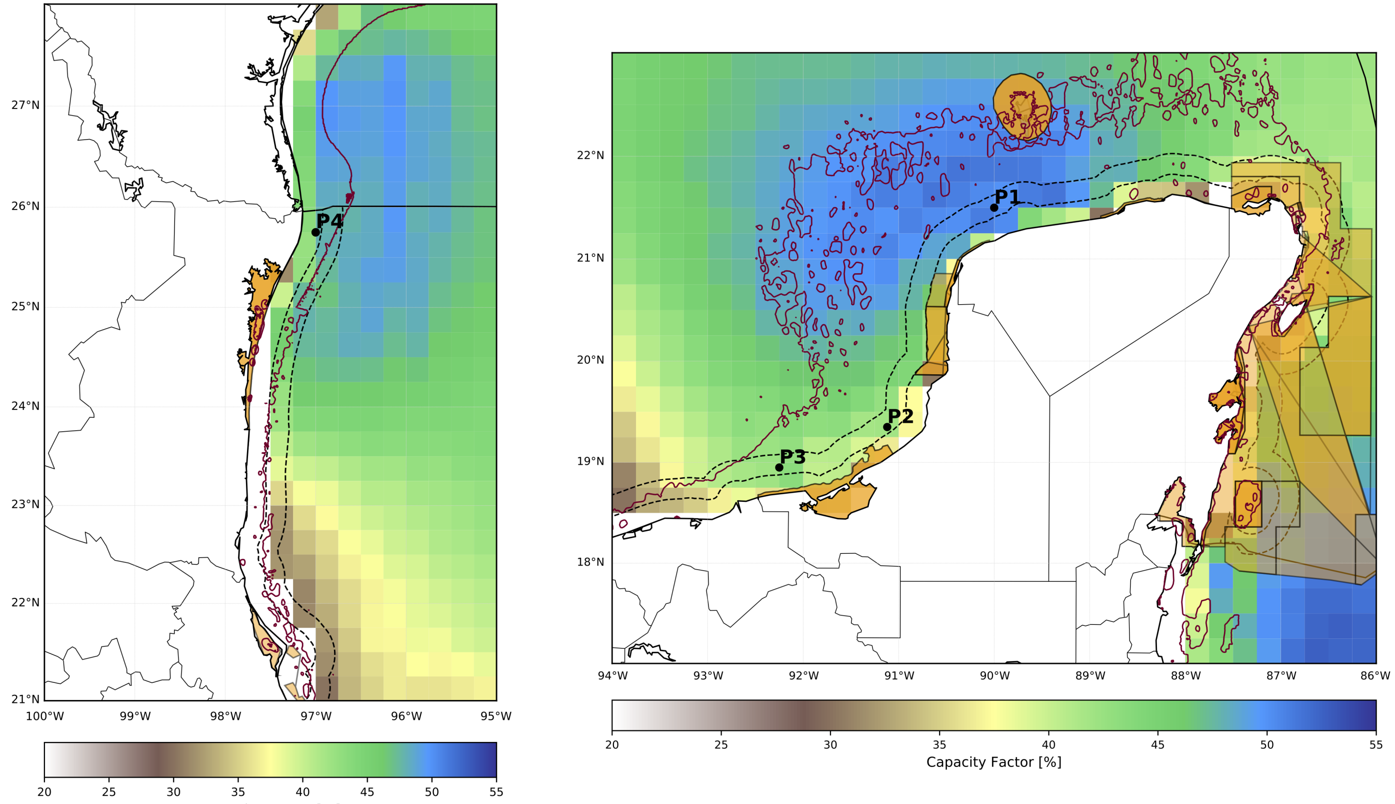
Those results can be compared with the obtained in the Dutch Offshore Wind Energy Converter wind farm located at the North Sea, where the accessibility is 71% considering wave heights up to 1.5 m [34]. In comparison, the results obtained for the zones located at the Gulf of Mexico do not represent an issue for the wind farms access.



(a) MERRA2

(b) ERA5

Figure 4.5: Restrictions in the Gulf of Mexico with capacity factors above 30% for the DTU wind turbine. Both models identify higher CFs in the same zones: the east of Tamaulipas and the northwest of the Yucatan Peninsula. Although both models present similar CFs in the same regions, ERA5 shows higher CFs values. Due to the higher resolution of ERA5, this model allows better visualization of the areas near the coast.



(a) Potential zones in Tamaulipas

(b) Potential zones in Yucatan Peninsula

Figure 4.6: Potential areas in the Gulf of Mexico. Three potential areas are located in Yucatan Peninsula: at the north of Yucatan (P1), at the west of Campeche (P2) and at the north of Ciudad del Carmen (P3), with available areas of 10800, 4500 and 6300 km^2 respectively. Also, one area is located at the east of Tamaulipas (P4), with an available area of 3600 km^2. In these areas, the total CF are above 35%. The max CF is presented in Yucatan (50%) and the min in Campeche (35%).

4.3 Seasonal CF Analysis by Region

Four areas have been selected as potentials, for each one, a point is selected as a reference (fig. 4.6). The power curve of the DTU's wind turbine is evaluated to calculate the energy produced and the capacity factors in each area.

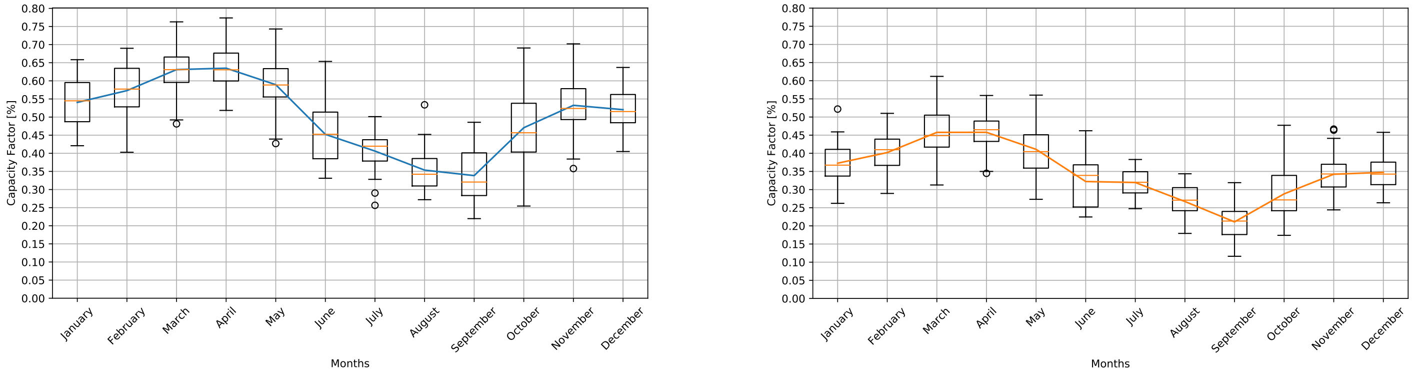
In figure 4.7, the boxplots for the monthly averages capacity factors for the 39 years are presented for each selected point, the continuous lines link the monthly averages.

Campeche and Yucatan have very similar behaviors, presenting maxima in March and April, and minimum in September. For the four cases, Yucatan is the one with the highest values, and Campeche the one with the lower CFs.

Ciudad del Carmen presents similar max values of 50% from December to April and a minimum value of 25% in September. Tamaulipas also has a period of max values of near 55% from November to May and its minimum value of 34% in August.

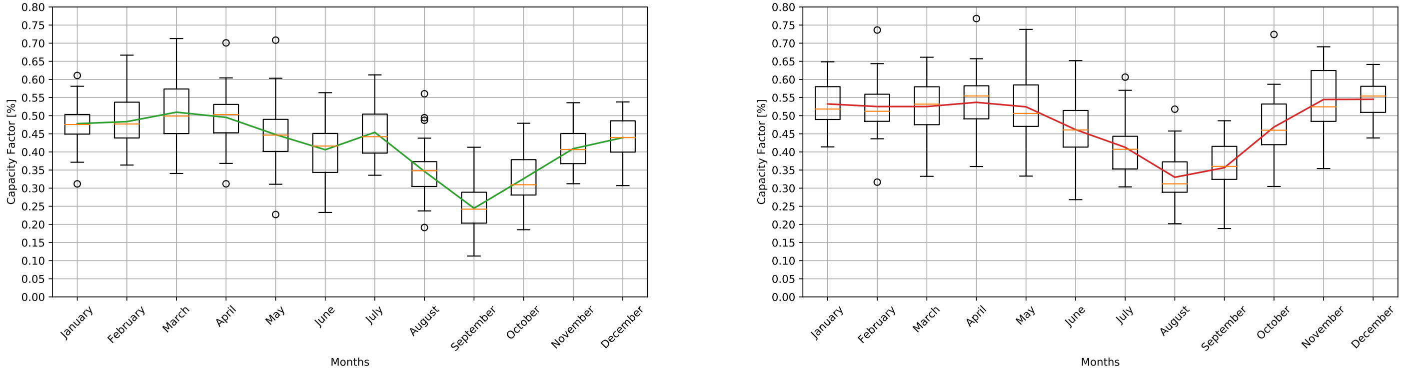
It is possible to identify two annual trends: one of high power production (November to May) an one of low power production (May to November). In four cases, the highest values of the capacity factors are presented between March and April, and the lowest between August and September. The lower seasons can be used for operation and maintenance, to minimize losses in the costs.

Despite being located in different places, all the zones show a similar behavior, probably due to their location in the Gulf of Mexico.



(a) Yucatan

(b) Campeche

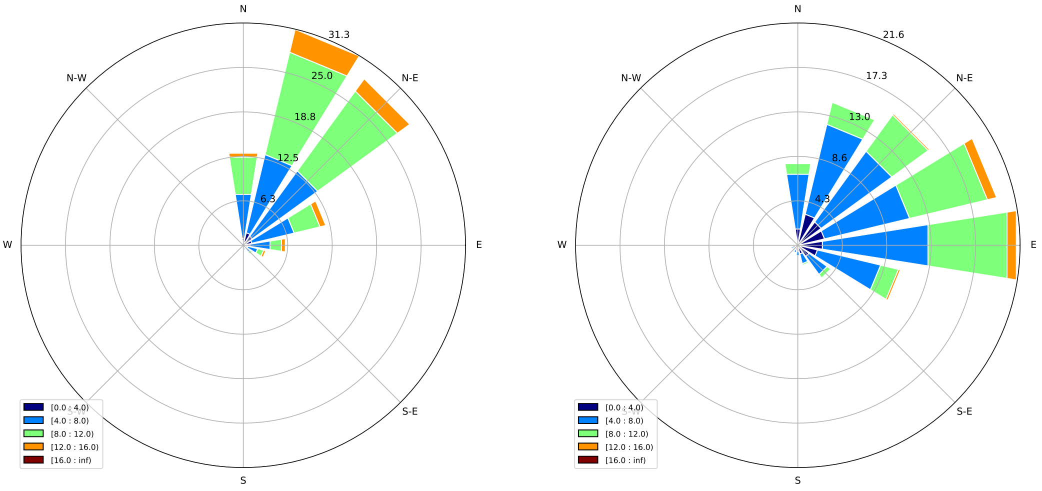


(c) Ciudad del Carmen

(d) Tamaulipas

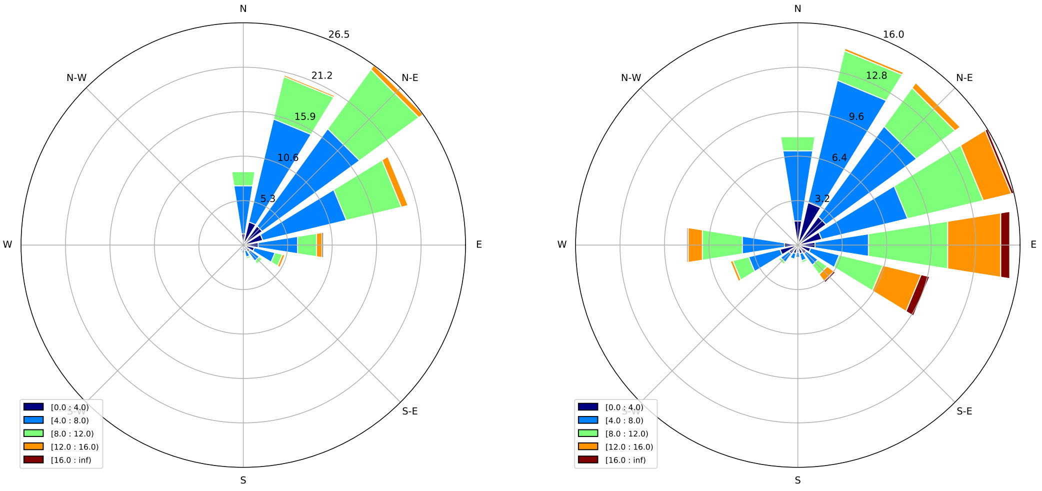
Figure 4.7: Boxplots for the monthly averages capacity factors for the 39 years, the continuous lines links the monthly averages. Campeche and Yucatan have very similar behaviors, presenting maximal values in March and April, and minimum values in September. For the four cases, Yucatan is the one with the highest values, and Campeche the one with the lower values. Ciudad del Carmen and Tamaulipas present a period of similar max values from December to April and a minimum value in September and August. It is possible to identify a season of high power production (November to May) an one of low power production (May to November). All the zones have similar behavior because all of them are influenced by the meteorological effects in the Gulf of Mexico.

The analysis of the wind directions is an important factor for the correct design of wind farms. The wind roses for each point for the 39 years are presented in figure 4.8. The points located at Yucatan and Ciudad del Carmen have a similar behavior being the prevailing winds from the Northeast, in Campeche the dominant direction is from both east and northeast; for these three points, most of the wind speeds are from 8 to 12 ms^{-1}, and the maximum is between 12 and 16 ms^{-1}, In Tamaulipas, the prevailing winds are from Northeast to Southeast, being the maximum above 16 ms^{-1}. For the four zones, the prevailing winds are from North to East, Tamaulipas is the only one presenting winds from the west.



Yucatan, P1

Campeche, P2



Ciudad del Carmen, P3

Tamaulipas, P4

Figure 4.8: Wind Roses. The points located at Yucatan and Ciudad del Carmen have a similar behaviour being the prevailing winds from the Northeast, in Campeche the dominant direction is from both east and northeast; for these three points, most of the wind speeds are from 8 to 12 ms^{-1}. In Tamaulipas, the prevailing wind are from North to East. For the four zones, the prevailing winds are from North to East, Tamaulipas is the only one presenting winds from the west.

4.4 Study Cases

From previous results, the power production from a wind farm located in each zone is calculated. For the study cases, a wind farm with 1 GW of installed capacity is proposed using the DTU's 10 MW reference wind turbine, this is, 100 machines. For the wind farm design, two issues must be considered: the area available for the farm and the looses by the wake effects.

Typically, on an offshore wind farm installation, the spacing between turbines in a row is from three to ten diameters of the rotor [36]. The DTU wind turbine has a rotor diameter of 178.3 m, considering the maximal distance between turbines (10 diameters) the area required for a 10x10 array is 257.51 km^2, which represent less than 1% of the available area for the smallest zone (Tamaulipas, P4). The size required for a 1 MW wind farm is not an issue for the proposed areas.

The annual energy produced for a typical year is calculated for each point. These results do not consider the wake effects, these can represent losses between 10% to 20% in power production [37]. In table 4.2, the AEP for each point is presented considering the variations on the losses by wake effects.

The range of average capacity factors for wind farms in Europe in 2018 is between 38% and 50% [5]. In a scenario of low losses (10%), all the zones have CFs higher than 30 %, except Campeche, with 25%. In a scenario of high losses (20%), the CFs are between 20 and 30%, except Campeche with 15%. These CFs are lower than those obtained in Europe, the analysis of these values in an economic context is an important factor for the installation of offshore wind farms in the Gulf of Mexico, to determine the viability of the projects.

	No Losses		**10% Losses**		**20% Losses**	
	AEP [GWh]	**CF [%]**	**AEP**	**CF**	**AEP**	**CF**
Yucatan	4689.57	50.35	4220.61	40.35	3751.66	30.35
Campeche	3259.37	35.00	2933.43	25.00	2607.50	15.00
Ciudad del Carmen	3912.97	42.00	3521.67	32.00	3130.38	22.00
Tamaulipas	4473.66	48.03	4026.30	38.03	3578.93	28.03

Table 4.2: Annual Energy Produced (AEP) [GWh] and Capacity Factors [%] calculated for the selected points and considering the losses by wake effects. Yucatan is the area with the highest energy production and Campeche the lowest. Considering 20% wake losses, the CFs, except Yucatan, are below 30 % and cannot be economically viable.

In Mexico, the national electricity system is divided into seven regions [38]. The Peninsular region includes the states of Yucatan, Quintana Roo, and Campeche, and the Northeast region includes Nuevo Leon, Tamaulipas, northern Veracruz, northern San Luis Potosi, and some municipalities of Coahuila. In 2018, the electricity demand in the Peninsular region was 5312.02 GWh and 21937.16 GWh in the Northeast [39]. Considering 10% of losses, the installation of a 1 GW wind farm in Yucatan could supply 79.45% of the demand on the Peninsular zone, and a 1 GW wind farm located in Tamaulipas could supply 18.35% of the Northeast demand.

Chapter 5

Conclusions

In this thesis, a study was realized to determine the feasibility of offshore wind energy in the Gulf of Mexico. The study can be divided into two stages: the delimitation of potential areas considering the wind resource and the technical and natural constraints and; a study case analysis of the energy that can be produced in each area.

In the first stage, two areas with high wind resources were identified on both reanalyses models MERRA2 and ERA5: at the northwest of the Gulf and the northwest of the Yucatan Peninsula with maximal average wind velocities between 9 and 10 ms^{-1}. The minimum values were along the coast. ERA5 shows bigger areas with maximal values.

The zones with high capacity factors, evaluating the NREL's 5 MW wind turbine and the DTU's 10 MW, were the same with high wind resources: at the northwest of the Gulf and the northwest of the Yucatan Peninsula, with maximum values between 50% and 55%, these are theoretical capacity factors as losses are not taken into account.

The criteria for the restrictions was realized by the next statements:

- Inside the EEZ to harnessing the offshore wind resource for Mexico.
- For depths above 50 m the fixed-bottom foundations are not economical viable and it is necessary to use floating structures.
- The Protected Areas must be avoided to preserve the biodiversity of the Country.
- Longer distances from the shore are associated with more transmission losses and also, with greater depths to the seabed.

By the superposition of the maps of the restrictions two potentials areas were delimited: the northwest of Yucatan Peninsula and the northeast of Tamaulipas, which coincide with the areas with the highest wind speeds and capacity factors, identified by both reanalysis models.

In the second stage, four areas were selected into the delimited zones as a reference: the north of Yucatan, the west of Campeche, the north of Ciudad del Carmen, and the east of Tamaulipas. In each area, the capacity factors were analyzed. Yucatan presents the highest values and Campeche the lowest, both have similar behaviors with its max values in March and April and the minimum in September. Tamaulipas and Ciudad del Carmen have periods of constant maximum values.

The location of the delimited areas represents an opportunity for port development, as is the case of Tamaulipas and Yucatán where there are important ports for the country. The available area for each zone is:

- Yucatan: $\sim$ 10800 km^2
- Campeche: $\sim$ 4500 km^2
- Ciudad del Carmen: $\sim$ 6300 km^2
- Tamaulipas: $\sim$ 3600 km^2

For the four selected areas, two periods of energy production are identified: one of high power production (November to May) an one of low power production (May to November). The prevailing winds in all cases are from North to East. Four areas show similar behaviors because all of them are influenced by the meteorological effects in the Gulf of Mexico.

A 1 GW wind farm installed in Yucatan and Tamaulipas, considering 10% of losses, could supply 79.45% of the electricity demand on the Peninsular zone and 18.35% on the Northeast zone, respectively.

An analysis of the waves at each site shows that the probability of obtaining wave heights of 1.5 m is less than 10%, except in Tamaulipas where it is less than 20%. Therefore, accessibility to wind farms for installation and operation and maintenance work is guaranteed.

There are zones identified with higher capacity factors, however are located above 40 km from the shoreline, which increments the costs and it is probable than the deep sea is larger than 50 m. A specific study for floating structures must be carried out to analyze its feasibility.

Although the use of reanalyses models is widely used in the literature to develop assessment studies for offshore wind energy, the studies are limited to the validation of these models. A more precise study requires comparing the model's data with real measurements which allows a better estimation of the annual energy production. Also, a higher resolution of the reanalysis models, which means a smaller size of the meshes, helps to optimize the selection of areas since the estimation of wind resources improves.

A more specific delimitation of the potential areas requires the analysis of extra restrictions as geology, aquaculture, recreational areas, and other, which were not used in this work due to their unavailability. If more constraints are included, the delimitation by superposition is more difficult and other analysis techniques are required.

As an additional comment, this work was realized using open-source data (reanalysis, wind turbines, GIS and others data sets) and software (python, linux).

Future Work

For the development of this work, just four spatial constraints were considered. For better detection of potential areas, more conditions have to be considered: hydrocarbons, minerals, military areas, maritime traffic, underwater lines, pipelines, and others. For a selection of specific potential zones, it is necessary to develop/use a proper methodology based on the multi-criteria analysis.

Economic analysis requires to consider diverse factors as the available technology, distance from the coast, foundations, interconnection to the electrical system, among others. A sensitivity analysis is suggested to estimate the costs into a Mexican context. Also, a study that focuses on floating structures can be developed to harnessing the wind resource above 50 m of the deep sea.

Due to the geographical location of Mexico, extreme weather conditions (hurricanes, cold surges, earthquakes) are presented in periodic seasons, its impact on energy production, and in the foundations must be analyzed to get better estimations of the power production.

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