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Harnessing Offshore Wind Energy along the Mexican Coastline in the Gulf of Mexico—An Exploratory Study including Sustainability Criteria

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Abstract: Mexico has more than 40 years of researching, investing, and obtaining electric power through wind energy. Within the country, there are highly windy areas, such as the Isthmus of Tehuantepec or the state of Tamaulipas, and there are about 2500 MW installed and 70,000 MW tested, all onshore. There are still no offshore wind farms in Mexico, despite having two main coasts, the East and the West, with the Gulf of Mexico and the Pacific Ocean, respectively. Although the Mexican coastal states of the Gulf of Mexico are Tamaulipas, Veracruz, Tabasco, Campeche, and Yucatán, this work focuses on the study and feasibility of offshore wind energy use on the coasts of the states of Tabasco, Campeche, and Yucatán. This is because of the availability of data in that region; however, sustainability criteria that can be used in other regions are also presented. MERRA-2 and ERA5 data were used employing WAsP and Windographer software. It was found that the capacity factor in the area of Tabasco, Campeche, and Yucatán is 32%, 37%, and 46%. It can be noted that, in the WF100% scenario, each of the wind farms could contribute more than 35% of the region's electricity consumption; those of Campeche and Yucatán stand out with contributions of more than 70%.

Keywords: Mexico; wind energy; offshore; sustainability

1. Introduction

The growth in electricity consumption globally and the need to supply it through clean energy sources pose great challenges to the electricity markets in different countries. According to the International Energy Agency [1], Mexico will have close to 150 million inhabitants by the year 2050, and this undoubtedly poses a challenge to energy supply. In addition, in 2015, it committed to the Paris agreement to reduce its emissions through the diversification of the national energy matrix. Specifically, it committed that 35% of the energy generated by 2024 and 43% by 2030 will come from clean sources [2].

This is not an easy task, since in conjunction with the decarbonization of the sector, a secure energy supply must be guaranteed. Energy security measures a nation's ability to reliably supply current and future energy demand and to recover quickly from environmental impacts (e.g., severe weather events). It also measures how effective a country is in managing energy resources, both domestic and foreign, as well as the reliability and resilience of its energy infrastructure. In the case of Mexico, in some areas, energy security has been affected by different causes, among which we can mention the imbalance between electricity supply and demand caused by the COVID-19 pandemic, the insufficiency of local electricity production, and the frequent congestion in several nodes of the national transmission grid.

Mexico's national electrical system is organized into ten control regions (Figure 1), seven of which are interconnected to form the National Interconnected System (NIS) and the other three operate in isolation. The Baja California system operates isolated from the NIS but is interconnected to the electrical grid of the western region of the United States of America, while those of Baja California Sur and Mulegé operate in complete isolation [3].

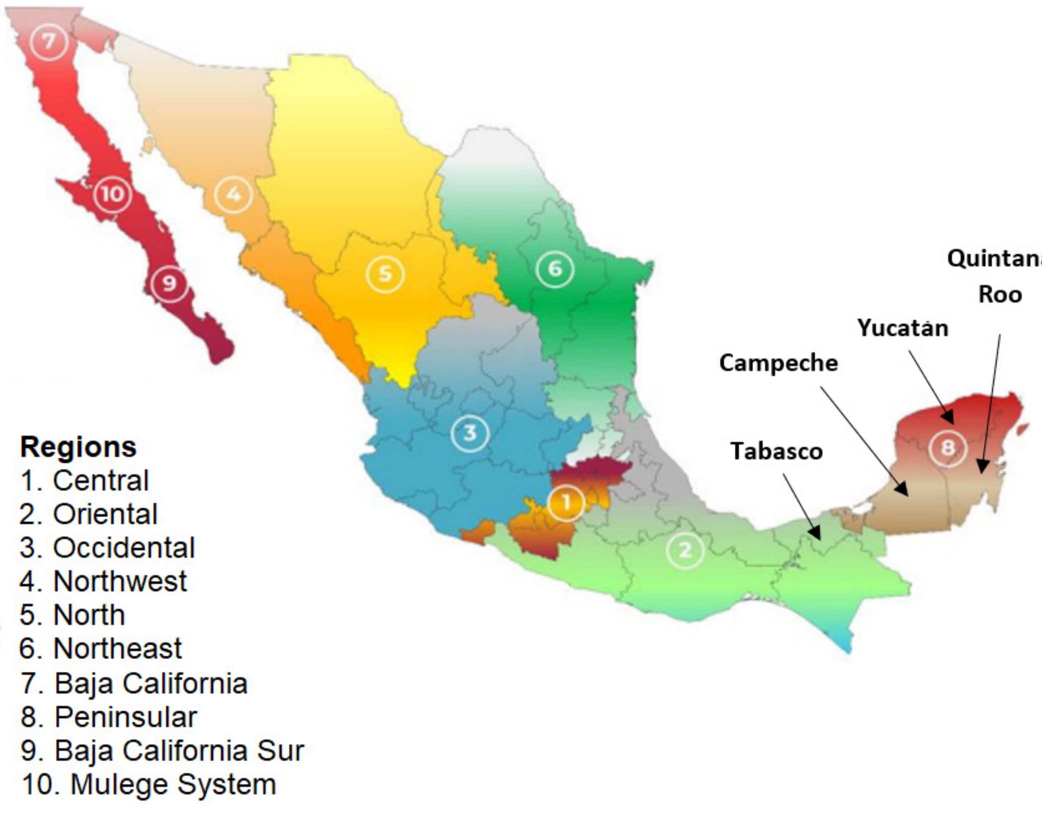

Figure 1. Mexico's National Electric System.

Within the NIS regions with coasts toward the Gulf of Mexico is the Peninsular Region, occupied by the states of Campeche, Yucatán, and Quintana Roo (Figure 1). It is one of the regions of the country that have suffered electricity shortage problems, which has affected a large part of the population and the different sectors of the economy. The fundamental causes of this have been congestion in the interconnection nodes with the NIS and insufficient electricity production in local power plants, most of which operate with natural gas and have frequent problems of shortage of this resource from other regions of the country.

The Peninsular Region has an installed capacity of 2205 MW, with 308 MW of clean technologies [3]. Of these, 244 MW corresponds to wind farms, and it is expected that by the end of 2021 this capacity will reach 304 MW due to the entry into operation of new wind farms in the state of Yucatán [4]. As for electricity consumption in this region, it experienced an average annual growth rate of 5.89% during the period 2015–2019, reaching the figure of 10,793 GWh in 2019 [5].

Another of the NIS regions with coasts toward the Gulf of Mexico is the Eastern region (Figure 1), which includes Tabasco, one of the states with the greatest hydrocarbon exploration and extraction activity, both onshore and offshore. The installed capacity in Tabasco is much lower than in other states in the region, with 4 MW in bioenergy plants and 267 MW in efficient cogeneration plants. Regarding electricity consumption, the average annual growth rate in that state was 1.65% during the period 2015–2019, a year in which consumption was 3336.10 GWh [5].

Regarding the development of future wind power facilities in Tabasco or in the Peninsular Region, there are no clear projections, since the legal and regulatory framework, influenced by the effects of the COVID-19 pandemic, has not fully favored the development of renewables in the country. In addition, in other states of the country, the onshore wind resource is more intense. However, there are important renewable energy resources, the use of which could contribute to achieving the goals of clean energy generation; in particular, there are large areas toward the Gulf of Mexico, unexplored so far, which could constitute important scenarios for offshore wind installations [6].

Offshore wind energy could contribute to the decarbonization of the global energy sector. According to the International Renewable Energy Agency [7], at the end of 2020, there was about 34 GW of offshore wind installations worldwide, and it is expected to reach 380 GW by 2030 and more than 2000 GW by 2050. The leading regions in this technology are Asia, Europe, and North America, which coincide with those where most of the research work published in internationally recognized journals has been carried out.

One of the problems we usually face when we want to evaluate offshore wind potential is the lack of data measured directly at the site of interest. An alternative is the use of reanalysis data obtained from various models such as WRF [8], ERA-Interim [9], ERA-5 [10], MERRA [11], and MERRA-2 [12], among others. There are some scientific publications that mainly make use of MERRA-2 and ERA5 data to evaluate wind potential. For example, ERA-Interim data were used by Mattar et al. [13] to assess offshore wind potential in Chile, as well as Onea and Rusu [14] in the Caspian Sea, while Nezhad et al. [15] used 40 years of data to assess wind potential around Samothraki Island in the Mediterranean Sea. In all the studies, the usefulness of ERA-Interim data to preliminarily identify sites of higher wind potential in each region is emphasized. Regarding the ERA-5 dataset, they have also been used in several studies of offshore wind potential. Such is the case of the study conducted by Soukissian et al. [16], who evaluated the feasibility of installing wind farms and floating photovoltaic plants at various points in the Mediterranean Sea. Similar studies were developed in the Colombian Caribbean [17], in the North Sea and the Baltic Sea [18], Oman [19], and Qatar [20]. Hayes et al. [21] presented a method for using ERA-5 weather data to model long-term (>40 years) hourly wind generation for individual offshore wind farms.

Regarding MERRA-2, Gruber et al. [22] evaluated different methods on four spatial resolutions using MERRA-2 with good results; Samal [23] compared MERRA-2 data and data measured on a 50 m high tower using wind potential density; Lee et al. [24] used 14 years of data generated with the WRF model to assess the offshore wind resource in Alaska. The results were validated using radiosonde measurements and surface observations, and they concluded that the WRF dataset can serve as a general guide for selecting potentially promising areas. Similarly, Li et al. [25] conducted a sensitivity study of the WRF model for assessing the offshore wind resource in the Baltic Sea, while Rybchuk et al. [26] determined, through a sensitivity analysis, that the factor that most affected the WRF model results in the assessment of the offshore wind resource in California was the planetary boundary layer (PBL) scheme [27]. The authors proposed as future work the need to compare the model results with offshore measurements taken with LIDAR technologies [28].

Of special interest is the study by Gruber et al. [29], who used ERA-5 and MERRA-2 reanalysis data, as well as generalized wind climate (GWC) data generated by different versions of the Global Wind Atlas (GWA) [30], to simulate the energy production of wind farms in different countries and evaluate the observed deviations from actual data measured at those farms. They concluded that ERA-5 performed better than MERRA-2 in almost all regions, showing higher correlations and lower relative errors, while in New Zealand, the performance of MERRA-2 was better. In addition, they observed no significant improvements when using the different versions of GWA.

MERRA-2 reanalysis data have been used in several wind resource studies. Sherman et al. [31] employed them to explore offshore wind potential in China, using 39 years of hourly data. Meanwhile, Tavares et al. [32] used MERRA-2, ERA-5, and CFSv2 (NCEP Climate Forecast System Version 2) data to assess the offshore wind resource in Brazil and compared the results with measurements recorded at Meteo-Oceanographic Buoys. Their results agreed with those of Gruber et al. [22] in the sense that the ERA-5 model had the highest degree of agreement with the measured data, except for one location where MERRA-2 showed a better performance than the rest of the models.

In the case of Mexico, there is a large knowledge gap regarding the available offshore wind potential. Only one study is reported that makes a comprehensive analysis of offshore wind resource utilization in Mexico, specifically in the northern half of the Gulf of California [33]. Its authors relied on 27 years of data generated with the N512 UPSCALE model and included techno-economic and socio-ecological constraints.

Other smaller studies were conducted by Soler et al. [34] and Perea et al. [35]. The former used data from a meteorological tower, located at the end of the Puerto Progreso pier, 6.65 km offshore in the state of Yucatán, to study wind and temperature profiles, while the latter used MERRA-2 data from 141 locations, including some offshore, to assess the wind resource. However, in none of them was the potential for offshore wind farm installation evaluated. Most of the studies conducted in Mexico have focused on the evaluation of the onshore wind resource, using various data sources, particularly reanalysis data [36–38].

However, the Global Wind Atlas [30] suggests that there is significant offshore wind potential in Mexico. For example, in large areas of the Gulf of Mexico, capacity factors of more than 40% could be achieved using Class III wind turbines, which could be higher than 50% in areas near the states of Tamaulipas and Yucatán. However, more detailed studies are needed to determine the net potential of the wind resource available in that region, for which not only technical and economic criteria must be considered but also environmental and social ones. That is why this work is aimed at analyzing the feasibility of taking advantage of the offshore wind potential available in the southeastern part of the Gulf of Mexico, specifically in the areas corresponding to the administrative marine boundaries of the states of Tabasco, Campeche, Yucatán, and Quinta Roo.

The research questions posed are the following: Are there areas available for the sustainable use of the offshore wind resource in the southeastern Gulf of Mexico? What is the net wind potential that can be installed outside the wind exclusion areas? Is the use of offshore wind energy in the study region economically competitive with electricity from the national interconnected system? What are the technological factors or variables of the electricity market that should be modified in the future to favor the viability of offshore wind farms in the Gulf of Mexico?

Contribution and Structure of the Paper

The main objective of this study is to evaluate the feasibility of exploiting the offshore wind potential in the southeastern Gulf of Mexico. However, unlike previous studies in this region, which have been limited to exploring the characteristics of the available wind resource, here we incorporate sustainability criteria that allow us to identify the areas of wind energy exclusion. With this, it is possible to select and plan more adequately the areas available for the use of this resource. In addition, different data sources are used comparatively, including reanalysis data and generalized wind climates, the latter generated by the Global Wind Atlas. On the other hand, this research incorporates microscale modeling of offshore wind farms and economic analysis based on the levelized cost of energy and sensitivity studies. Valuable information is provided on the factors that could affect the competitiveness of offshore wind in the supply of electricity to the Peninsular Region through the National Interconnected System (NIS).

The paper is structured as follows: Section 1 is the introduction. Section 2 describes the materials and methods used in the research. This is divided into three subsections (Sections 2.1–2.3). Section 2.1 shows the location of the study area and describes the sources of meteorological data used. Next, Section 2.2 explains the procedure followed to determine the wind exclusion areas and describes the sustainability criteria used for this purpose. Once the wind exclusion areas were identified, three sites located outside them were selected. Section 2.3 details the methodology followed to perform the wind resource assessment at each site, as well as to carry out the microscale modeling and the economic feasibility study of the wind farms.

Section 3 describes and analyzes the results achieved. This section is divided into four subsections (Sections 3.1–3.4). Section 3.1 describes and analyzes the results corresponding to the analysis of the wind exclusion zones, as well as the installable wind capacity in the three administrative marine boundaries studied. Then, Section 3.2 is dedicated to describing the characteristics of the wind resource in each site, which were obtained by Windographer using MERRA-2 and ERA-5 reanalysis data. In addition, the results of the microscale modeling in areas of 20 km^2 are described, using the aforementioned data and generalized wind climates, generated in the Global Wind Atlas. Section 3.3 analyzes the energy production results of three offshore wind farms in the study sites; it analyzes their contribution to the region's energy matrix, to the achievement of national goals of clean energy generation, and to the decarbonization of the sector.

Section 3.4 is devoted to analyzing the economic feasibility of the wind farms studied. The results of the sensitivity analysis, which investigates the incidence of the cost of wind technologies on the levelized cost of energy, are discussed. Measures for the sustainable use of renewable energies in the country, and particularly offshore wind energy in the Gulf of Mexico, are proposed. Finally, in Section 4, the main conclusions of the study are formulated.

2. Materials and Methods

2.1. Study Area

The selected study area corresponds to the administrative marine boundary (AMB) of the States of Tabasco, Campeche, and Yucatán (Figure 2).

The study was conducted using the MERRA-2 mesoscale data series at 50 m height, as well as ERA-5 data at 100 m and GWC generated by the Global Wind Atlas. MERRA-2 data corresponded to the period 1 January 1980, to 1 June 2021, while ERA-5 covered the period 1 January 1979, to 1 April 2021. The GWC files were downloaded from the GWA.

2.2. Determination of Wind Exclusion Areas

The following exclusion criteria were used to determine the technical, environmental, and social restrictions in the southeastern Gulf of Mexico for the installation of offshore wind farms and thus identify wind exclusion areas:

- Areas of exclusive use by the hydrocarbon industry. The information available in the Map of the Hydrocarbon Industry of the National Center of the Hydrocarbon Industry [39] was used. Shape files with extension *shp were exported with geo-referenced information of all the layers that were of interest to the study, those corresponding to areas where there are hydrocarbon exploitation infrastructures (fields, wells, pipelines), as well as those that have already been assigned for future exploration and exploitation activities. The guidelines established in the Official Journal of the Federation (OJF) were then used to determine the wind exclusion areas around the hydrocarbon infrastructures already referenced. The guidelines used are those that establish the safety zones for navigation and overflight in the vicinity of oil facilities and the integral and sustainable use of fishery and aquaculture resources in Mexican marine areas [2,40].

- According to these guidelines, the wells, platforms, and other facilities for the exploration and extraction of hydrocarbons will have an individual safety zone of 2500 m around them. Therefore, wind exclusion zones were established as those within a radius of 2500 m around the infrastructure, as well as the polygons that enclose the fields with reserves, areas with resources, assigned areas, and those corresponding to the five-year plan 2020–2024.
- Natural protected areas (NPAs). The information available on the website of the National Commission of Natural Protected Areas [41] was used, specifically on the interactive map "Protected Natural Areas of Mexico" [42]. All areas within an NPA were considered wind exclusion zones.
- Water depth. The study prioritized areas with water depths less than 50 m since deeper water depths require more expensive technologies, such as floating platforms. The shp files with bathymetric information were obtained from the Hydrocarbon Industry Map [43].
- Distance to the coast. The distance of offshore wind farms from the coast is a factor that influences their social impact. Although there is no consensus regarding the minimum recommended distance, some authors such as Betakova et al. [44] and Sullivan et al. [45], cited by Virtanen et al. [46], suggested distances of 10 km and 16 km, respectively, to decrease negative social impacts; meanwhile, Tavares et al. [32] considered a minimum distance of 18 km for offshore wind farms in Brazil. However, the distance to the coast also affects the installation, operation, and maintenance costs of wind farms and therefore their economic viability. Most of the wind farms operating in the world are within 20 km of the coast, with a global average of 18.8 km [47]. In our case, we took the value of 20 km as a reference; that is, areas within 20 km from the coast were considered wind exclusion areas. This distance also considered that, in the study region, several coastal communities are engaged in fishing, using some means that allow them to penetrate several kilometers offshore.

Figure 2. Location of the study area in the Gulf of Mexico.

2.3. Wind Resource Assessment and Modeling of Offshore Wind Farms

Three sites were selected to assess the feasibility of installing offshore wind farms, located outside the wind exclusion areas in each AMB studied (Table 1). The coordinates of the sites selected for wind farm modeling are shown in Table 1.

Table 1. Location of the three sites selected for the study.

AMB to Which the Study Site Belongs	Coordinates and Distances to the GWC Point		
	GWC Point	Nearest MERRA-2 Point	Nearest ERA-5 Point
Tabasco	18.98, −93.89	18.5, −93.75 17.25 km	18.5, −94.0 14.63 km
Campeche	19.61, −91	19.5, −91.25 28.94 km	19.5, −91 12.24 km
Yucatán	21.64, −89.42	21.5, −89.37 16.42 km	21.75, −89.5 14.74 km

Viewing Table 1, the wind resource characteristics were evaluated using Windographer 4.0 software [48]. From Windographer, tab files were exported, containing the observed wind climate at 150 m height, for both MERRA-2 and ERA-5 data. This height coincides with that of the hub of the reference wind turbine IEA 15 MW [49], which was used in the study.

The IEA 15 MW reference wind turbine was selected because it corresponds to a model designed for offshore sites, with low average wind speeds. In addition, it represents the technological evolution of offshore wind turbines expected to be available in the market by 2030 [50], with long wind rotors and small specific powers. Several authors have used such a turbine in similar studies [51–54]. Some of its parameters are shown in Table 2 [49].

Table 2. Parameters of the reference wind turbine IEA 15 MW.

Parameter	Value
Power rating	15 MW
Turbine class	IEC Class 1B
Specific rating	331.57 W/m^2
Cut-in wind speed	3 m/s
Rated wind speed	10.88 m/s
Cut-out wind speed	25 m/s
Rotor diameter	240 m
Hub height	150 m

Figure 3 shows its power curve, with data available from IEA [55].

The vertical extrapolation of wind speed up to 150 m height was performed in Windographer using the power-law expression, Equation (1). In the case of MERRA-2 data, the extrapolation was performed from 50 m, and for ERA-5 data from 100 m.

$$V_H = V_{H_0}\left(\frac{H}{H_0}\right)^{\propto} \quad (1)$$

where V_H and V_{H_0} are the wind speeds at heights H (150 m) and H_0 (50 m or 100 m), respectively (in m/s), while $\propto = 1/7$ is the value used for the power-law exponent.

Meanwhile, WAsP version 11 software was used to perform microscale modeling at the three selected sites [56]. WAsP is a program that allows the vertical and horizontal extrapolation of the wind, based on several models that allow it to describe the wind flow over different types of terrain and obstacles. It consists of five stages or calculation blocks:

- Analysis of raw wind data. In this block, the analysis of any time series of wind speed measurements is performed. As a result, an observed wind climate (OWC) is obtained, which is dependent on the specific site.
- Generation of wind atlas data. At this stage, the wind data are "cleaned" to site-specific conditions (orography, roughness), resulting in a generalized wind climate (GWC), independent of the site.
- Wind climate estimation. From the generalized wind climate, the program predicts the wind climate (PWC) at any specific point and height, for example, at the location of a wind turbine. For this purpose, it introduces the terrain characteristics around the point and performs the inverse procedure of the second block; therefore, it is said that WAsP performs a double vertical extrapolation.
- Estimation of wind power potential. The energy content of the wind and the energy production of a given wind turbine is calculated from its power curve.
- Calculation of wind farm production. In this block, the power and thrust curves of the wind turbines, as well as the layout of the wind farm, are used to calculate the wake losses of each turbine. These losses are deducted from the total energy production of the wind farm to obtain its net production.

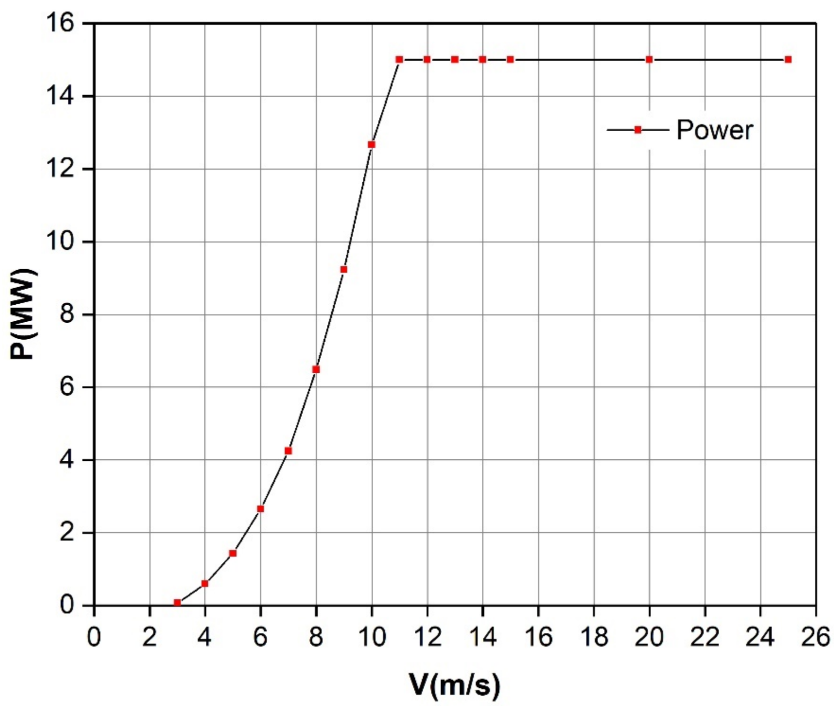

Figure 3. IEA 15 MW power curve.

In this study, wind resource modeling was performed in areas of 50 km by 50 km, centered on the GWC points of each site (Table 1). The resolution used was 1 km, and all calculations were performed at 150 m height.

The location of the wind turbines within each wind farm considered separations of ten diameters between rows and five diameters between wind turbines in the same row. The location of each of them and their main parameters are shown in Figure 4 and Table 3, respectively.

Capacity factor (*CF*) gives a measure of how much the installed rated power of a wind turbine is utilized. It depends both on the wind characteristics at the installation site and on the wind turbine's characteristics (power curve) and is determined by Equation (2).

$$CF = \frac{P_{av}}{P_r} \quad (2)$$

where P_{av} is the average power of the wind turbine and P_r its rated power.

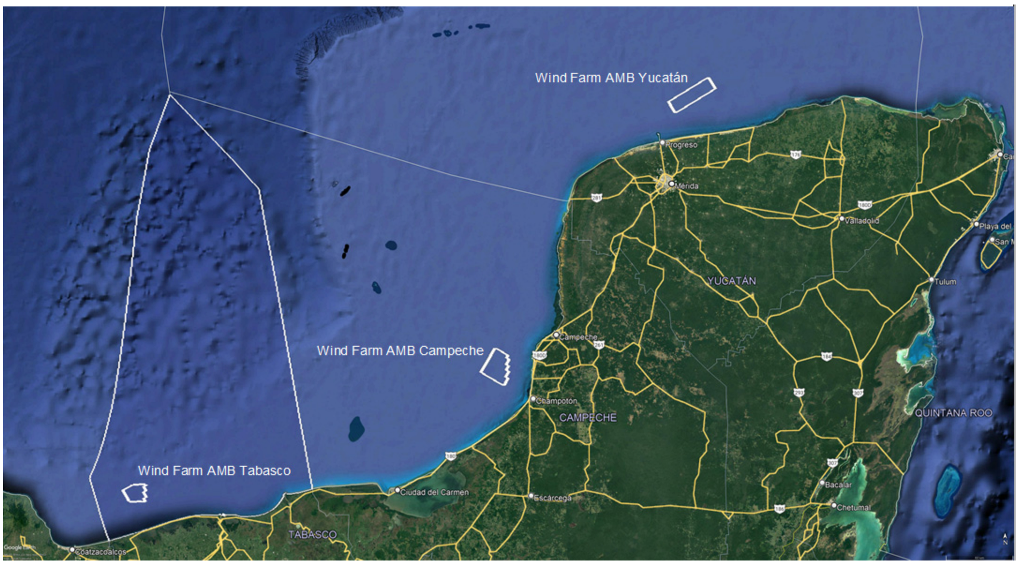

Figure 4. Location of the three wind farms evaluated.

Table 3. Wind farm parameters.

Wind Farms	Wind Turbine Model	Selected Area (km^2)	Wind Turbines	Total Power Output (GW)
AMB Tabasco		272	94	1.41
AMB Campeche	IEA 15 MW	442	170	2.55
AMB Yucatán		451	170	2.55
		Total	434	6.51

Equation (2) is valid for both a wind turbine and a wind farm. In this study, the capacity factor of each of the three wind farms was determined following the procedure described above.

Annual expected energy: The estimation of the energy delivered by each wind turbine was performed using the WAsP 11. The methodology is based on Equation (3):

$$P_{av} = \int_{V_{cut\ in}}^{V_{cut\ out}} P(v)p(v)dv \quad (3)$$

where $V_{cut\ in}$ and $V_{cut\ out}$ are the wind speeds at which the wind turbine starts and stops delivering power, respectively, $P(v)$ is the function that determines the power delivered by the wind turbine for each wind speed (power curve), and $p(v)$ is the Weibull probability density function (Equation (4)), which gives the probability of occurrence of each wind speed at the study site.

$$p(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad (4)$$

where k is the shape factor (dimensionless), and c is the scale factor (m/s).

The algorithm used by WAsP to determine the Weibull parameters k and c is based on the following requirements [57]:

- The average power density determined using the Weibull probability density function should be equal to that obtained from the measured data.
- The proportion of the data above the mean velocity (v_{av}), determined using the Weibull distribution function, is the same as that obtained from the distribution of the measured data.

From the first requirement, Equation (5) is obtained to determine the value of the parameter c:

$$c = \sqrt[3]{\frac{\sum_{i=1}^{N} {v_i}^3}{N\Gamma\left(1 + \frac{3}{k}\right)}} \tag{5}$$

where there is a dependence on the parameter k. Γ is the Gamma function, evaluated on argument $\left(1 + \frac{3}{k}\right)$, and N is the amount of wind speed data.

Then, to determine k, an iterative calculation process is performed from Equation (6), which is obtained from the second requirement, and then factor c is determined by Equation (5):

$$-Ln(F(v \geq v_{av}) = \left(\frac{v_{av}}{\sqrt[3]{\frac{\sum_{i=1}^{N} {v_i}^3}{N\Gamma\left(1+\frac{3}{k}\right)}}} \right)^k \tag{6}$$

where $F(v \geq v_{av})$ is the proportion of data above the mean, obtained from the distribution of measured data.

Once the average power of each wind turbine has been calculated, the gross annual energy delivered is obtained by multiplying this value by the time (hours per year). However, the gross energy is reduced by the wake effects (W_l) to calculate the net energy produced (Equation (7)).

$$AEP = 8760 \times P_{av} \times (1 - W_l) \tag{7}$$

The procedure followed by WAsP to calculate wake losses is described by Barthelmie and Jensen [58]. According to this procedure, for offshore applications, it is advisable to use a wake decay constant equal to 0.04. For this reason, the default WAsP value of 0.75, which is more recommended for onshore applications, was replaced by 0.04.

However, WAsP does not consider loss factors other than those caused by a wake in its calculations. Therefore, factors related to technical availability (U_l) of wind turbines and transmission losses (T_l) were introduced in this study. The values considered were 10% for each of them. Technical unavailability losses refer only to the downtime of wind turbines due to repair or maintenance. Both loss factors could be lower. However, since grid constraints, balance-of-plant issues, and other site-dependent loss factors were not considered in this study, it was preferred to use a total loss value of 20%, which is quite close to the values used by Musial et al. [50] in a similar study.

The equation for calculating the net annual energy delivered by each wind turbine is expressed in Equation (8).

$$\begin{aligned} AEP_{net} &= AEP \times (1 - U_l - T_l) \\ &= AEP \times (1 - 0.1 - 0.1) \\ &= 0.8 \times AEP \end{aligned} \tag{8}$$

Finally, the net energy delivered by each wind farm (AEP_{net_WF}) is the sum of the net energy delivered by each of its component wind turbines, see Equation (9).

$$AEP_{net\_WF} = \sum_{i=1}^{N_{wt}} AEP_{net\_i} \tag{9}$$

where N_{wt} is the number of wind turbines that make up the wind farm.

The calculation of the annual energy produced by the wind farms was performed using MERRA-2, ERA-5, and GWC data to make a comparative analysis of the results obtained. The GWC data were used as a reference or basis for comparison since measured data were not available at the time of this study.

Then, the values of annual energy produced by the offshore wind farms were compared with the annual electricity consumption of the entire Peninsular Region (Campeche, Yucatán, Quintana Roo) and with the Southeast Region of Mexico (Tabasco, Peninsular

Region). The above was done with the interest of evaluating how much offshore wind farms in the Gulf of Mexico could contribute to the achievement of national goals in terms of electricity generation from clean energy.

For this purpose, electricity consumption data corresponding to 2019, available in the Energy Information System of the Secretariat of Energy (SENER), were used [5]. It was preferable not to use the 2020 data since it was an atypical year in terms of electricity consumption, which decreased drastically in all the states of the region, and in the whole country, due to the COVID-19 pandemic. This was one of the effects that the pandemic had on the national electricity system. Many institutions were forced to carry out activities virtually, and the different productive sectors decreased their production levels due to the confinement measures. This directly influenced electricity consumption, such that at the national level, there was a decrease of 5.6% in 2019. Meanwhile, in the peninsular and southeast regions of Mexico, the reductions were 12.1% and 9%, respectively.

As a result, the Mexican government took measures regarding the dispatch of energy from intermittent sources, such as wind and solar, establishing regulations that favored even more conventional sources, thus guaranteeing the country's energy security. As a consequence, many wind projects that were underway were halted, and the promotion of renewables ceased to be a priority for the country, jeopardizing the national goals in terms of clean energy. This is an aspect that is taken up again in the final part of this article due to its importance within the sustainable energy transition process required not only by Mexico but also by the rest of the world.

Regarding the annual emissions saved that could be avoided (E_{saved}) with the production of electricity in the wind farms, they were estimated using Equation (10).

$$E_{saved} = AEP_{net\_WF} \times EF \tag{10}$$

where EF is the emission factor of the Mexican electricity grid, expressed in tons of CO_2 equivalent per unit of energy produced (0.494 tCO_2eq/MWh) and whose most recent value corresponds to 2020 [59].

The following evaluation criteria were used to determine the economic pre-feasibility of the wind farms:

The levelized cost of energy ($LCOE$) includes the life-cycle costs of the project and was expressed in USD/kWh. This indicator was calculated using Equation (11).

$$LCOE = \frac{(CRF \times CapEx) + OpEx}{AEP_{net\_WF}} \tag{11}$$

where $CapEx$ is the capital cost (USD), $OpEx$ is the annual operation and maintenance cost (USD/year), AEP_{net_WF} is the annual energy delivered by the wind farm (kWh/year), and CRF is the capital recovery factor (Equation (12)).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{12}$$

where i is the interest rate, and n is the number of years of project life. In this study, $n = 25$ was taken because the useful life of wind turbines is approximately 20 to 25 years [13,60,61]. In addition, although wind project developers seek to increase the useful life of the turbines, as it is more economical than repowering the wind farms, in practice, it is rare to find projects with power purchase agreements (PPAs) longer than 25 years [62].

CapEx is the cost element that contributes most to the *LCOE* of an offshore wind farm and is influenced by a set of factors [50]: site conditions (water depth, distance to ports and interconnection points, wave height), project size, supply chain characteristics, and changes in electricity and raw material prices, among other factors.

Hdidouan and Staffell [63] used Equations (13)–(17) to determine the *CapEx* of offshore wind turbines (USD/MW).

$$CapEx = T_C + F_C + G_c + Bos_C \tag{13}$$

$$F_c(d > 30\ m) = E_{R}{}_{USD}^{EUR}(282666 + 12700d) \tag{14}$$

$$F_c(d < 30\ m) = E_{R}{}_{USD}^{EUR}(363000 + 9800d) \tag{15}$$

$$G_c = G_{C\_onsh} + G_{C\_offsh} \tag{16}$$

$$G_c = E_{R}{}_{USD}^{EUR}\left(10900L_{onsh} + 785714 + 2857L_{offsh}\right) \tag{17}$$

where T_C is the cost of the wind turbine, F_C is the cost of the smelters, G_c is the cost of the interconnection power grid, and Bos_C is the balance-of-system cost (all in USD/MW); d is the water depth (m), G_{C_onsh} is the onshore grid cost, G_{C_offsh} is the offshore grid cost, L_{onsh} is the onshore grid length (km), and L_{offsh} is the offshore grid length (km). $E_{R}{}_{USD}^{EUR}$ is the euro to US dollar exchange rate (1 EUR = 1.1447 USD, 6 February 2022).

Musial et al. [50] pointed out that the cost of wind turbines represents between 25% and 45% of the *CapEx*, while Hdidouan and Staffell [59] considered that the Bos_C reaches approximately 7% of the *CapEx*. In this study, we evaluate the incidence that the cost of wind turbines has on the *LCOE* to evidence the need to develop the Mexican wind industry. Therefore, Equation (14) is written as a function of the fraction m that represents the cost of the wind turbine about the *CapEx*.

Regarding the Bos_C, a value of 10% of the *CapEx* is suggested, considering what was suggested by Arenas and Badaoui [64]. Considering the above, the *CapEx* was determined from Equation (18).

$$CapEx = \frac{F_C + G_c}{0.9 - m} \tag{18}$$

Substituting Equations (14) or (15) (for $d > 30$ m or $d < 30$ m, as the case may be) as well as Equation (17), Equation (18) is expressed as follows.

$$CapEx(d > 30\ m) = \frac{E_{R}{}_{USD}^{EUR}\left(1068380 + 12700d + 10900L_{onsh} + 2857L_{offsh}\right)}{0.9 - m} \tag{19}$$

$$CapEx(d < 30\ m) = \frac{E_{R}{}_{USD}^{EUR}\left(1148714 + 9800d + 10900L_{onsh} + 2857L_{offsh}\right)}{0.9 - m} \tag{20}$$

On the other hand, *OpEx* was determined following the methodology described in Arenas and Badaoui [64] and Cavazzi and Dutton [65], who based their calculations on Equation (21).

$$OpEx = M_c + P_c + \left(\frac{L_p V_c}{100}\right) \tag{21}$$

where M_c is the fixed maintenance cost (20.60 USD/MWh), P_c is the port fee (3.43 US/MWh), L_p is the distance from the wind farm to the nearest port (km), and V_c is the variable cost (6.87 USD/MWh).

The levelized avoided electricity cost (*LACE*) gives a measure of how economically competitive the wind farm is compared to electricity from the national grid. It is also expressed in USD/kWh and results from the difference between the local marginal price (*LMP*) and the *LCOE* (Equation (22)).

$$LACE = LMP - LCOE \tag{22}$$

If the *LACE* is positive, the project is attractive, while if it is negative, it is not viable. The *LMP* is defined as the price of electricity in each NodeP of the National Electric System. In turn, according to the National Energy Control Center [3], a NodeP corresponds to one or several nodes of connectivity of the network, and in it, a physical injection or withdrawal of energy is modeled. The energy price for financial settlements in the wholesale electricity market is determined in each P-Node.

Data for the year 2019, available from CENACE, were used for LMPs in the real-time wholesale market (*MTR*), corresponding to the NodesP closest to each of the wind farms studied. The selected nodes were the following: Node 02CHT for the Tabasco wind farm; Node 08CMO for the Campeche wind farm; and Node 08PPO for the Yucatán wind farm.

3. Results

3.1. Wind Power Exclusion Zones and Installable Capacity

Data in [39,41] show the most important results regarding the determination of the wind exclusion zones. The values shown were determined from information available on the website of the National Commission of Natural Protected Areas [41], as well as from shape files, which were exported from the Map of the Hydrocarbon Industry of the National Center of the Hydrocarbon Industry [39].

It can be noted that the three AMBs occupy a total area of 384,833 km^2, of which 74.2% is not feasible for the installation of wind farms due to environmental, social, and technical restrictions. A total of 26.7% of the total area is in waters with depths less than 50 m, with an extension of 102,923 km^2, but 26.3% of it corresponds to wind exclusion zones.

In the AMBs of Tabasco and Campeche, the wind exclusion zones due to the presence of the hydrocarbon industry stand out, with areas of 7138 km^2 and 6189 km^2, respectively, that are exclusively used by this industry. Meanwhile, the wind exclusion zones due to environmental restrictions are more important toward the Campeche and Yucatán AMBs, with areas of 3569 km^2 and 1614 km^2, respectively, and with no presence of them in the Tabasco AMB.

The total area available for the installation of offshore wind farms in water depths less than 50 m is 75,894 km^2. Considering a specific power of 5.18 MW/km^2, the installable power in the AMBs of Tabasco, Campeche, and Yucatán, in waters less than 50 m deep, would be 2.2 GW, 140.7 GW, and 250.6 GW, respectively, for a total of 393.42 GW in the entire studied area of the Gulf of Mexico.

3.2. Characteristics of the Available Wind Resource

Regarding the available wind resource, it is observed that the shapes of the daily average wind speed profiles obtained with MERRA-2 and ERA-5 data are similar, although there are differences in the mean values, which is inherent to the characteristics of each mesoscale model used (Figure 5). According to MERRA-2 data, the mean velocity at 150 m height is 7.2 m/s, 6.9 m/s, and 6.7 m/s in Tabasco, Campeche, and Yucatán, respectively. While from the ERA-5 data, the values obtained are 6.2 m/s, 7.1 m/s, and 8.2 m/s. The largest absolute deviations are observed at the Tabasco and Yucatán sites, with values of 1 m/s and 1.5 m/s, respectively.

Regarding wind behavior by heading sectors, both MERRA-2 and ERA-5 give similar results. In Tabasco, MERRA-2 identifies three directions with the highest percentages of the total energy contained in the wind: northeast, north-northeast, and north; meanwhile, ERA-5 identifies northeast, north-northeast, north, and north-northwest. In Campeche, both models coincide in that the north-northeast, north, east-southeast, and southeast are the directions with the highest percentage of energy, while in Yucatán, MERRA-2 identifies the northeast and ERA-5 as the east-northeast (Figure 6).

Table 4 shows the mean power density values at the three GWC sites, as well as those obtained by microscale modeling with the WAsP using MERRA-2 and ERA-5 data. If the GWC values are taken as a reference, it will be noticed that in the ERA-5 data, the highest relative error is 22%, by default, obtained in the case of Tabasco, while there are no differences for the case of Yucatán. Meanwhile, for MERRA-2 data, the lowest relative error is obtained in Tabasco (1.43%) and the highest in Yucatán (48.16% default). In general, the ERA-5 data showed a higher degree of coincidence with the GWC data.

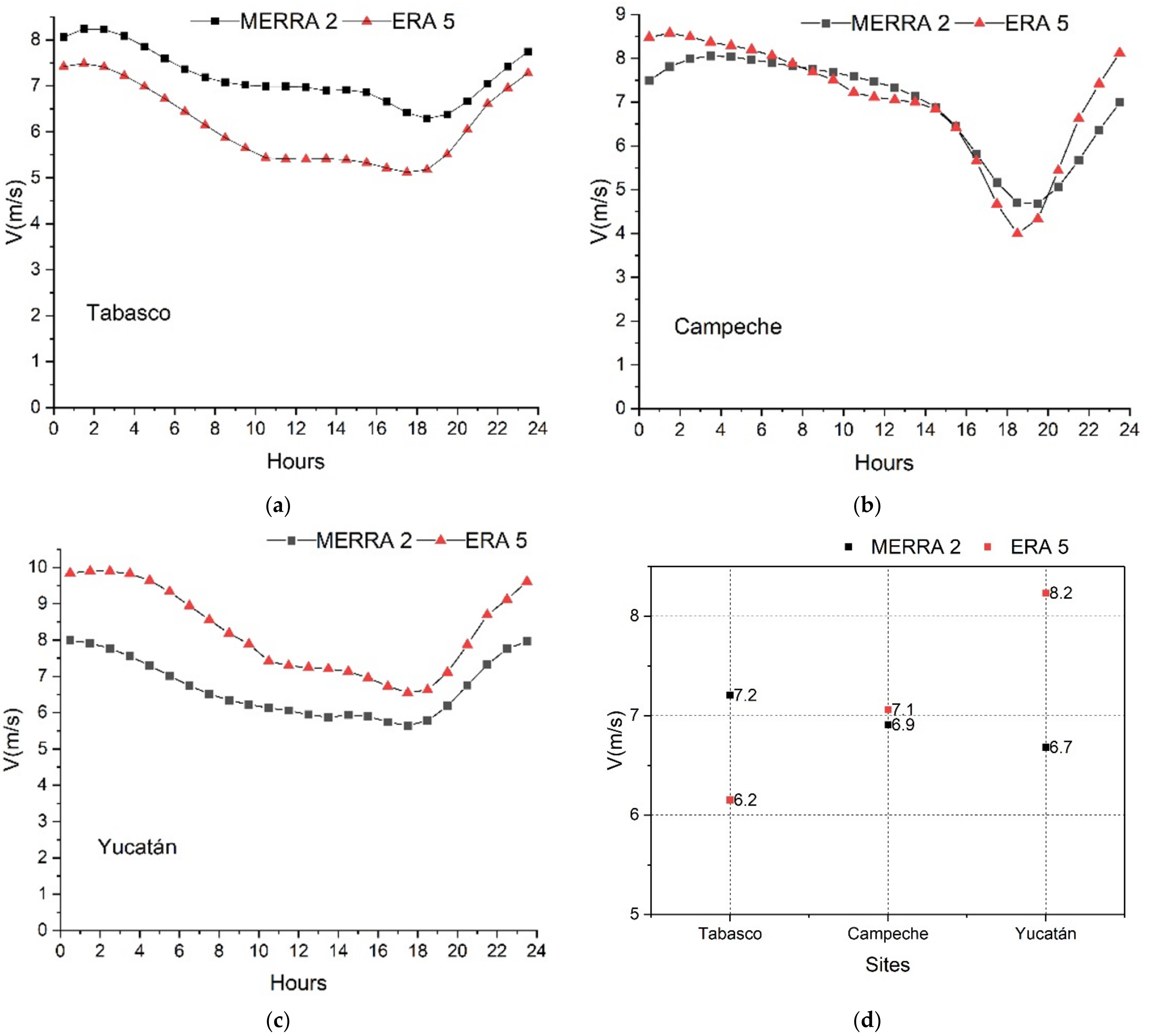

Figure 5. Daily wind speed profiles (**a**–**c**) and average values (**d**) at the three study sites at 150 m height.

Table 4. Average power density (P_d) and relative error (E_r) concerning the GWC values at 150 m altitude.

Sites	GWC	ERA-5		MERRA-2	
	P_d (W/m^2)	P_d (W/m^2)	E_r (%)	P_d (W/m^2)	E_r (%)
Tabasco	350	273	−22.00	355	1.43
Campeche	380	329	−13.42	304	−20.00
Yucatán	490	490	0.00	254	−48.16

The spatial distribution of the average available power density, at 150 m height, is shown in Figure 7. Of the sites selected for the wind farms, the Yucatán site has the highest average value.

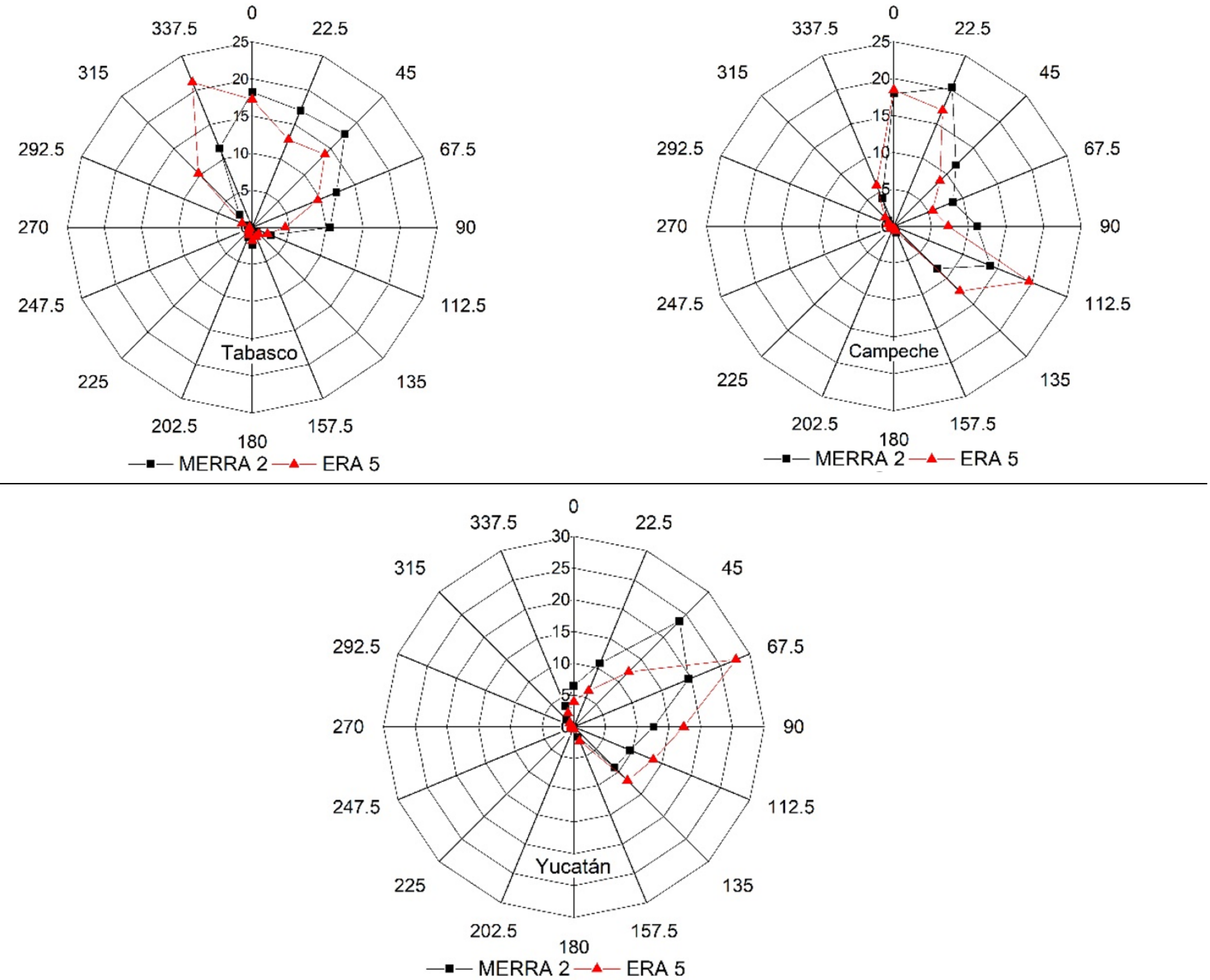

Figure 6. Energy wind roses.

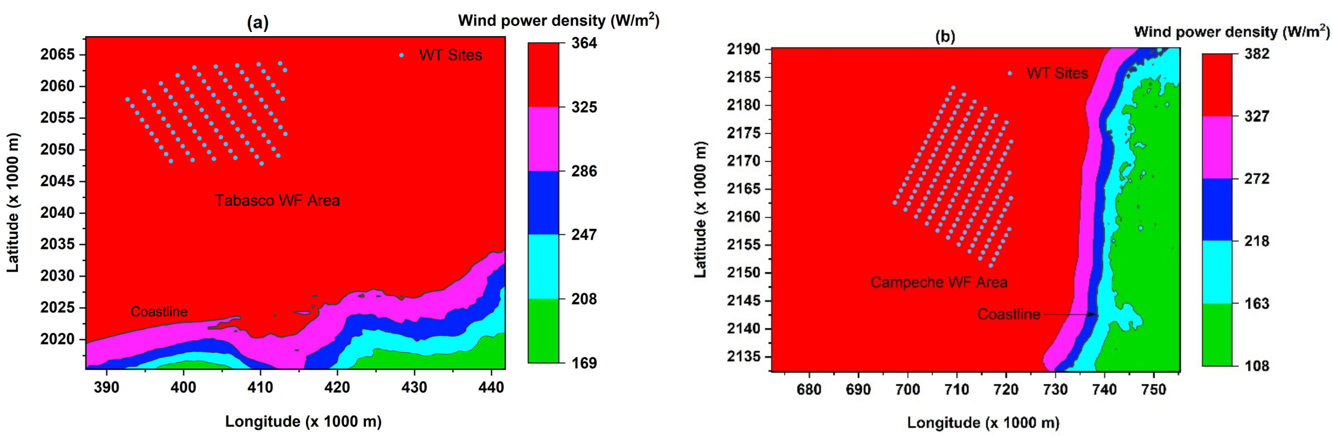

Figure 7. *Cont.*

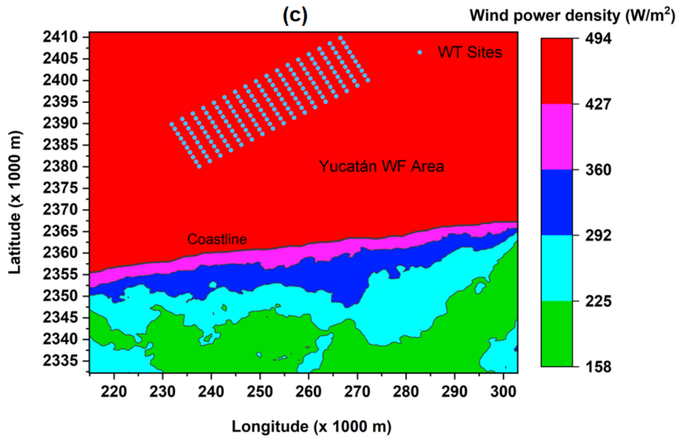

Figure 7. Maps of mean available power density in the study areas (**a**) Tabasco; (**b**) Campeche; (**c**) Yucatán.

3.3. Modeling of Wind Farms

To calculate the energy production of the wind farms, the three data sources indicate that with the ERA-5 data, the highest relative deviation concerning the GWC is 23.7%, while for the MERRA-2 data, it is 40.3%. The annual energy delivered by the wind farms (results with GWC data) would be 4000.90 GWh in Tabasco, 8381.50 GWh in Campeche, and 10,438.50 GWh in Yucatán (Table 5).

Table 5. Annual net energy delivered by each wind farm (AEP_{net_WF}) and relative error (E_r) concerning GWC values at 150 m height.

Sites	Power Output (GW)	GWC	ERA-5		MERRA-2	
		AEP_{net_WF} (GWh/y)	AEP_{net_WF} (GWh/y)	E_r(%)	AEP_{net_WF} (GWh/y)	E_r(%)
Tabasco	1.41	4000.90	3052.00	−23.72	4330.00	8.23
Campeche	2.55	8381.50	7639.00	−8.86	7025.00	−16.18
Yucatán	2.55	10,438.50	10,498.00	0.57	6232.00	−40.30

As shown in Table 6, the capacity factors, estimated from the GWC data, could reach values of 32% in Tabasco, 37% in Campeche, and 46% in Yucatán. Additionally, in terms of annual emissions avoided, the wind farm in Tabasco could avoid the emission of 1976.4 $MtCO_2eq$, the wind farm in Campeche 4140.5 $MtCO_2eq$, and the wind farm in Yucatán 5156.6 $MtCO_2eq$, contributing to the decarbonization of the Mexican electricity sector.

Table 6. Contribution of wind farms to the region's electricity supply and annual emissions avoided (results with GWC data).

Wind Farms	Capacity Factor (%)	Percentage Concerning 2019 Annual Consumption (%)		Annual Emissions Saved (MtCO2eq/y)
		Peninsular Region	Southeastern Mexico	
Tabasco	32	37	28	1976.4
Campeche	37	78	59	4140.5
Yucatán	46	97	74	5156.6
Total	40	212	161	11,273.5

Electricity consumption in the Peninsular and Southeast Regions of Mexico during the period 2015–2019 had an average annual growth of 5.89% and 4.65%, respectively. In 2019, which was taken as the base year for our analysis, electricity consumption in the Peninsular Region was 10,793 GWh, while in the entire Southeast Region, it was 14,129 GWh (Figure 8).

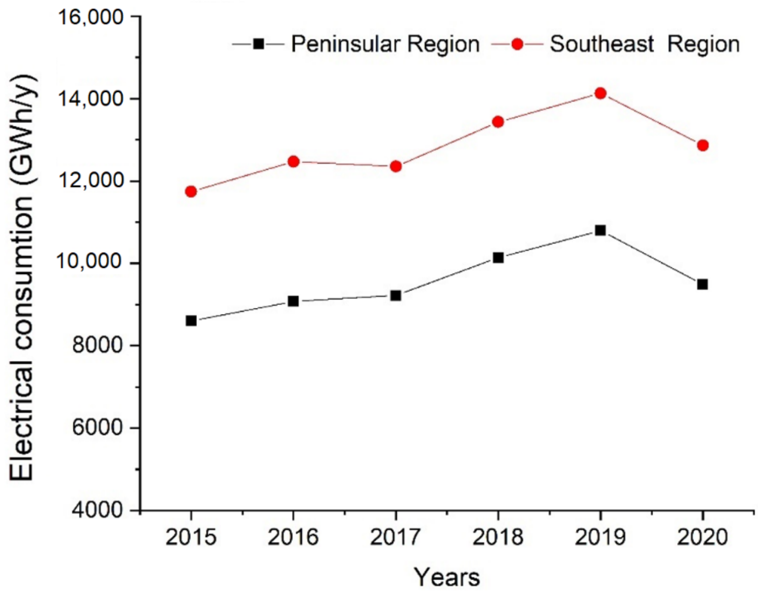

Figure 8. Annual electricity consumption for the period 2015–2020.

If the values of annual energy delivered by the wind farms are compared with the electricity consumption of the Peninsular Region and the Southeast Region of Mexico in 2019, it is observed that their contribution to the electricity matrix of these regions would be considerable (Table 6). For example, the Yucatán wind farm, which has the highest capacity factor, could supply 97% of the annual consumption of the Peninsular Region or 74% of the consumption of the entire Southeast Region of Mexico.

The goal established by Mexico concerning clean energy production is 35% by the year 2024. Figures 9 and 10 show the contribution that the wind farms in the Gulf of Mexico could have in achieving this goal, under three scenarios of installed capacity (to the total power of each wind farm considered in Table 7). The first scenario considers the installation of 100% of the capacity of each wind farm ($WF_{100\%}$), the second scenario considers the installation of 50% of the capacity ($WF_{50\%}$), and the third scenario considers the installation of only 30% of the capacity ($WF_{30\%}$).

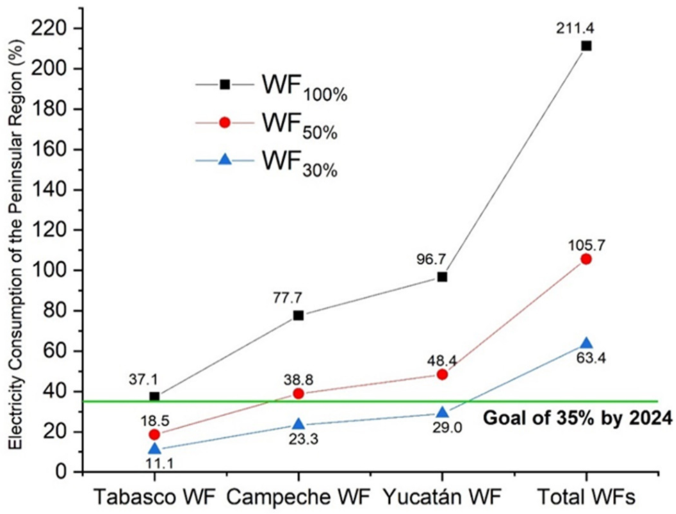

Figure 9. Contribution of wind farms to the electricity consumption of the Peninsular Region in three installed capacity scenarios.

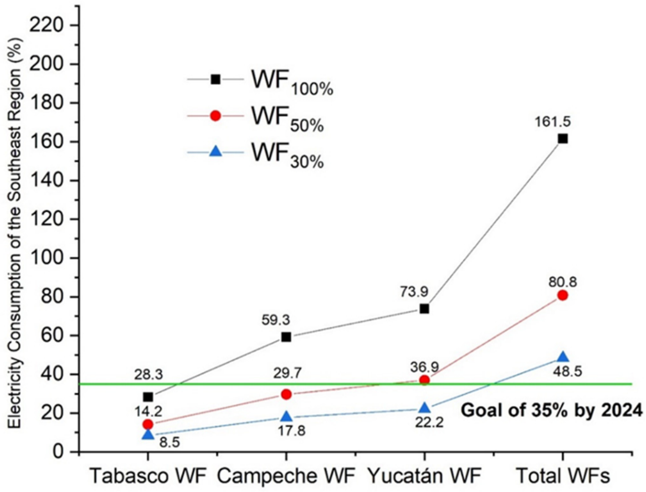

Figure 10. Contribution of wind farms to electricity consumption in the Southeast Region under three installed capacity scenarios.

Table 7. Scenarios considered.

Wind Farms	**Capacity (GW)**		
	$WF_{100\%}$	**$WF_{50\%}$**	**$WF_{30\%}$**
Tabasco	1.41	0.71	0.42
Campeche	2.55	1.28	0.77
Yucatán	2.55	1.28	0.77

Figure 9 corresponds to the expected contributions to the annual consumption of the Peninsular Region. In the $WF_{100\%}$ scenario, each of the wind farms could contribute more than 35% of the region's electricity consumption, with those of Campeche and Yucatán standing out with contributions of more than 70%. Meanwhile, in the $WF_{50\%}$ scenario, the Campeche and Yucatán wind farms would contribute more than 35%, while in the $WF_{30\%}$ scenario, the Yucatán wind farm would contribute 29%.

Regarding the expected contributions to the annual consumption in the Southeast Region (Figure 10), the behavior is similar to that of the Peninsular Region in the case of the $WF_{100\%}$ scenario, but in the $WF_{50\%}$ scenario, only the Yucatán wind farm could have a contribution higher than the 35% target, and in the $WF_{30\%}$ scenario, the contributions would be lower than this value but around 20% for both Campeche and Yucatán.

The analysis carried out considering the scenarios $WF_{100\%}$, $WF_{50\%}$, and $WF_{30\%}$ also had the intention of comparing the values of the capacities of each of the wind farms in the Gulf of Mexico, with the offshore wind capacities already installed in other countries, that is, to place our analysis in the international context, to have a better idea of the reality of the total capacities of the proposed wind farms.

In this regard, it should be noted that, for example, the 2.55 GW capacity of the Campeche and Yucatán wind farms in the $WF_{100\%}$ scenario is comparable to the new offshore capacity installed by China in 2020, which was 2.17 GW. It is also well below the offshore wind capacity under construction in China and the UK in 2020, which is 16.52 GW and 3.7 GW, respectively [42]. Furthermore, the capacities considered for the Campeche and Yucatán wind farms in the $WF_{50\%}$ and $WF_{30\%}$ scenarios are comparable to that installed in Denmark, the UK, and the Netherlands in the first half of 2021, which reached 1.34 GW in total [53].

3.4. Preliminary Economic Feasibility Analysis

Table 8 shows the mean water depth values, as well as the lengths of the offshore and onshore power grids for each of the wind farms studied. The closest ports to each wind farm are Coatzacoalcos for the Tabasco WF, which is 61 km away; Seybaplaya for the Campeche WF, 20 km away; and Puerto Progreso for the Yucatán WF, located 23 km away. The distances to the coasts are 23 km, 24 km, and 22 km for the Tabasco, Campeche, and Yucatán wind farms, respectively. Meanwhile, the interconnection points to the onshore substations correspond to the NIS nodes closest to the coasts, located in the town of Chontalpa for the Tabasco WF (02CHT), in Champotón for the Campeche WF (08CMO), and in Puerto Progreso for the Yucatán WF (08PPO).

Table 8. Parameters used in the *CapEx* and *OpEx* calculation.

Parameters	Tabasco Wind Farm	Campeche Wind Farm	Yucatán Wind Farm
Average water depth, d (m)	62	15	25
Length of the offshore power grid, L_{offsh} (km)	23	24	22
Length of the onshore power grid, L_{onsh} (km)	41	2	19
Distance to the nearest port, L_p (km)	61	20	23

The Tabasco wind farm has the longest length of the terrestrial electrical grid (41 km); it also has the greatest average depth (62 km) and the greatest distance to the nearest port (61 km). The lengths of marine and land-based power lines, as well as water depth, directly affect *CapEx* (Equations (19) and (20)), while the distance to the port affects the *OpEx* (Equation (21)). These aspects mean that, for this wind farm, the *CapEx* and *OpEx* values are higher than those of Campeche and Yucatán (Table 9). Therefore *CapEx* and *OpEx* are directly related to the LCOE (Equation (11), and it is therefore to be expected that it will be higher precisely at the Tabasco wind farm, which, as we have already seen, also has the lowest capacity factors (Table 6).

Table 9. Economic indicators for four values of the sensitivity variable (m).

Economic Indicators		m			
		0.25	**0.35**	**0.45**	**0.55**
CapEx (USD/kW)	Tabasco WF	4154	4909	6000	7714
OpEx (USD/kWh) [a]	Tabasco WF	0.034			
LCOE (USD/kWh) [a]	Tabasco WF	0.187	0.221	0.270	0.347
LMP_{Avg} (USD/kWh) [b]	Tabasco WF	0.078			
$LMP_{Avg\text{-}LPT}$ (USD/kWh) [c]	Tabasco WF	0.085			
CapEx (USD/kW)	Campeche WF	2431	2873	3511	4515
OpEx (USD/kWh) [a]	Campeche WF	0.030			
LCOE (USD/kWh) [a]	Campeche WF	0.099	0.117	0.143	0.183
LMP_{Avg} (USD/kWh) [b]	Campeche WF	0.088			
$LMP_{Avg\text{-}LPT}$ (USD/kWh) [c]	Campeche WF	0.097			
CapEx (USD/kW)	Yucatán WF	2918	3448	4215	5419
OpEx (USD/kWh) [a]	Yucatán WF	0.031			
LCOE (USD/kWh) [a]	Yucatán WF	0.095	0.112	0.137	0.177
LMP_{Avg} (USD/kWh) [b]	Yucatán WF	0.090			
$LMP_{Avg\text{-}LPT}$ (USD/kWh) [c]	Yucatán WF	0.100			

[a] The energy values considered for the calculations were those obtained from the GWC data. [b] Average value considering the *LMP* values for the whole year. [c] Average value that only considers hourly average values (local marginal price averaged over a limited period of time) that are greater than LMP_{Avg}, i.e., over a limited period.

If we compare the global average value reached in the *CapEx* of offshore wind projects in the year 2020 (3750 USD/kW [50]) with those obtained from the analysis of the three wind farms in the Gulf of Mexico (Table 9), we can see that for the Tabasco WF, the *CapEx* is always higher, regardless of the value of the fraction m representing the cost of the wind turbine.

However, in the case of the Campeche WF, the *CapEx* would only exceed the global average when this fraction is greater than 45%, that is, when the cost of wind turbines weights the *CapEx* beyond the 45% indicated by Musial et al. [50] at the global level. Similarly, the Yucatán wind farm would have a *CapEx* lower than the global average when the fraction m is lower than 35%. This indicates the need to develop the national wind industry to reduce wind turbine costs and thus obtain lower *CapEx* in offshore wind farms in the Gulf of Mexico, supported by the country's experience in the exploitation of hydrocarbon deposits in this marine area.

Regarding the *LCOE*, in Table 9 and Figure 11, we can observe that the highest values correspond to the Tabasco WF, varying from 0.347 USD/kWh for m = 0.55 to 0.187 USD/kWh for m = 0.25. On the contrary, in the Campeche and Yucatán wind farms, the values are lower due to the existence of a higher wind potential (according to GWC data) and better site conditions, which make both *CapEx* and *OpEx* lower.

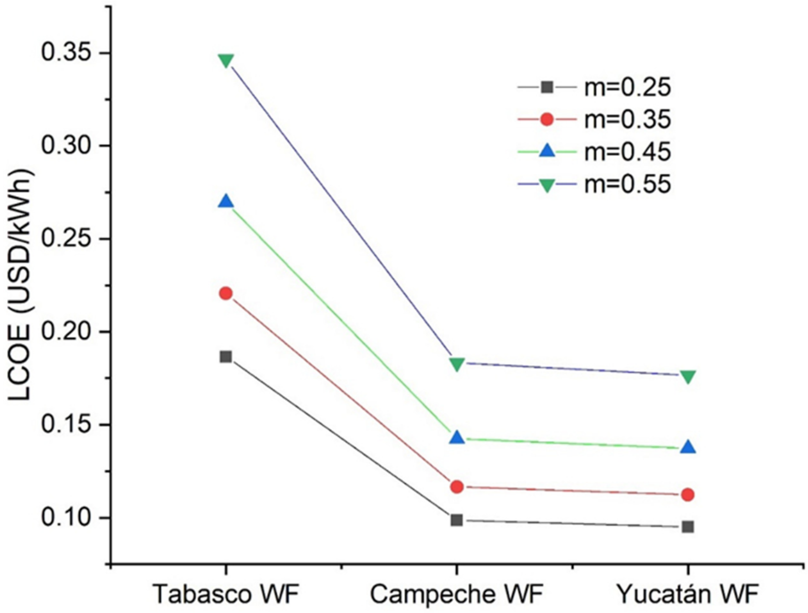

Figure 11. Sensitivity of LCOE to fraction m for three wind farms in the Gulf of Mexico.

It can be noted that in the case of the Campeche WF, the *LCOE* varies between 0.099 USD/kWh for m = 0.25 and 0.183 USD/kWh for m = 0.55, while for the Yucatán wind farm, the values are slightly lower: between 0.095 USD/kWh for m = 0.25 and 0.177 USD/kWh for m = 0.55. Musial et al. [50] noted that the global average *LCOE* in 2021 was 0.095 USD/kWh, varying between 0.078 USD/kWh and 0.125 USD/kWh for projects that started operation in 2020. If we compare this range of variation with the estimated values for the Campeche and Yucatán wind farms, we can see a decrease in the cost of wind turbines, such that the fraction m < 0.35 would allow reaching *LCOE* like those reported internationally.

Now, if we evaluate what would happen with the avoided levelized costs, then we can see that the *LCOE* would always be higher than the LMP_{Avg} of the corresponding nodes (Table 9). That is, it might be preferable to continue importing energy through the NIS instead of producing it locally. However, it is important to make the following observations, particularly for the Campeche and Yucatán wind farms:

- The differences between *LCOE* and LMP_{Avg} in Campeche could be between 11% and 25% for m = 0.25 and m = 0.35, respectively, while in Yucatán, it could be as low as 5.3% for m = 0.25 and 19.6% for m = 0.35. In practice, this difference could change substantially, not only due to the deviations that could exist between the values of the energy delivered by the wind farms, estimated in this study, and the actual production but also due to the volatility of conventional fuel prices, which dominate the Mexican electricity matrix and which could narrow the margin between the cost of electricity from offshore wind farms (*LCOE*) and that of the national electricity grid LMP_{Avg}. Additionally, it is interesting to note that the range of variation of the *LMP* at nodes 08 CMO and 08PPO is quite large, with a range of 0.492 USD/kWh and maximum values of 0.51 USD/kWh at each of them (Figure 12).

- If we consider the hourly behavior of the LMP in the three interconnection nodes (Figure 13), we can see that there is a wide session of the day during which the hourly averages are higher than the LMP_{Avg}. For example, in the nodes corresponding to the interconnection of the Campeche (08CMO) and Yucatán (08PPO) wind farms, the hourly average LMP is higher than the LMP_{Avg} during 15 h of the day, from 9:00 am to 11:00 pm.

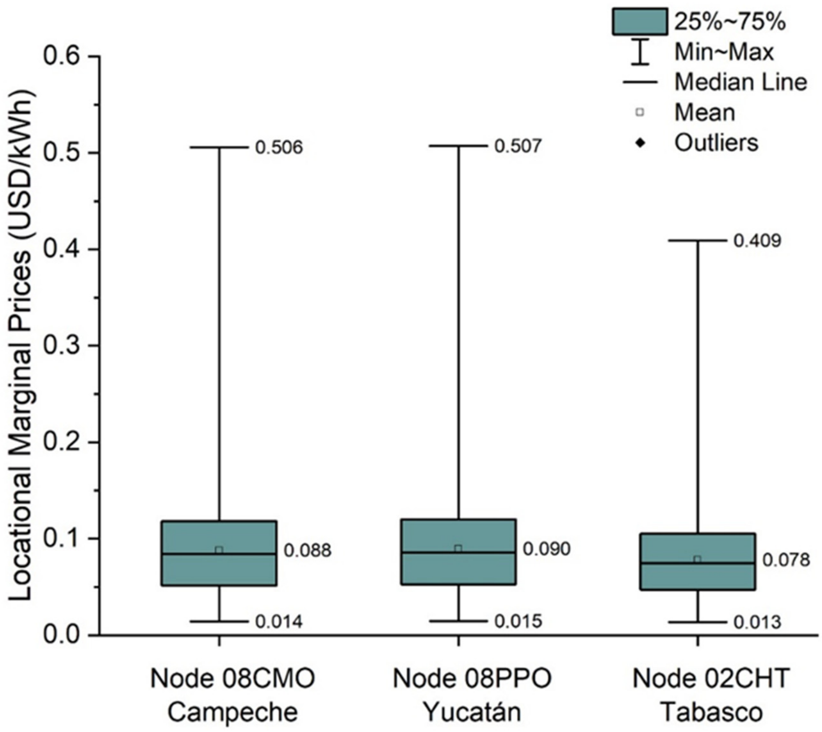

Figure 12. Average values and range of variation of *LMP* at the three interconnection nodes.

According to this behavior, it is interesting to compare the *LCOE* values with the average *LMP* value that only considers the hourly average values that are greater than the LMP_{Avg} of the whole year, i.e., limited to the 15 h mentioned above ($LMP_{Avg\text{-}LPT}$). Table 9 shows the values obtained for the nodes corresponding to each wind farm. In the case of the Tabasco WF, the *LCOE* is also higher than the $LMP_{Avg\text{-}LPT}$, but in the Campeche and Yucatán wind farms, the difference between values is much narrower. Even in the case of the Yucatán WF, the *LCOE* could be lower than the $LMP_{Avg\text{-}LPT}$ for m = 0.25 or very close to it for m = 0.35.

That is, when the *LCOE* comparison is made for the average value of the *LMP* during peak hours, the wind farms of Campeche and Yucatán are favored from the point of view of their economic viability. Here it is important to remember that one of the biggest problems faced by the peninsular electricity system has to do with network congestion, which affects the security of service in this region. These problems are accentuated precisely during the 15 h mentioned above, causing increases in the *LCOE* of the electricity coming from the NIS.

This constitutes an opportunity for the generation of electricity from offshore wind farms in the Gulf of Mexico areas of Campeche and Yucatán. However, public policies should be implemented, as well as strategies for electricity dispatch by regulators, to encourage the development of offshore wind farms in the Gulf of Mexico.

In addition, the results of this study draw attention to the need to carry out in situ measurements to verify the estimates made. It also shows the importance for Mexico of developing a national wind industry that will allow the country to move toward a new energy development model, based on the sustainable use of its resources and thus in the search for national energy sovereignty and security.

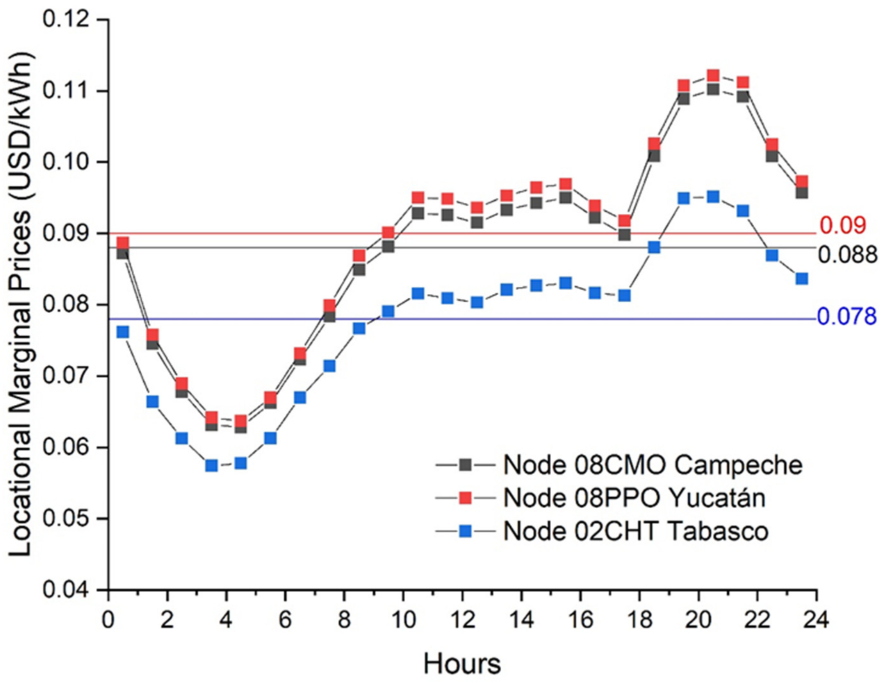

Figure 13. Hourly average values of the local marginal price in real time, in the three interconnection nodes. (The LMP_{Avg} are identified with horizontal lines, whose colors coincide with the ones assigned to each node in the daily profile represented.)

This is an aspect of great relevance for the country, not only for the future use of offshore wind energy but for all renewables in general. Mexico must make a great leap forward in terms of energy sustainability, but to do so, it needs to face challenges that will allow it to overcome both technical and non-technical barriers. Some studies such as the one developed by Amir and Zubair [66,67] propose measures for the African continent and Mexico, respectively. Taking them as a reference, and relying on what was proposed by the Mexican Government within the update of the Transition Strategy to Promote the Use of Cleaner Technologies and Fuels, in terms of the Energy Transition Law [68], some general proposals that could boost the country's transition toward a new model of sustainable energy development are mentioned below:

- Narrow the talent gap in the renewable energy sector, through the development of sustainable energy education programs, both formal and non-formal, as well as through the training and formation of high-level human resources.
- Promote the development of sustainable cities, establishing regulations that allow for adequate planning with a focus on eco-design, sustainable waste management, and efficient energy use.
- Increase investments in energy efficiency and distributed power generation projects, as well as in adequate transmission and distribution networks.
- Advance toward the development of smart grids and new energy soul-feeding systems that allow a greater participation of renewable energies in the national energy matrix.
- Facilitate access to renewable and energy-efficient technologies by providing financing through low-interest loans.

- Increased use of renewable energies but with minimal negative social and environmental impacts.
- Develop a favorable legal and regulatory framework that encourages the participation of the national private sector in the development of efficient energy infrastructure, as well as foreign investment with a focus on technology transfer.
- Create funds to finance research and technological development activities in renewable energies and energy efficiency. In particular, allocate human, material, and financial resources to carry out a better evaluation of the potential available in offshore energy resources, such as oceanic, offshore wind, and solar resources for floating photovoltaic systems.
- Develop information systems that facilitate sustainable energy planning, including the country's marine space. Here, it is important to emphasize that energy information systems are needed with a much broader scope than those that currently exist in the country. To this end, it is necessary to include not only national statistical information but also georeferenced information on the potential of renewable energy resources and available energy infrastructure, integrating the use of geographic information systems and multi-criteria analysis tools to better support decision making.
- Formulate and implement strategies and programs to advance the development of the national renewable energy industry, particularly the wind energy industry, seeking to guarantee energy security and sovereignty, accessibility, and affordability of sustainable energy services and environmental protection.

4. Conclusions

The results obtained show that 74.2% of the area of the Gulf of Mexico, located within the administrative marine boundaries of the states of Tabasco, Campeche, and Yucatán, is not feasible for the sustainable use of wind energy due to the existence of environmental, social, and technical restrictions.

The AMB corresponding to the state of Tabasco is the one with the highest percentage of wind exclusion areas, 96.4% of its total area, mainly due to the strong presence of the hydrocarbon industry, which has almost exclusive use of the area. In addition, only 14.6% of its total area is located at depths less than 50 m, and only 6.5% of it has no environmental, social, or hydrocarbon industry restrictions on installing wind farms. The total available area in depths less than 50 m is 425 km^2, with an installable power of 2.2 GW. Additionally, the Tabasco AMB is the one with the lowest wind potential.

In contrast, in the AMBs corresponding to the states of Campeche and Yucatán, there is greater availability of areas outside the wind exclusion zones. In the Campeche AMB, 67% of the total area is at depths less than 50 m, and 68.5% of it is not a wind exclusion zone. Therefore, the area available for the sustainable use of wind energy in this AMB would be 27,135 km^2, with an installable power of 140.7 GW. Similarly, in the AMB of Yucatán, the20.2% of its total area is located at depths of less than 50 m, and 85.2% of it does not constitute an exclusion zone. The total available area is 48,334 km^2, with an installable power of 250.5 GW.

Regarding the wind resource available in the study area, the highest power density values at 150 m height are found in the marine zones of Campeche and Yucatán, with values higher than 300 W/m^2 and 400 W/m^2, respectively. At the points selected for wind farm modeling, the average values are 380 W/m^2 in Campeche and 490 W/m^2 in Yucatán. Likewise, the estimated capacity factors are 37% in the Campeche wind farm and 46% in the Yucatán wind farm; these values are comparable with the 2018 global average for offshore wind farms, which was 33%, and with the 45% achieved on average in European wind farms in the same year. The Yucatán wind farm could supply 97% of the annual consumption of the Peninsular Region, or 74% of the consumption of the entire Southeast Region of Mexico.

Regarding the levelized cost of electricity, the highest value corresponded to the Tabasco wind farm and the lowest value to the Yucatán wind farm. In the latter, the range of values was between 0.095 USD/kWh and 0.177 USD/kWh, decreasing as the contribution of the cost of wind turbines to the *CapEx* becomes lower.

Based on the availability of areas outside the wind exclusion zones, the available wind potential, and the estimated levelized costs, the best administrative marine boundary for the installation of offshore wind farms would be Yucatán, followed by Campeche. Finally, the sensitivity analysis carried out showed the need to develop the Mexican wind industry to take advantage of the wind potential available in the Gulf of Mexico.

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