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Study Concerning the Expected Dynamics of the Wind Energy Resources in the Iberian Nearshore

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Abstract: The objective of the present study is to show a comprehensive assessment of the wind resource dynamics along the Spanish coastal environment of the Iberian Peninsula. After studying the historical resources (reported at 100 m height) for the 20-year period from 1999 to 2018 by analyzing the ERA5 time series of wind speed data, the 10 locations with highest historical wind resources are considered. For these, the study of the future dynamics for the 30-year period from 2021 to 2050 under the climate change scenario RCP 4.5 is carried out. After further selection, mean and maximum values, as well as the seasonal and monthly variability of the wind power density, are obtained for six locations along the Spanish coasts. Furthermore, a performance and economic dynamics assessment is presented for four different wind turbine technologies with rated capacities ranging between 3 and 9.5 MW. A further comparison with other locations in the Baltic Sea and the Black Sea is presented to provide a critical image of the Spanish wind resources dynamics in the European framework. The results indicate a noticeable gain of wind resources in various locations of the Atlantic and Mediterranean coasts, with others presenting slight losses.

Keywords: Spanish nearshore; wind energy; future projections; coastal environment; climate change

1. Introduction

In the current global energy market, there is a clear trend promoting the instauration and development of renewable energies [1–3]. This trend is a response with a variety of motivations based on ecological, economic, and political interests. From an ecological point of view, taking into consideration that the world population and energy demand continue to increase, this trend is the result of a global response aiming to reduce the emission of polluting gases, such as CO_2, which cause the so-called climate change [4,5]. It exists an increasing level of environmental awareness, and the popular knowledge of the deterioration caused in different ecosystems by the humans generates a feeling of individual responsibility. This results on the population taking measures on a personal level with objectives such as reducing the residual waste or reducing their energy consumption. Thus, renewable energies have obtained a well-established and rapid globally growing support. Nevertheless, far from being the only motivation powering this trend, economic and political underlying interests motivate this transition, providing it with a strong substitutive character. The global energy market has historically been dependent on fossil resources, something that has led to regions rich in these to achieve great economic benefits. Historical events such as the 1973 oil crisis have shown that energy dependence on imported resources also provides these regions with great political power [6,7]. In this way, with a view to a future where the use of these resources will be increasingly limited, aiming to reduce energy dependence, as well as lower the energy production costs, there are clear objectives established by international organizations such as the European Union (EU). Institution whose strategy in terms of energy production added to objectives regarding the reduction of polluting emissions, promotes rapid development of the renewable energy industry [8,9].

Within the use of these natural resources, wind energy is currently the renewable industry that manages to produce electricity at a lower cost, with Levelized Cost of Energy (*LCOE*) values located around 0.07 EUR·kWh^{-1} [9,10]. This is due to the creation of state-of-the-art technologies in conjunction with the great scalability presented by the industry throughout decades of operation and development. At the moment, wind farms located onshore present a general trend of increase in the rotor size [11,12], as well as new multirotor approaches designs. Until now it has been possible to take advantage of the onshore wind resources with better performance achieving notable reductions in the *LCOE*, providing these projects with a great economic viability. However, the technological development of the industry opens the possibility of taking advantage of the wind resources present in the offshore areas, where numerous studies conclude that the wind speeds are steadier and stronger when compared with onshore locations. This provides these offshore areas with remarkable energetic resources [8,10,13]. In this way, thanks to the improvement in the construction materials, as well as due to the development of floating platform technologies, it is possible to meet the higher requirements that the marine environment would impose to a wind farm, as well as the creation of projects in locations further from the coast where the seafloor depth is much greater [14–16].

Taking into account that wind energy production is directly related to the wind speed, an atmospheric parameter that in turn largely depends on the climate, it is feasible to ensure that electric energy production is closely related to climatic variations [17,18]. In this way, the changes in global temperature induced by the climate change will seriously affect the distribution of this energetic resource. These variations could lead to the creation of locations of interest, also known as hot-spots, where the use of these offshore resources would be of special relevance. On the other hand, this also could lead to areas which present high historical wind resources suffering slight to medium losses in their resources as a consequence of the climate variations [19–22].

The target area of the present study is the Spanish coastal environment located along the Iberian Peninsula. A variety of studies focused on the Iberian territory conclude that the wind in this area present notable energetic resources [23,24] that makes of the peninsular territory a location to consider for the development of offshore wind projects [25]. Thus, the previous study of Onea et al. [26], presents an in-depth assessment of the historical wind resources along the Spanish continental coastal environment. It is concluded that, when considering a historical period, the development of offshore wind installations is viable and of great interest in the Spanish territory. However, despite the remarkable characteristics, as well as the economic benefits that it would bring, the Spanish offshore wind industry is still in an early stage of development. Due to this, despite the great potential that this territory presents, there is no optimal usage of this natural resource.

The present study aims to provide an in-depth representation of the dynamics of the wind energy resources along the Spanish nearshore. Furthermore, by considering the performance of a series of wind turbine technologies, the work seeks to present a direct comparison between the Spanish historical and expected near future wind energy conditions. In addition, an economic prediction of the considered wind turbine technologies performance is presented, placing these dynamics in the European energy framework. Finally, to provide a contextualized image, the results of the present study are compared with those reported in similar studies in areas along the coastal environment of the European continent.

In this context, the present work is defined by the following elements of novelty:

(a) Estimate the expected dynamics of the Spanish offshore wind resources by making a direct comparison between the historical and future expected wind conditions;

(b) Identify the performances of some large wind turbines (>8 MW) that are expected to be installed in the near future;

(c) Perform a preliminary economic analysis to see how a future wind project can fulfil the current EU recommendations.

2. Materials and Methods

2.1. Methodology

The study presents a comprehensive assessment of the wind dynamics along the continental Spanish coastal environment with the aim of identifying hot-spots where the future magnitude of the wind resources would make the installation of offshore wind farms viable. In this context, Figure 1 presents, through a flowchart, the methodology followed in the study.

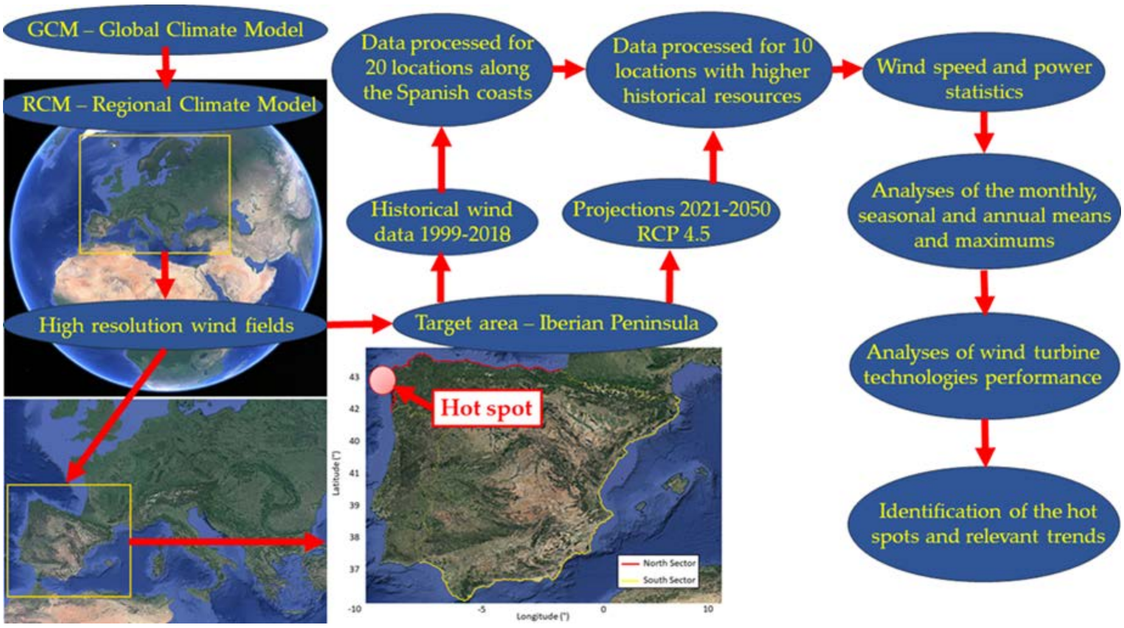

Figure 1. Flow chart of the methodology followed in the present work.

As presented, the study starts from the consideration of the high-resolution model obtained from the Global Climate Model (GCM) ERA5, a global climate reanalysis data set produced by the European Center for Medium-Range Weather Forecast (ECMWF) [27,28]. ERA stands for “ECMWF Re-Analysis” and refers to a series of research projects at the ECMWF, which produced various dataset generally considered for offshore wind assessments. By reanalyzing the time series of the wind speed data for the 20-year period from 1999 to 2018, the historical resources are studied for 20 locations along the Atlantic and Mediterranean Spanish coastal environment [29,30].

After assessing the historical resources, and taking into consideration that the main objective of this study is to present a comprehensive image of the wind resources dynamics, the 10 locations with higher historical wind resources are considered for the wind dynamics assessment for the 30-year period from 2021 to 2050 under the Representative Concentration Pathway RCP 4.5 scenario [31]. This climate change scenario is an energetic model which considers an increase in the emissions of contaminant gases until the year 2040 with a subsequent reduction that results in the Force Radiation level stabilizing in the year 2100 at a value of 4.5 W/m^2, something that would lead to an increase of 2 to 3 °C in the global temperature. The choice of considering RCP 4.5 in the present study is that, assuming that the enhancement of the CO_2 emissions will be stopped around the year 2040, RCP 4.5 can be considered the most realistic scenario in relationship with RCP 2.6 and RCP 8.5. Thus, RCP 2.6 assuming that enhancement of the CO_2 emissions will be stopped in 2020 is more optimistic, but the reality does not indicate that this target will be accomplished. On the other hand, RCP 8.5 assuming that the CO_2 emissions will continue to grow along the entire 21st century and afterwards can be considered a more pessimistic scenario implying also that humanity will not be able to counteract the effects of climate change. However, it has to be highlighted at this point that climate could change a lot and there are still many uncertainties concerning possible climate changes in near future.

In this context, by means of the reanalysis of a Regional Climate Model (RCM) under this scenario, average and extreme values for wind parameters related to the energetic capacity of the wind well as statistics regarding the variability during determined monthly and seasonal periods of time are obtained. Furthermore, considering four different wind turbine technologies, some of the most relevant performance parameters are studied for each turbine in the selected locations.

Thus, by comparing the historical and the estimated future wind resources, as well as wind turbine technologies' performances, this study presents a comprehensive comparison of the wind resources and the viability of an offshore wind project along the Spanish nearshore.

2.2. Target Area

Spain has two distinct peninsular coasts, the Atlantic coast located in the northern part of the Iberian Peninsula, and the Mediterranean coast along the southern and eastern parts of the Spanish territory. Thus, the present study considers two different sectors, the North and South, corresponding to the Atlantic and Mediterranean coasts, respectively. Along both sectors, 20 locations were initially considered, 10 in each of them.

When selecting the study locations for an offshore wind assessment, different approaches can be taken into consideration, the main being a seafloor depth-based selection. This criterion is based on the fact that, due to technical characteristics of the wind turbine foundations, until now it was of special interest to consider locations where the water depth did not exceed 50 m [16,32], something that allows the foundations to be fixed to the seabed. However, the development of foundations based on floating platform technologies allows the possibility for offshore wind turbines to operate in sites with much greater depth. However, due to the fact that one of the main characteristics of the bathymetry of the Spanish coast is the great depth of the seafloor even near to the coastline, this selection method is not very appropriate for the Spanish territory. For this reason, and taking into consideration the existence of projects announced in locations with depths greater than 200 m, the present study ruled out applying this criterion when selecting the locations of interest [33]. In this context, it was taken into consideration the relevance of the locations as considered by the national entity Puertos del Estado [29], with responsibilities related both to the port system as well as taking meteorological measurements of atmospheric parameters along the Spanish territory [30]. Due to this, 20 of the meteorological stations of geographical relevance owned by the national entity were selected as on land reference points. After this, the selected offshore study points are located five kilometers into the sea and related one to one with the 20 aforementioned meteorological stations of Puertos del Estado. This methodology provides the study with points of geographical relevance for which representative results are also available. Furthermore, such approach gives the possibility to directly compare wind offshore and onshore resource values and characteristics. Thus, Figure 2 presents the 10 offshore locations selected for each sector, being denoted as ON1 to ON10 for the points located in the North Sector, and OS1 to OS1o for the reference points located in the South Sector.

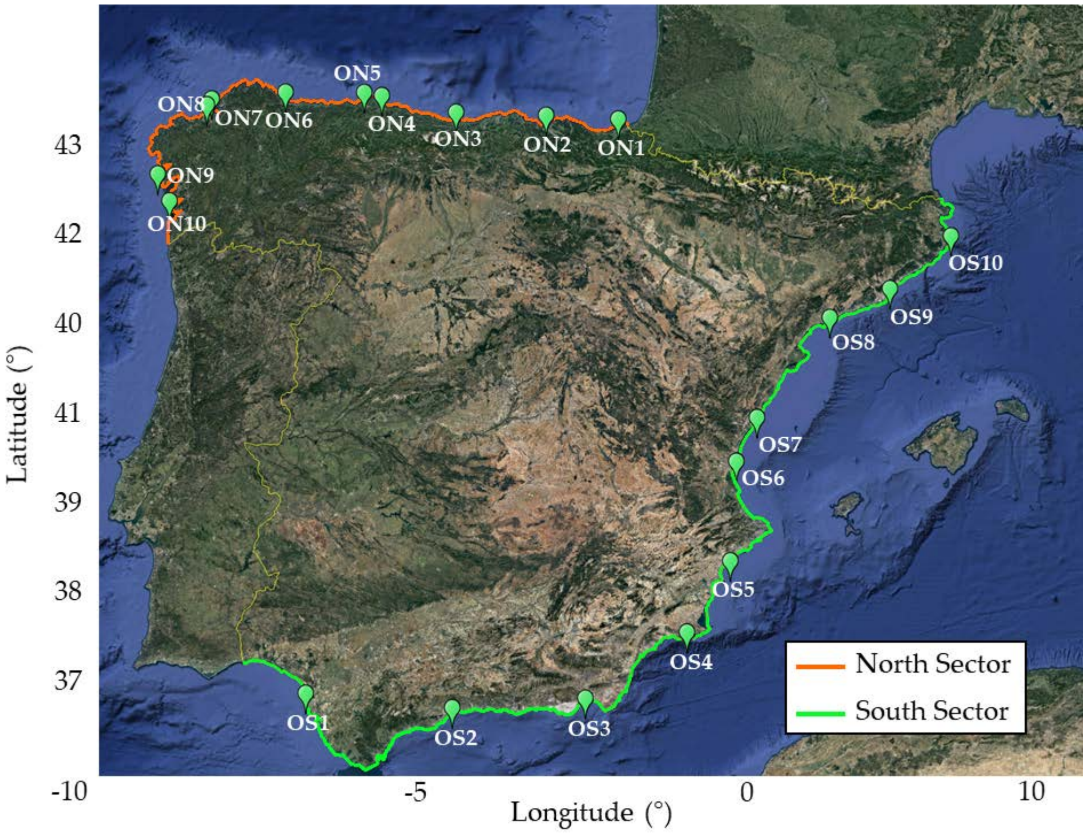

Figure 2. Map of the Iberian Peninsula and the reference locations considered [26].

This terminology corresponds with Offshore North and Offshore South for the locations of the North Sector (ON1 to ON10) and South Sector (OS1 to OS10), respectively. After analyzing the historical resources of the 20 points, a further selection was made to analyze the future estimations under the climate change model. Thus, Table 1 presents the main characteristics of five locations of each sector that present the highest historical wind resources out of the 20 locations considered initially. It is relevant to highlight the fact that some of the locations such as ON3 or OS10 present seafloor depths of 102.5 and 169.9 m, respectively [34]. Taking into account that, when considering offshore wind farm locations, both are relatively proximate to the shore, these great values highlight the aforementioned bathymetric characteristics, supporting the methodology considered for the selection of the reference points.

Table 1. Main characteristics of the locations considered [26].

Sector	Point	Longitude (°)	Latitude (°)	Water Depth (m)	Distance from the Coast (Km)
N	ON6	−7.21	43.61	74.95	5
N	ON7	−8.38	43.49	50.2	5
N	ON8	−8.45	43.42	64.75	5
N	ON9	−9.14	42.59	52.25	5
N	ON10	−8.92	42.29	64	5
S	OS1	−6.48	36.78	11.6	5
S	OS3	−2.48	36.79	77.31	5
S	OS4	−1.01	37.53	87.1	5
S	OS5	−0.36	38.33	58.4	5
S	OS9	2.24	41.36	60.45	5
S	OS10	3.28	41.93	169.6	5

2.3. Wind Datasets

The study presents a comparison of the wind speed historical values against estimates of future values under a climate change scenario. The historical values of the wind speed are obtained from the historical time series of wind speed data ERA5 [27], a dataset provided by the European Center for Medium-Range Weather Forecast (ECMFW) [35]. The ERA5 dataset is a well-known time series of data considered in many offshore wind studies [10,25,36,37]. Data are available for the period from 1950 to 5 days before the time of consultation. For the present study, the authors considered a 20-year period going from 1999 to 2018 of wind speed values reported at 10 m above sea level with a spatial resolution of $0.25° \times 0.25°$ equivalent to approximately 31 square kilometers. The time resolution considered is six hours. Thus, in the present study four values per day are processed and analyzed associated with the hours 00:00–06:00–12:00–18:00 UTC (Coordinated Universal Time) [38].

Beyond the reanalysis of the historical time series of wind speed data, it is of special relevance to consider how climate change will affect different characteristic wind parameters of interest as this could lead to the appearance of new and different hotspots where the installation of an offshore wind farm would be more viable [39].

To consider the different scenarios that could take place in the near future, there are a number of different climate change models; these are energetic models that analyze how the variation in global temperature produced by emissions of contaminant greenhouse gases such as carbon dioxide could affect different atmospheric parameters [40]. The scenario considered for the study is one of the so-called Representative Concentration Pathways (RCP). These scenarios assess the different climatic futures that would occur depending on the volume of greenhouse gases that will continue to be emitted during the next years. There are four main RCP scenarios, RCP 4.5 being the one considered herewith [31]. This is a scenario that estimates that the amount of emissions will continue to increase until the year 2040 with a subsequent decrease that would lead to the Radiation Forcing Level to stabilize at a value of $4.5\ \mathrm{W{\cdot}m^{-2}}$ in the year 2100.

The present study considers the wind speed values for the 30-year period comprehending the years from 2021 to 2050 and the same time resolution as the ERA5 dataset (four values per day corresponding with the hours 00:00–06:00–12:00–18:00 UTC).

2.4. The Wind Turbine Technologies Considered

Aiming to establish the current viability of the offshore wind industry along the Spanish peninsular nearshore, the present study evaluates not only the characteristic energetic parameters of the wind, but also assesses the performance that an offshore project would present if it is installed in the selected locations. Furthermore, by looking at the offshore wind market we can notice that there are two categories of projects: (a) operational—turbine capacity <5 MW; (b) under construction/proposed—turbine capacity >8 MW. Since the present work involves the use of historical and near future estimated wind data, considering a wider range of turbines will be possible to provide a more complete picture of the solutions that can be considered for implementation for the Spanish nearshore areas.

For this reason, four different wind turbine technologies are considered to evaluate their relevant performance parameters that they would present in the locations considered along the Spanish coast. Thus, obtaining a broader picture of the viability of the offshore industry, this at the moment is in its initial development phase in the country. The main operational characteristics of the four wind turbine technologies considered are presented in Table 2. It is relevant to note that, to obtain representative results regarding the current viability, each of the selected wind turbine technologies are currently installed in other locations. In this way, the results do not depend on the evolution of technologies that would otherwise be still under development [41–44].

Table 2. Technical specifications of the technologies considered [26].

Turbine	Rated Power (MW)	Cut-in Speed ($m{\cdot}s^{-1}$)	Rated Speed ($m{\cdot}s^{-1}$)	Cut-Out Speed ($m{\cdot}s^{-1}$)	Hub Height (m)	Reference
V90-3.0 MW	3	4	15	25	100	[41]
M5000-116	5	4	12.5	25	100	[42]
V164-8.8 MW	8.8	4	13	25	100	[43]
V164-9.5 MW	9.5	3.5	14	25	100	[44]

With rated capacity values going from 3 MW for the lowest rated turbine, the Vestas V90-3.0 to 9.5 MW for the Vestas V164-9.5 MW, such wider range of capacity provides a better insight of the wind resources along the Spanish peninsular nearshore. Figure 3 represents the characteristic power curve for each of the four wind turbine technologies. Some differences can be noticed in the operational characteristic parameters, the cut-out speed value is the only parameter that all four wind turbines share, while the cut-in speed value is the same for three out of the four wind turbines. The power curves present different shapes and when analyzed together with the wind resources provide different performances for each one.

For the present study, it was considered adequate to establish a mean operational hub height of 100 m above sea level for all the technologies, since all of them can be adapted to be installed at that height [13,45,46].

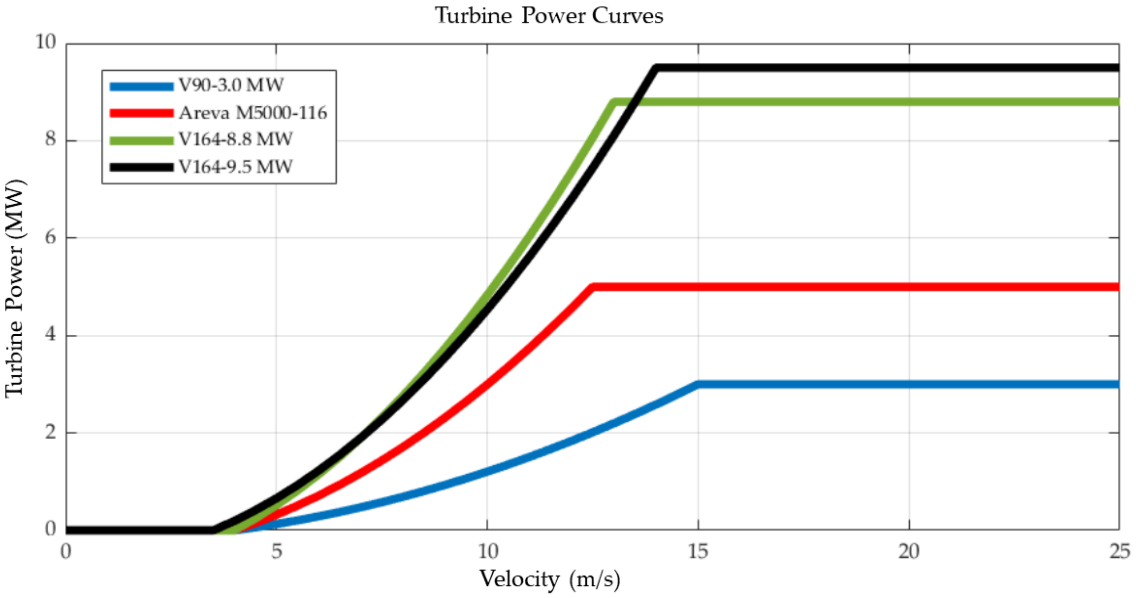

Figure 3. Power curves of the selected wind turbines [26].

2.5. Methods

To determine the energy resources of the wind in each of the selected locations, a series of characteristic wind energetic parameters are evaluated due to the aforementioned fact that the considered datasets provide wind speed data reported at 10 m above sea level. The first step to evaluate any parameter is to interpolate the time series of wind speed values to the operational height of 100 m above the sea level. Thus, the logarithmic law is applied following the Equation (1) [47]:

$$U_z = U_{z\,ref}\frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)} \quad (1)$$

In this equation, the U_z parameter corresponds to the wind speed value at the operational height z, having z in the present study an aforementioned value of 100 m above sea level. The U_{zref} parameter is the wind speed value reported by the considered dataset, being the reference height z_{ref} equal to 10 m above sea level for both ERA5 and RCP 4.5 time series of wind data. Lastly, the parameter z_0 represent the surface roughness length, for which in the present study the authors consider an average value of 0.0002 m [45].

After applying the logarithmic law to the wind speed values, it is possible to start obtaining some energetic parameters of special relevance that provide representative information about the wind resources in each of the locations selected along the Spanish Iberian nearshore.

The first parameter to consider is the Wind Power Density (P_{wind} in W·m^{-2}). The value of this parameter provides an insight into the energetic capacity of the wind. In the present study, this parameter was obtained with the Equation (2) [10,13,48,49]:

$$P_{wind} = \frac{1}{2}\rho_{air}(U_z)^3 \tag{2}$$

where ρ_{air} is the air density, with a considered average value of 1.225 kg·m^{-3} and U_z is again the wind speed at the operational hub height (100 m above sea level in this case) [13]. Being the analysis of wind resources under the climate change scenario RCP 4.5 the central body of the present study, it is important to highlight the relevance of this parameter. Since this parameter is directly related to the cube of wind speed, the variations in the energy potential of the wind are more notable than when considering the wind speed values directly. Thus, the study of this parameter provides a clearer insight of the wind speed resources dynamics.

To provide an in-depth wind speed resources assessment, and taking into consideration that one of the main characteristics of the wind as an energy resource is its irregular nature, it is of special relevance to consider how these resources vary throughout specific periods. Therefore, the present work studies the variability of the P_{wind} for monthly and seasonal periods [13].

To continue with the study and to be able to obtain further wind energetic parameters, it is necessary to adjust the wind speed values to a probability distribution. In this way, statistical methods can be applied, and further information can be obtained. For both datasets, the two-parameter Weibull distribution was considered to define the wind speed values at operational height (U_{100}). This probability distribution is considered to representatively define the wind speed for both onshore and offshore locations, so the authors consider its use to be adequate in this context, its defined by Equation (3) [50]:

$$f(U) = \frac{k}{c}\left(\frac{k}{v}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{3}$$

where k and c are the two parameters which values dictate the shape and scale of the wind speed probability distribution, respectively. The k parameter is dimensionless and provides information on the variability of the wind speed, being this function of the width of the distribution. The c parameter, measured in m·s^{-1}, always presents a null or positive value and is representative of the magnitude of the wind speed values in the determined location [13,51,52].

By varying the values of these two parameters, it is possible to create different probability distributions that adjust correctly to the wind speed values in each of the selected locations. Thus, the statistical study of these distributions provides representative information, being possible to obtain further energetic parameters.

Once the wind speed at operational height (100 m above sea level) has been adjusted to its probability distribution for each location, it is possible to give way to the study of the characteristic performance parameters of the considered wind turbine technologies. The first parameter obtained is the annual Operating Time percentage, which is a dimensionless rate expressed as a percentage. Its value dictates the amount of time that a wind turbine is in operational state at the considered location throughout a year, and it is the result of comparing the number of measures taken which value is comprehended between the *cut-in* and *cut-out* characteristic operational parameters of each wind turbine with the total number of values taken during that period of one year t, equivalent to the Equation (4) [45]:

$$Operating\ Time = \frac{\sum_t Number\ of\ operational\ values}{\sum_t Number\ of\ values} \tag{4}$$

In the present study, given that the wind turbine technologies Vestas V90-3.0, Areva M5000-116 and Vestas V164-8.8 present the same operational *cut-in* and *cut-out* values, 4 and 25 $\text{m}\cdot\text{s}^{-1}$, respectively, it is to be expected for these technologies to present the same values for this parameter.

The next parameter that provides an insight on the performance of the four considered wind turbine technologies is the Annual Electricity Production parameter (*AEP* in MWh). It measures the amount of electricity that a certain turbine produces during a defined period of one year in a determined location. For the present study, this parameter is obtained using the Equation (5) [45,50]:

$$AEP = T \times \int_{cut-in}^{cut-out} [\, f(U)P(U) \,]\, dU \tag{5}$$

where T is the annual operational time of the turbine, for the present study and aiming to provide direct representative comparisons of the *AEP* value for each of the considered wind turbine technologies, the authors considered a mean value of 8760 h/year for all four technologies [13]. The P function of the wind speed U is the expression of the characteristic power curve for each of the wind turbine technologies considered [53,54]. The f function of the wind speed U is the two parameter Weibull probability distribution that fits the wind speed in each location. Lastly, the *cut-in* and *cut-out* integration limits correspond to the operational characteristics of each turbine. The *cut-in* value is the wind speed at which the wind turbine comes into operation, the turbine operates normally until the wind goes again under the *cut-in* value, or in other case goes above the *cut-out* value. This is a limit above which a brake system is activated in the turbine in order for it to avoid any possible mechanical damage or deterioration that may lead to its failure [55,56].

Finally and aiming to show representative results on the economic viability of an offshore project in the current European and Spanish energy framework, a study of the Levelized Cost of Energy parameter is carried out for each of the four wind turbine technologies in the selected locations [57,58]. This economic parameter, measured in $\text{EUR}\cdot\text{kWh}^{-1}$, shows the production cost of the electric energy generated by a wind turbine in a specific location for period of one year. To do so, it considers both the Capital Expenditure ($CAPEX_t$) and the Operational Expenditure ($OPEX_t$) during the period of time t equivalent to one year. There are different approaches when obtaining the *LCOE*, in the present study the authors considered the Equation (6) [59,60]:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{\mu} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}} \tag{6}$$

where $CAPEX_t$ and $OPEX_t$ are the aforementioned expenditures during the one-year period t and AEP_t is the Annual Electricity Production parameter of the considered turbine in the determined location for that year. The remaining parameters r and μ are the discount rate and the life expectancy of the considered wind turbine.

This parameter is essential when aiming to determine the viability and rentability of any renewable energy installation project within the actual energetic framework. The current energetic market is characterized by a high volatility of the prices, the fossil fuel value continues to increase, and this opens up a world of possibilities for the so-called green energies [1,2]. Thus, when evaluating the viability of an offshore energy project, two main factors must be taken into account. The first one being the reduction of *LCOE* that this industry continues to present in a stable and steady manner thanks to the development of its technology. The second one is the reduction of contaminant emissions to the atmosphere that would not take place if the considered project is installed and operational [61].

3. Results

This section presents the results obtained from the analysis of the two aforementioned time series of wind speed data. To present a clear and representative image of the wind resources dynamics, the results are presented as direct comparisons. These show the existing variations for the values obtained for the historical period of 20 years (1999–2018) from the ERA5 dataset and those obtained for the future estimations of the 30 year period (2021–2050) under the RCP 4.5 climate change scenario.

The analysis of the historical wind resources made for the 20 initial locations along the Spanish nearshore, presented as a complete assessment in Onea et al. [26], leads to a further selection of the study points. Thus, the five locations that present higher historical wind resources are initially considered for the assessment of the future resources under the climate change scenario. To do so, and with the aim of reducing the inter annual variability that the annual mean presents for the P_{wind} parameter, a five-year running mean filter is applied. Once the filter is applied, the analysis of the evolution of the parameter for the historical and future periods considered leads to a subsequent selection of three out of the five locations with highest historical wind resources along each sector.

Hence these points are ON6, ON7 and ON10 for the North Sector and OS1, OS4 and OS10 in the case of the South Sector. That way, the six selected locations along the Spanish coastal environment are those that present not only the best historical resources, but also future estimations concordant to both the historical values and the wind resources dynamics results presented in other studies [23,39,62].

Presenting now the results for the selected study locations, Figure 4 illustrates the time evolution of the annual P_{wind} mean after the five-year running mean filter has been applied for the North Sector locations. It can be noticed that the locations ON6 and ON7 present a slight downward trend during the 20-year historical period, something that continues to happen but in a less notable way during the 30-year future period under the climate change scenario. This translates, when comparing the historical and future average, on a decrease of 8.62 and 26.75 W·m^{-2}, respectively, in these two locations of the Spanish Atlantic coast. However, the location ON10 with steady trends for both the historical and future periods, presents a clear increase of the P_{wind} average values for the future period under climate change scenario.

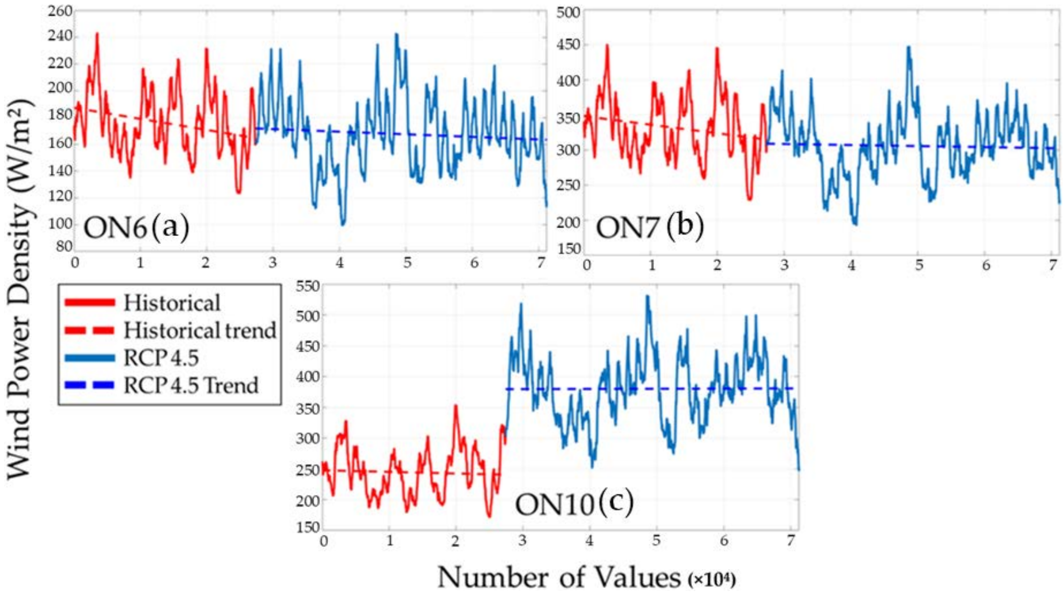

Figure 4. Annual mean time series after applying the five-year running mean filter in the selected North Sector locations, computed for the historical period considered (1999–2018 from ERA5) and the future projections (2021–2050 under RCP 4.5 climate change scenario) for the North Sector locations, where: (**a**) ON6; (**b**) ON7; (**c**) ON10.

This gain of wind resources is concordant with the results presented in Bernardino and Soares [23], where P_{wind} average values in the north region of the Portuguese coast (Agucadora, −8.79 E 41.43 N) are obtained for the 30 year period going from 2040 to 2069 under the same RCP 4.5 climate change scenario considered in the present study. With values of about 450 W·m^{-2} for an operational height of 80 m and being the ON10 point located at a distance shorter than 100 km, the results are concordant with the 380 W·m^{-2}. future average value obtained in the present study. Considering how the ON10 location presents a noticeable increase of over 50 W·m^{-2} in the average values when comparing the values from 1999 to 2018 with the ones from 2021 to 2050, it is feasible to think that this increasing trend could continue to take place during the following years. Something backed by the aforementioned values for the 2040 to 2069 future period along the nearby Portuguese nearshore.

The same results for the South Sector locations are represented in Figure 5. Similarly to the North Sector locations ON6 and ON7, the point of the Spanish Mediterranean coast OS10 presents a slight downward trend for both periods considered, being it more noticeable during the 20-year historical period, with a difference of 31.75 W·m^{-2} between the historical and future average values. However, the OS1 and OS4 South Sector locations show a clear upward trend, being much more noticeable in the second one.

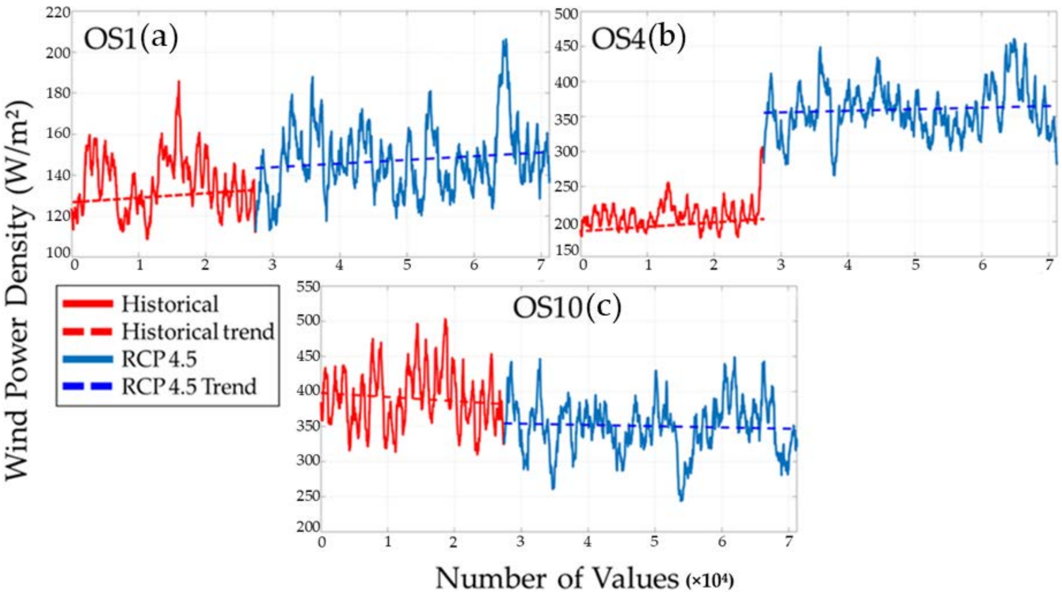

Figure 5. Annual mean time series after applying the five-year running mean filter in the selected South Sector locations, computed for the historical period considered (1999–2018 from ERA5) and the future projections (2021–2050 under RCP 4.5 climate change scenario) for the North Sector locations, where: (**a**) OS1; (**b**) OS4; (**c**) OS10.

Generally, the results present a certain inter annual variability even after the five-year running mean filter has been applied. However, this is not characteristically greater during the future period under the climate change scenario.

Table 3 presents a direct comparison of the main characteristics of the P_{wind} parameter for the selected locations along the Spanish nearshore for the considered historical (20 years 1999–2018, ERA5) and future (30 years 2021–2050, RCP 4.5) periods. It is relevant to highlight the fact that, when comparing the historical and future maximum values, the locations ON10, OS1 and OS4, with differences of 5880, 4430 and 5380 W·m^{-2}, respectively, present a considerable increase. While the remaining points (ON6, ON7 and OS10) do not present any relevant variation in terms of the maximum value. This way, considering the increase in the means during the future period, and the greater future maximum values, the ON10, OS1 and OS4 locations presented positive wind resources dynamics so far.

Table 3. Wind power density (in W·m^{-2}) characteristics at 100 m for the locations considered, computed for the historical period (1999–2018 from ERA5) and the future projections (2021–2050 under RCP 4.5 climate change scenario).

Point	**ON6**		**ON7**		**ON10**		**OS1**		**OS4**		**OS10**	
Period	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**
Mean	176.42	167.80	332.58	305.83	244.17	379.92	136.14	147.58	209.75	360.83	383.00	351.25
Maximum	6820	5530	10,900	10,300	7520	13,400	6170	10,600	5420	10,800	9530	8480
25th	18.40	15.50	41.40	31.30	25.60	32.60	19.40	17.50	23.00	55.30	26.60	24.20
50th	74.30	57.60	165.00	126.00	104.00	154.00	66.40	59.50	86.80	182.00	117.00	113.00
75th	233	186	456	385	316	468	172	169	255	459	440	446
95th	694	768	1238	1272	971	1560	517	627	857	1370	1840	1530

However, when considering the 95th percentile values with a historical value of 694 W·m^{-2}, the location ON6 presents a greater future value of 768 W·m^{-2}. While the ON7 site 95th percentile stays in a steady 1230 W·m^{-2}, this makes it feasible to think that even with a slight descent in the average value, these locations could still present good wind resources during the oncoming years under the climate change scenario.

Compared to the future wind data, the historical ERA5 dataset indicates in general higher values, excepting the points ON10 and OS4. The relative variations of the mean value start from 4.89% (ON6 point) and reaches a maximum of 55.6% (ON10), compared to 50th indicator where the differences can go up to 110% (OS4). For the 95 percentile, only the site OS10 indicates higher values for the historical data (16.8%), while the remaining points from Table 3 indicate values in the range 10.7% (ON6)–60.7% (ON10).

To determine this, and further assess the dynamics of the wind resources, and taking into consideration that variability is one of the main characteristics of the wind, seasonal and monthly periods are considered within the 20-year historical and 30-year future periods. This way, by obtaining seasonal and monthly characteristic values of the P_{wind} parameter, a more in-depth image of the wind resources dynamics can be presented.

Starting with the seasonal values, Figure 6 presents a comparison between the historical and future P_{wind} seasonal means. As it could be expected, the northern hemisphere seasonal cycle is quite notable in all locations. It is characterized by lower values during the summer season that increase during the autumn reaching the greater averages in the winter months.

In the North Sector, the locations ON6 and ON7 present a general decrease of the seasonal means, this is to be expected as both locations present the less favorable mean value and trend under the climate change scenario. However, during the winter season the point ON6 shows a noticeable increase, this is somewhat relevant due to the fact that the area presents characteristically high resources during the winter months [63]. Something that could lead to the area being an interesting location.

Generally, when making a direct comparison, the study of the results obtained from the seasonal analysis does not show a noticeable difference in the seasonal variability. However, when considering monthly periods, a slight wind resource transfer can be noticed. With the early winter months presenting slightly lower values under the climate change scenario, that reach maximum averages during the final months of the winter and lead to a slight resource gain in the first month of the spring, occurrence clearly represented in Figure 7. Being the South Sector location, OS10 is the only location that, in a different manner, presents P_{wind} average loss during the spring and summer months while presenting lower values during the autumn and winter months. Given the characteristic local wind patterns of the area where OS10 is located, this is somewhat to be expected [63].

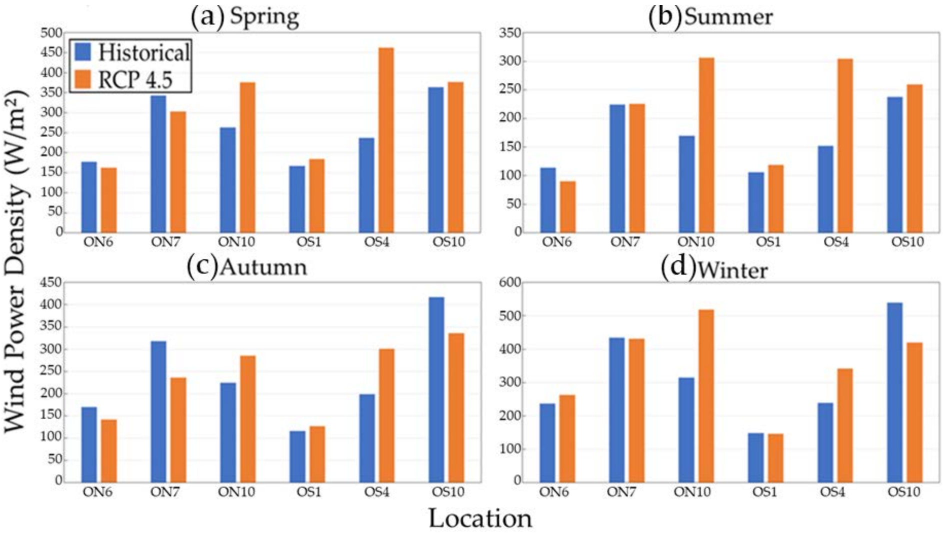

Figure 6. Wind power density seasonal variability in the reference locations selected at the hub height of 100 m computed for the historical period (1999–2018 from ERA5) and the future projections (2021–2050 under RCP 4.5 climate change scenario) where: (**a**) Spring; (**b**) Summer; (**c**) Autumn; (**d**) Winter.

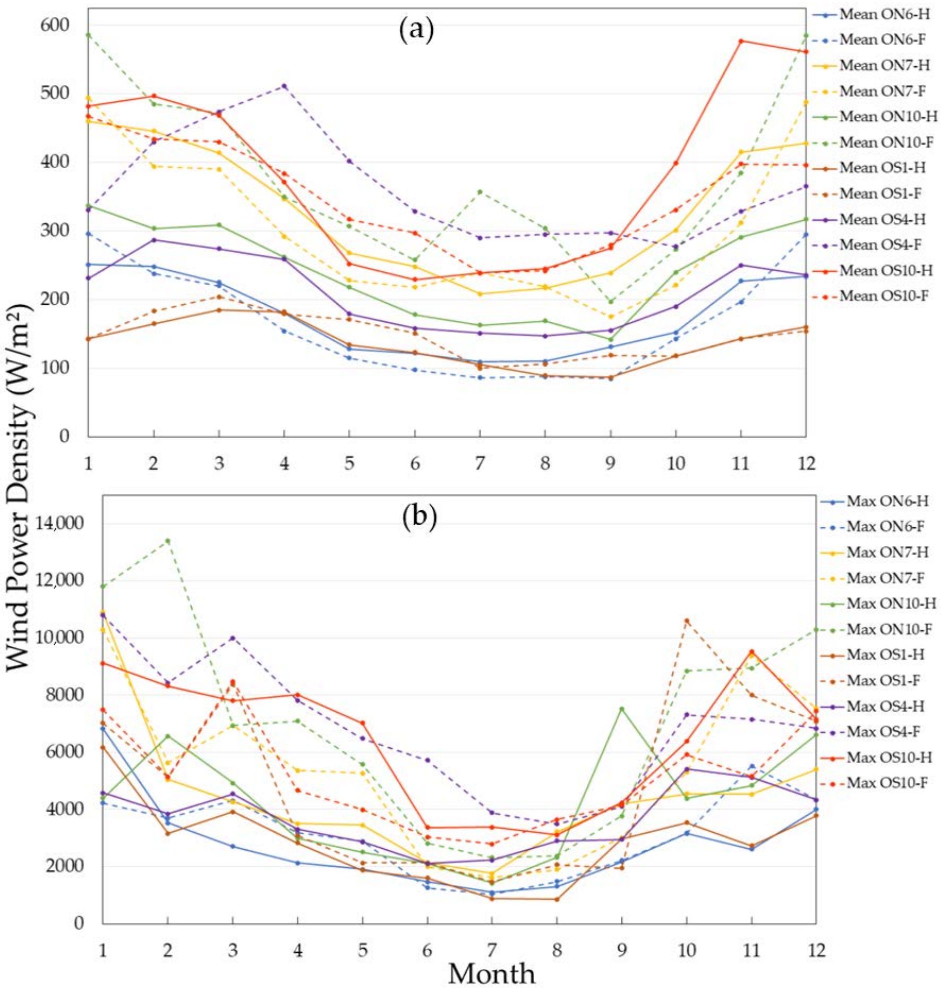

Figure 7. Wind power density monthly means and maximum values in the locations selected at the hub height of 100 m, computed for the historical period (1999–2018 from ERA5) and the future projections (2021–2050 under RCP 4.5 climate change scenario) where: (**a**) North Sector; (**b**) South Sector.

After presenting the results regarding the characteristic energetic parameters of the wind, the study follows with the assessment of the performance and operational dynamics of the four considered wind turbines technologies. In this way, Table 4 presents the annual *Operating Time* percentage mean values of each of the wind turbine technologies in each of the selected locations along the Spanish nearshore environment. The results are presented for both the 20-year historical period (1999–2018, ERA5) and the 30-year future period (2021–2050, RCP 4.5) under the considered climate change scenario.

Table 4. Annual operating time percentage (%) of the wind turbine technologies considered in the selected locations for the historical period (1999–2018 from ERA5) and the future projections (2021–2050 under RCP 4.5 climate change scenario).

Point	**ON6**		**ON7**		**ON10**		**OS1**		**OS4**		**OS10**	
Period	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**
V90-3.0	62.40	58.81	75.77	71.62	68.22	72.68	61.87	59.35	66.47	79.98	69.46	68.10
M5000-116	62.40	58.81	75.77	71.62	68.22	72.68	61.87	59.35	66.47	79.98	69.46	68.10
V164-8.8	62.40	58.81	75.77	71.62	68.22	72.68	61.87	59.35	66.47	79.98	69.46	68.10
V164-9.5	69.54	66.87	81.05	77.43	74.58	77.71	69.68	67.58	73.04	84.53	75.16	73.94

These values, as result of the amount of measures in which the wind speed value is comprehended in the operating wind speed range of each turbine, are a direct representation of the percentage of the turbine operating time. This provides a representative information of the performance and efficiency of the wind turbine in the considered location.

These results are represented in Figure 8. Considering that the *cut-in* and *cut-out* (4 to 25 m·s^{-1}) operational parameters are the same for the wind turbine technologies V90-3.0, M5000-116 and V164-8.8, the annual *Operating Time* percentage parameter is represented by joint form. This is so, to show a concise comparison with the values obtained for the V164-9.5 wind turbine. Technology that, due to its wider operational range (3.5 to 25 m·s^{-1}) presents higher percentages that the three aforementioned turbines. This is something that translates into better efficiency. Thus, since the installation of any model of wind turbine in an offshore environment entails a considerable economic investment, the difference in the value of this parameter could be a determinant factor when considering different wind turbine technologies for the development of an offshore wind farm project [26].

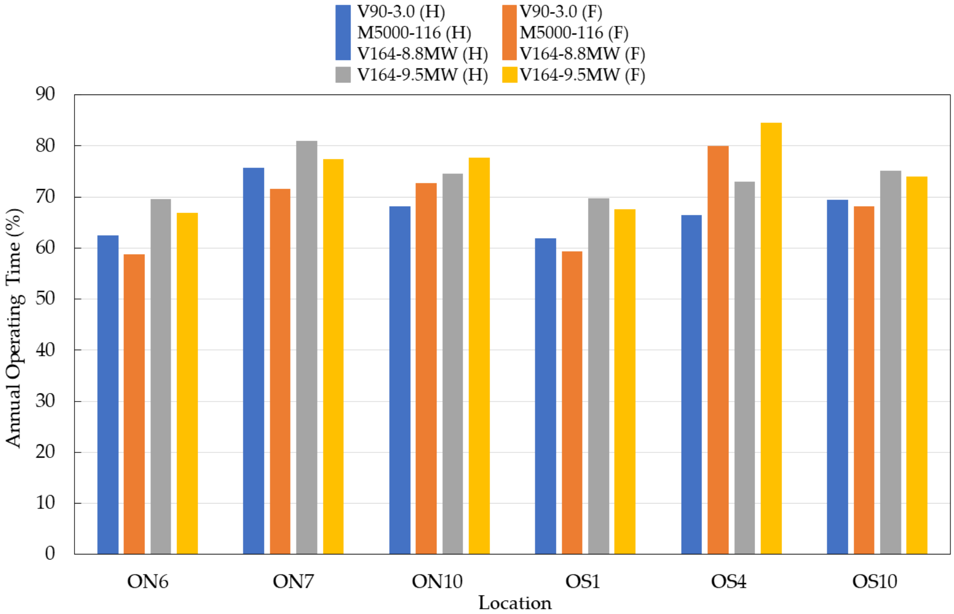

Figure 8. Percentage of mean annual operating time in the locations selected for the historical data (ERA5) and future projections (RCP 4.5) for the four wind turbine technologies considered.

Focusing now on the dynamics of the performance parameters, there is a slight general decrease of the mean annual *Operating Time* percentage. With the North Sector locations presenting better values, even though the point ON7 suffers the greatest percentual loss. With a 4.15% and 3.17% decrease for the three-turbine group (V90-3.0, M5000-116 and V164-8.8) and the V164-9.5 turbine, for this location, respectively. However, the locations ON10 and OS4 show a clear gain of percentage for the *Operating Time*.

These variations in the performance dynamics lead to occurrences such as, the North Sector location ON7, that with 81.01% used to present the highest annual *Operating Time* percentage for the historical period. This would, due to its 3.61% decrease, be surpassed by the South Sector location OS4 when considering the V164-9.5 wind turbine. This way, OS4, with a future percentage mean of 84.53% presents the highest values for the future 30-year period under the RCP 4.5 scenario.

After the study of the annual *Operating Time* percentage of each wind turbine technology, the next relevant parameter studied is the *Annual Electricity Production* (*AEP*). Table 5 presents the results obtained for the four considered wind turbine technologies studied in each of the selected locations. It is to be expected that the higher rated wind turbines produce a greater amount of electricity, but the differences between the mean historical and future values show in a representative manner the evolution of the wind turbine performance dynamics. Thus, comparing the historical and future *AEP* values provide a relevant insight of the wind energy resources along the Spanish nearshore.

Table 5. Annual electricity production (in MWh) of the wind turbine technologies considered in the selected locations for the historical period (1999–2018 from ERA5) and the future projections (2021–2050 under RCP 4.5 climate change scenario).

Point	**ON6**		**ON7**		**ON10**		**OS1**		**OS4**		**OS10**	
Period	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**	**Hist.**	**Fut.**
V90-3.0	2948	2708	5283	4768	3963	5605	2276	2410	3405	5611	5446	5210
M5000-116	7274	6620	12545	11,180	9495	12,843	5651	5961	8273	13,153	12,160	11,930
V164-8.8	11,788	10,766	20,535	18,343	15,525	21,213	9116	9655	13,465	21,593	20,175	19,713
V164-9.5	11,743	10,821	20,150	18,177	15,375	20,993	9312	9759	13,430	21,303	20,215	19,560

In general, the *AEP* mean values are somewhat lower for the future period under the RCP 4.5 climate change scenario, with the North Sector locations ON6 and ON7 presenting the most notable mean *AEP* loss. This also occurs, but in a less notable way, in the South Sector location OS10, where the decrease of the mean *AEP* value ranges between 230 and 655 MWh for the M5000-116 and V164-9.5 wind turbines, respectively.

Figure 9 represents the mean historical and future *AEP* values. It is relevant to highlight the fact that the locations ON10 and OS4 show a noticeable positive difference between the historical and future *AEP* mean values, something concordant with the improving wind energetic characteristic dynamics that have been presented in the study so far. Thus, for the location ON10 the relative enhancements expected for the future are 41.4% for V90-3.0, 35.3% for M5000-116, 36,6% for V164-8.8 and 36.5% for V164-9.5, while for OS4 the relative enhancements expected for the future are 64.8% for V90-3.0, 59% for M5000-116, 60,4% for V164-8.8 and 58.6% for V164-9.5.

This way, once the results of the wind turbine technologies performance parameters dynamics have been presented, and with the aforementioned objective of analyzing the economic viability of an offshore project in the European energy framework, it is relevant to consider the *Levelized Cost of Energy* (*LCOE*) economic parameter [13].

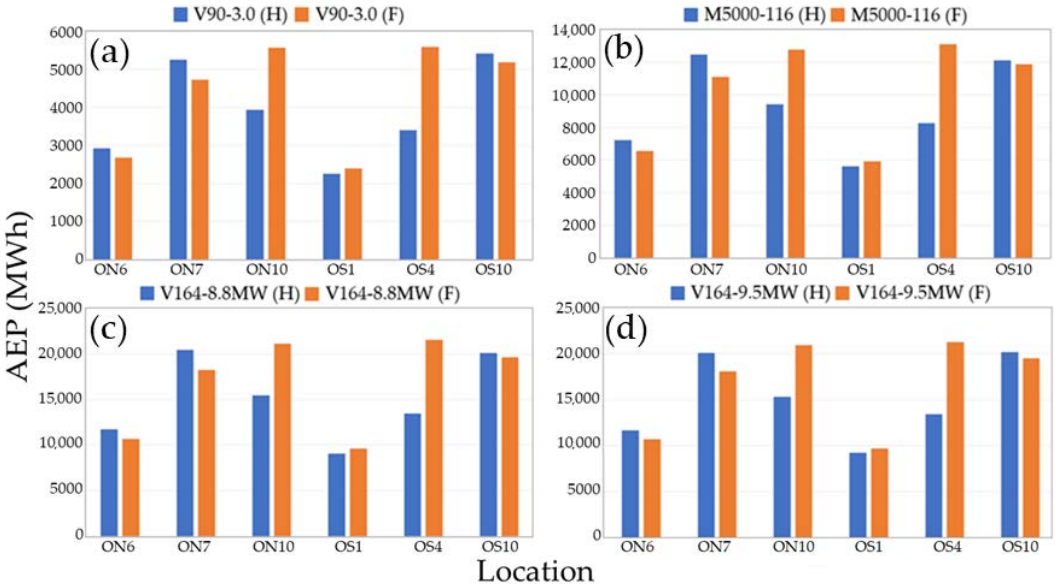

Figure 9. Mean annual electricity production in the locations selected for the historical data (ERA5) and future projections (RCP 4.5) for the four considered wind turbine technologies where: (**a**) V90-3.0; (**b**) M5000-116; (**c**) V164-8.8; (**d**) V164-9.5.

To do so, Figure 10 represents the results obtained by studying the *LCOE* of the four considered wind turbine technologies in the selected locations along the Spanish coastal environment. The figure shows both the historical and future mean *LCOE* values as well as the target values established by the European Union for the offshore wind energy *LCOE* for the years 2025 (0.0962 EUR·kWh^{-1}) and 2030 (0.07 EUR·kWh^{-1}) [64].

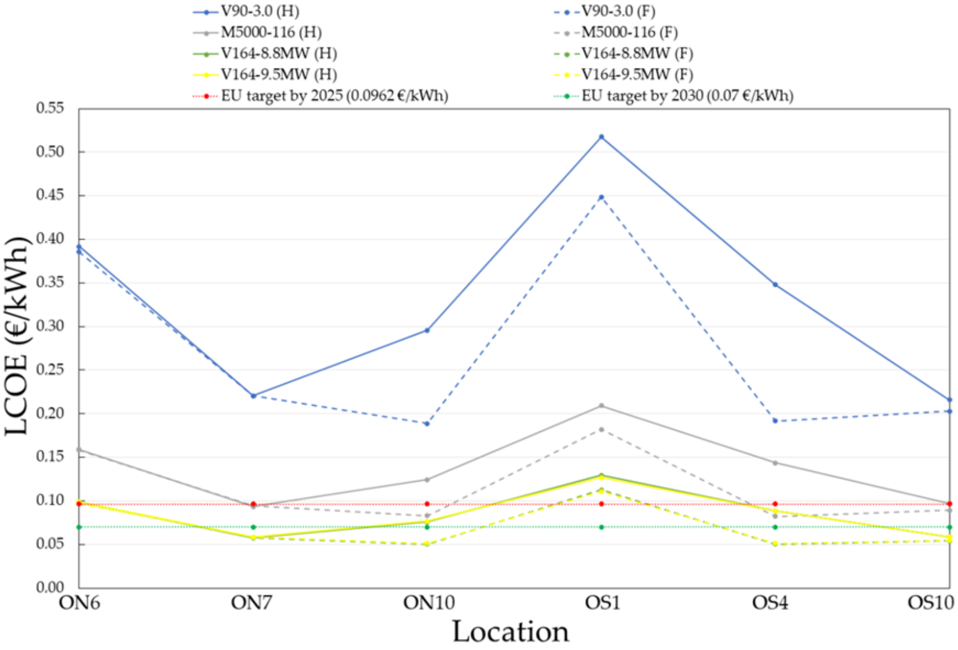

Figure 10. Levelized cost of energy in the locations selected for the historical data (ERA5) and future projections (RCP 4.5) for the four wind turbine technologies considered.

A general reduction in the *LCOE* values can be noticed when comparing the historical and future means. This occurrence provides some locations, where historically only certain wind turbine technologies were able to achieve *LCOE* values below the stablished objective, the possibility of considering other viable technologies. This is because these would present, in the near future, thanks to the aforementioned *LCOE* decrease under the climate change scenario, values below the European Union offshore wind *LCOE* targets.

The North Sector location ON10 is a clear example of this, from a historical perspective, for the 20-year period going from 1999 to 2018, only the V164-8.8 and V164-9.5 wind turbines were able to achieve *LCOE* values under the 0.0962 EUR·kWh^{-1} target established by the European Union for the year 2025, with values of 0.0752 EUR·kWh^{-1} and 0.0761 EUR·kWh^{-1} respectively. However, during the incoming 30-year period comprehending the years between 2021 and 2050 under the RCP 4.5 climate change scenario, both wind turbines would present a notable reduction of their *LCOE*. With future values of 0.0655 and 0.0664 EUR·kWh^{-1}, respectively, both of them would manage to generate electricity below the 2030 European Union target value of 0.07 EUR·kWh^{-1}. In addition, the wind turbine M5000-116—which, with a historical *LCOE* mean value of 0.1224 EUR·kWh^{-1} did not meet any of the European Union objectives—would be able to achieve a *LCOE* below the European Union target for 2025 with a cost of 0.0831 EUR·kWh^{-1} in the near future.

In the work Rusu et al. [10], the wind resources dynamics corresponding to locations in the Black Sea and Baltic Sea among other European coastal environments are assessed. A comparison of the results between the 30-year historical period from 1976 to 2005 and those obtained when considering the same 30-year future period from 2021 to 2050 under the RCP 4.5 climate change scenario. Thus, taking into account the relevance of the differences that might exist in the wind resources dynamics along different European nearshore areas, the results of the present study along the Spanish coasts are compared with the ones presented in the aforementioned study [10]. To do so, six locations where various studies assessing the offshore wind resources agree to conclude the fact that the wind presents great energetic resources, are selected.

In Figure 11, the location of the six European sites selected for comparison is represented together with the North and South Sector points of the Iberian Peninsula.

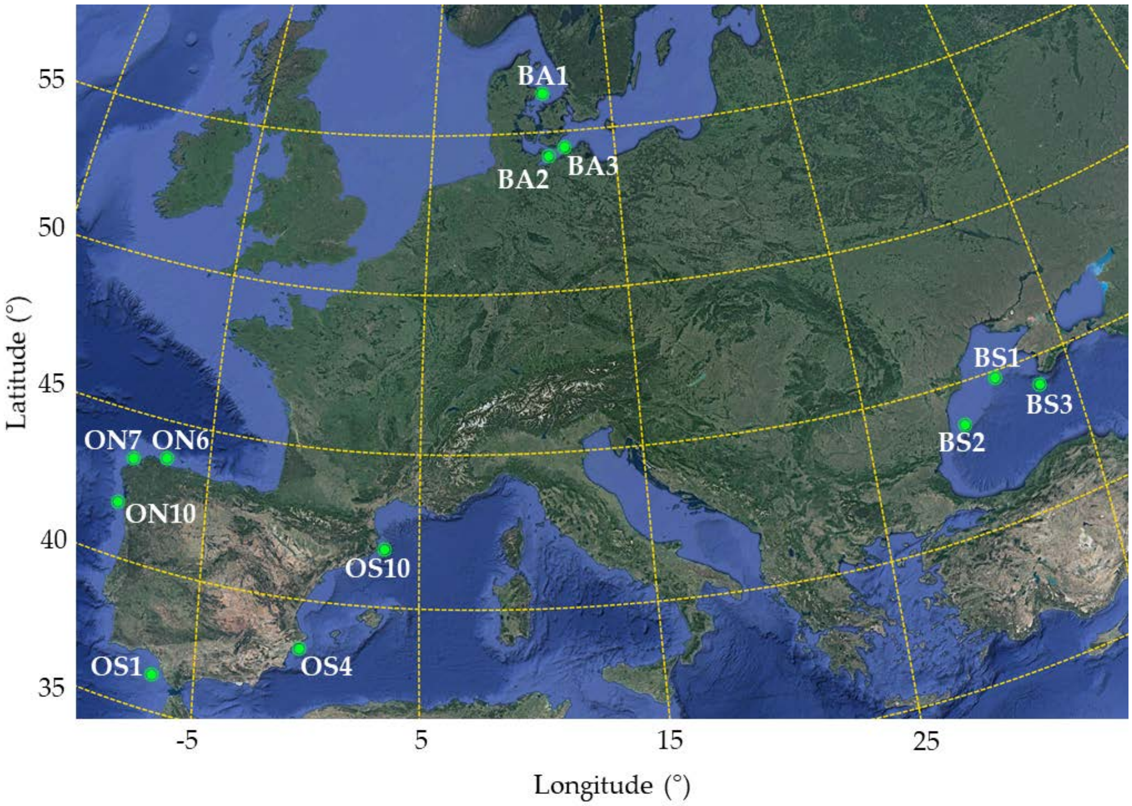

Figure 11. Map of Europe and the reference locations considered for the comparison.

Three locations in the Baltic Sea are considered and denominated BA1, BA2 and BA3, being the three other considered locations located in the Black Sea and denominated BS1, BS2 and BS3. Table 6 presents the main characteristics of the Baltic Sea, North Sector, South Sector and Black Sea locations.

Table 6. Main characteristics of the locations considered for the comparison [10].

Sea	Point	Long (°)	Lat (°)	Water Depth (m)	Distance from the Coast (Km)
Baltic Sea	BA1	11.21	56.60	15.75	23
Baltic Sea	BA2	11.55	54.56	5.76	8
Baltic Sea	BA3	12.65	54.61	17.55	18
Atlantic Ocean	ON6	−7.21	43.61	74.95	5
Atlantic Ocean	ON7	−8.38	43.49	50.20	5
Atlantic Ocean	ON10	−8.92	42.29	64.00	5
Mediterranean Sea	OS1	−6.48	36.78	11.60	5
Mediterranean Sea	OS4	−1.01	37.53	87.10	5
Mediterranean Sea	OS10	3.28	41.93	169.60	5
Black Sea	BS1	31.59	45.07	56.10	79
Black Sea	BS2	29.58	43.88	68.65	49
Black Sea	BS3	33.62	44.35	10.00	9

It is relevant to highlight how, despite the fact that the European sites sourced from Rusu et al. [10] are selected much further to the coast than the Spanish locations considered in the present study, both the Baltic Sea and the Black Sea points present much shallower seafloor depths. This is a direct consequence of the rapid descent of the continental platform along the Spanish nearshore, an aforementioned characteristic of the Iberian Peninsula bathymetry [34].

Due to the fact that the considered operational hub height of 80 m above sea in Rusu et al. [10] differs to the 100 m above sea level considered in the present study, to be able to directly compare the values, the logarithmic law is applied to the values reported. In this way, the wind power density values for the same period, under the same climate change scenario, for the same operational hub height are obtained. Due to this, it is feasible to affirm that the conclusions obtained from the direct comparison of the Spanish locations with the other six European points provide representative information. By doing so, a further assessment of the wind resources of the Spanish locations selected for the present study is presented.

Figure 12 shows the mean and maximum values for the P_{wind} parameter obtained for the operational height of 100 m above sea level. It is noticeable that the locations along the nearshore of the Baltic Sea present considerably higher values when compared to the points located in the Iberian Peninsula. Similarly, but less drastically, the locations of the Black Sea present slightly higher values than the North Sector and South Sector sites. This is to be expected due to the Northern European coasts presenting the highest wind resources of all the European continent [13,48,65–67]. However, leaving aside the differences in the magnitudes, it is relevant to focus on the dynamics of the resources under the climate change scenario.

In this way, it is noticeable how the Spanish North Sector location ON10 and South Sector location OS4, present the highest percentage for the wind power density positive variation when comparing the historical and future period. Something that, added to the results presented for the wind turbine technology performance assessment, could lead to these locations gaining relevance in the near future when considering the development of an offshore project.

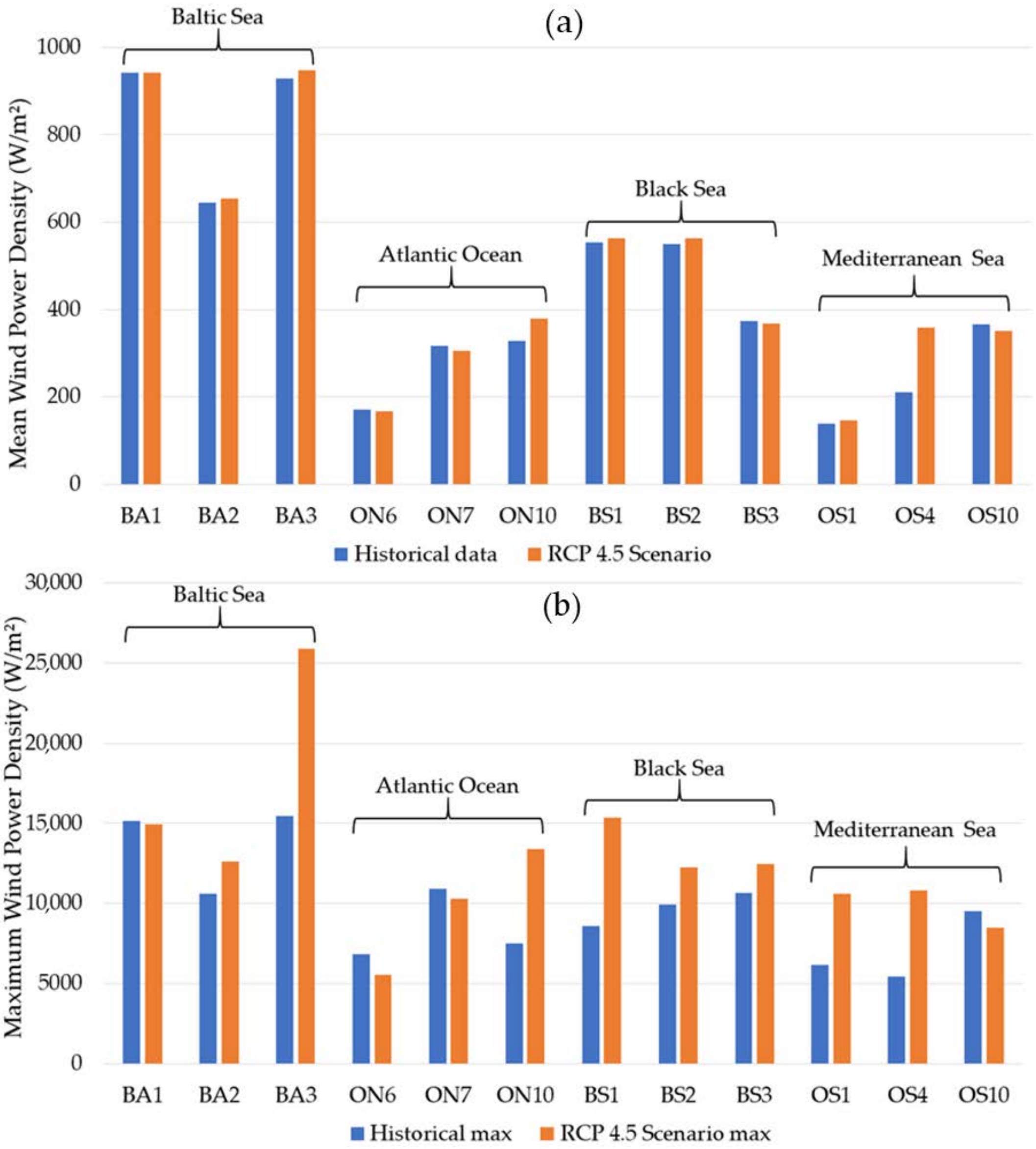

Figure 12. Mean and maximum wind power densities in the reference locations considered at the hub height of 100 m for the Spanish points and hub height of 80 m for the Baltic Sea and Black Sea points for the historical data (ERA5) and future projections (RCP 4.5) where: (**a**) Mean values; (**b**) Maximum values.

4. Discussion

In the context of the European continent, due to its southern location, the Iberian Peninsula is one of the areas where the effects of the climate change such as the increase of the global temperature, will be more notable. This will directly influence the atmospheric parameters of the area, something that will lead to changes in the wind speed dynamics. Taking into consideration that the wind resources are directly related to the wind speed, it is feasible to affirm that the wind resources of the Iberian Peninsula will suffer changes as consequence of the climate change [5,68].

Thus, to understand how these modifications can affect a region that has historically presented remarkable wind resources along its coasts, this section presents an in-depth analysis of the values obtained by studying the dynamics of the wind energy resources. Along with the performance and economic viability dynamics of some wind turbine technologies, the results are analyzed and compared with other studies of special relevance. In this way, a critical image of the dynamics obtained in the present study is presented.

Analyzing the results obtained after studying the annual averages of the wind power density once the five-year running mean filter is applied. There are no relevant statistical variations when the 20-year historical period (1999–2018) and the 30-year future period (2021–2050) are compared. The interannual variability is not characteristically greater during the near-future period, as it could even present a slight reduction in the peninsular territory under the considered RCP 4.5 scenario [21,69]. Furthermore, by comparing the time series presented in Figures 4 and 5 (historical against future expected) it was possible to identify the relative variations, where a negative value indicates that the historical data presents higher values. Thus, the following variations are noticed: −0.1% (ON6); −4.92% (ON7); 56.8% (ON10); 14.8% (OS1); 76% (OS4) and −13.1 (OS10).

In general, a very slight decrease in the average values can be noticed with respect to the historical period. However, the locations ON10 and OS4 show remarkable gains of P_{wind}. This increase of the resources is also represented by a notable increase in the maximum P_{wind} values. Both ON10 and OS4 locations show much higher maximum values for the future period, dynamic that could be interpreted as an increase in the intra annual variability, something that would be directly represented in the seasonal and monthly average values.

In this context, the analysis of the seasonal means of the wind power density in the selected locations shows that the characteristic seasonal cycle continues to be present. With the North Sector location ON10 presenting a slight increase during the winter, season that characteristically presents higher resources in the Spanish Atlantic coast [26]. However, there is a general transfer of resources from the winter months to the spring season in the locations of the South Sector. With the most noticeable resource gains taking place during April.

This, far from being a trivial occurrence, is directly provoked by the increase of the global temperature, which is one of the main consequences of the climate change. Under the considered scenario, the surface of the Iberian Peninsula would present an increase of its land temperature more notable than the sea areas that surround it. This would lead to greater atmospheric pressures in, causing a greater pressure difference between the onshore and adjacent offshore areas, resulting in an increase of the wind speed fields. With the onshore temperature raise being more notable during the warm months of the year, this explains the transfer of resources from the winter months, season during this would practically not occur.

In Soares et al. [70], where wind dynamics are studied under the RCP 4.5 and 8.5 scenarios for locations in the north of the African continent, the aforementioned resource transfer is presented in an equally significant way. Considering heights of 100 and 250 m above the sea level, it is concluded that the resource transfer is greater under the RCP 8.5 scenario and when considering the greater height [71]. Thus, taking into consideration that this transfer is a direct consequence of the increase in the global temperature, and since the RCP 4.5 scenario considered in the present study estimates an increase ranging between 2 and 3 °C. It is feasible to conclude that the dynamics obtained in the present study would be somewhat more dramatic if worse climate change scenarios were considered.

After analyzing the dynamics of the energetic characteristics of the wind, it is of special relevance to study how these would affect to the performance of the four wind turbine technologies considered. The annual *Operating Time* percentage is a direct representation of the efficiency that an offshore installation would present in the selected locations. In this context, the results obtained show a generalized slight decrease. being the the V164-9.5 turbine technology the less affected due to having a somewhat greater operational range. These dynamics are also perceptible when studying the *AEP*, a parameter for which the loss of performance translates into reductions that are quite notable in the North Sector location ON7.

However, the North Sector location ON10 presents some gains for the annual *Operating Time* percentages. This translates into an average *AEP* for the near future period under the climate change scenario around 30% higher than the historical average. These performance estimates are similar to those obtained in the aforementioned Bernardino and Soares [72], where results obtained for the northern area of the Portuguese coast for the V80-2.0 wind turbine. Technology with the same operational range as three of the wind turbine technologies considered in the present study (*cut-in* 4 m·s^{-1} and *cut-out* 25 m·s^{-1}). For a considered operational hub height of 80 m above the sea level, during the same period (2021–2050) under the RCP 4.5 scenario, annual Operating Time percentage values above 80% are obtained. These values are slightly greater but concordant with the ones obtained in the present study.

The analysis of the *LCOE* dynamics clearly shows an improvement in the already notable viability that the offshore wind industry presents along the Spanish nearshore of the Iberian Peninsula. In this way, and thanks to the reductions that take place during the near future under the RCP 4.5 climate change scenario, a greater number of wind turbine technologies produce energy with *LCOE* below the targets set by the European Union. Something positive as it opens the possibility of considering different wind turbine technologies for the development of an offshore wind farm project.

When analyzing the comparative presented with the dynamics obtained in Rusu et al. [10] for the locations from the Baltic and Black seas. It is relevant to highlight the great difference that these results show when compared to those obtained in the present study for the locations of the Iberian Peninsula. The Spanish locations in the Mediterranean and Atlantic coasts suffer a slight general resource loss. However, the wind power density in both the Baltic Sea and the Black Sea locations present higher averages under the considered climate change scenario [37,65,73]. This slight improvement of the wind resources is also reflected in somewhat higher maximum values, being the BA3 location of the Baltic Sea the point where this variation is most notable.

It is also relevant to highlight the fact that, unlike the locations of the Iberian Peninsula, the Baltic Sea and Black Sea sites do no present resource transfer towards the spring months. Taking into consideration the direct cause of this transfer, it is feasible to conclude that a minor increase in the onshore surface temperature occurs. The northern areas of the European coasts will be less affected by this occurrence. Furthermore, it is important to remark that, due to its geographical characteristics, as it is a peninsula, the Iberian territory is more susceptible to this temperature induced wind resource variations.

The wind turbulence represents an important factor for the performance of a wind turbine, since may significantly influence the energy production and the lifetime of a particular generator. Thus, the wind characteristics can change very rapidly in space and time being usually identified throughout in situ measurements (ex: anemometers; SODAR; LIDAR) taken at short time intervals, like 10 min. However, the two wind datasets (ERA 5 and RCP 4.5) considered in the present does not provide enough information to assess such fluctuations, since only four data per day where considered while the wind roses were not processed for the present work. To tackle, this issue in the future works will be considered the implications for the performance of a wind turbine, by including more data per day (ex. 24 values) and also by using the 10 m wind gust parameter that is available in the ERA 5 database.

5. Conclusions

In the present study, an assessment of the wind resources dynamics along the Spanish coastal environment in the Iberian Peninsula is presented. By studying the variations of mean and maximum values, as well as seasonal and monthly variability of the wind power density parameter, relevant trends are identified. Furthermore, an assessment of the performance and economic viability dynamics for various wind turbine technologies is presented.

From this perspective, it can be concluded that wind energy resources suffer a slight general loss under the climate change scenario. However, the existence of specific locations in the Atlantic and Mediterranean coasts, where the dynamics are much more positive is also highlighted.

Furthermore, after an in-depth analysis of the wind resources variability considering seasonal and monthly time slices, a characteristic trend of the Iberian region is identified and described. This being a resource transfer towards the spring months, direct consequence of the increase in temperature caused by climate change. This trend is observed most notably in the locations of the South Sector during the month of April.

In the economic field, it is feasible to conclude that the offshore industry is a viable option to consider in the Spanish nearshore territory. With historical LCOE values that place it well within the European energy framework, and with a dynamic that presents a continuous reduction. The study of the dynamics of representative performance parameters for four wind turbine technologies leads to conclude that the locations of the Atlantic coasts of the Iberian Peninsula continue to present remarkable offshore wind resources.

The coastal environment of the Iberian Peninsula is a suitable area for development of renewable projects, and therefore some other research directions may be considered for assessment, such as:

(a) What are the representative wind turbines that can be considered for implementation in the North Atlantic and Mediterranean Sea areas;
(b) Highlight the best sites to implement offshore wind projects by taking into account a multi-criteria analysis that includes some restricted zones (ex: water depth, maritime routes, protected areas, etc.);
(c) Establish the viability of some hybrid/mixed projects that involve multiple energy sources such as solar, wind or waves, respectively.

Author Contributions: The conceptualization belongs to E.R., F.O. established the methodology and perform the validation. A.R. performed the formal analysis, the investigation, data curation and prepared the original draft of the manuscript. E.R. performed the review and editing and supervision while F.O. The visualization. E.R. was in charge also with the project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript. Analyzed the data designing the figures.

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