Technical-Economic Assessment of Wind Energy Resources in Southern Morocco

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Abstract: Due to the development of renewable energy technologies in recent decades, the demand of energy researchers, and energy planners and investors for reliable data on the spatial distribution of their potentials and costs has increased. The accurate and comprehensive description of wind resources is an essential factor for wind farm planning and for knowing the effect of wind behaviour on the performance of selected wind turbines and the stability of energy produced. Wind offshore potential exploration is still in its early stages, unlike the case of onshore wind potential. This paper reviews three modes of wind energy production in southern Morocco, based on 10 years of hourly data at a height of 100 m, and assumptions for analysing economic, geographical, technical, and feasible onshore, nearshore, offshore wind potentials. We address each of these potentials in turn, including aspects related to field criteria, and technical developments of wind turbine characteristics such as capacity factory and annual energy production. Economic aspects of potential assessments are discussed on a turbine and system level including levelized costs depending on locations.

1. INTRODUCTION

In 2009, Morocco developed an ambitious vision related to the field of national energy strengthening and made energy independence a national priority. Morocco faces major challenges in meeting the growing domestic demand for energy, as well as the volatility of global energy markets, as it is the largest importer in North Africa [1]. Based on these indications, the strategy adopted aims to accelerate the pace of the use of renewable energy sources, in particular solar energy (the Noor project) and wind energy (more than 20 wind farms), with a view to achieving an installed electrical capacity of 52% from clean sources by 2030 [2]. The established electricity capacity from renewable sources in 2021 amounts to 3950 MW, of which the share of wind energy is 1430 MW [3].

Morocco has a very promising potential for wind energy, which is reflected in the quantity and volume of wind projects in operation or under construction throughout its territory, but it should be noted that it is limited to the onshore wind energy type overall, due to a lack of programming of offshore wind projects. It is also reflected in the lack of data and measurements in the Moroccan maritime domain, which prevent an accurate estimation of the real extent of this potential.

In this context, this qualitative study aims to determine the theoretical differences in wind potential between the three spatial modes of onshore, nearshore and offshore wind turbines, as well as to estimate the performance of selected wind turbines in each of them and compare them in terms of economic feasibility, based on a reliable source of data, we refer to reanalysis data, in the absence of real observation sources.

Section 2 includes comprehensive information on the wind data used, the mathematical tools, the set of equations collected, and the technical specifications of the wind turbines selected for each site. Section 3 is divided into two main sections, the first with an analysis of the wind characteristics and their distribution in terms of temporal and spatial distribution of the mean wind speed and standard deviation at a specified height, as well as the wind direction pattern through the wind rose diagrams. Also, the distribution of wind speeds using the Weibull model, the monthly and diurnal series of wind speeds, and finally the wind power density and productivity results of the selected wind turbines. At the end of this section, we discuss the economic feasibility comparison based on the LCOE index and the annual productivity of each turbine.

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2. MATERIALS AND METHODS

This study was conducted on a specific scale in southern Morocco in the area between the city of Dakhla (23.73°N and -15.92°W) and Lamhiriz (22.19°N and -16.76°W), The three selected locations were taken randomly (see Figure 1).

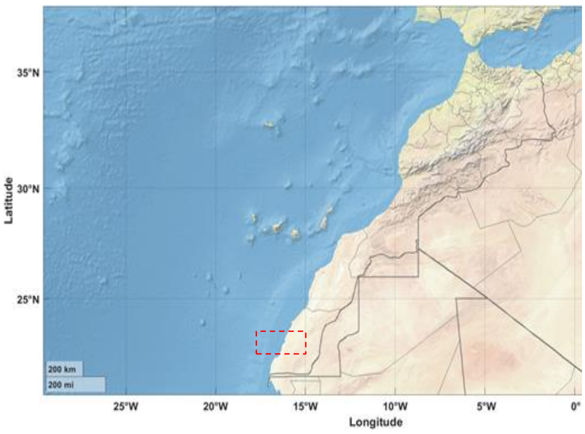

Figure 1: Map showing the location of the study area in southern Morocco.

2.1 Data Sources

The wind speed data used are from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis database model, which is considered a reliable source in climatology, validated on a large scale regionally and globally, with a spatial resolution of 0.25° × 0.25° (atmosphere) and 0.5° × 0.5° (ocean waves) [4]. Data are available at two heights of 10 m and 100 m. It should be noted that the wind data used in this study are hourly at each location for greater accuracy in the results for a 10-year time period extending from (2011-2020) in southern Morocco.

2.2 Technical Analysis

Among the many different nonlinear numerical methods for estimating wind potential, whether probability density distributions (PDFs) or cumulative distributions (CDFs), the Weibull distribution model stands out as the most effective for estimating wind potential and a better representation of site-specific wind speed plots based on several previous studies [5], [6].

The distribution function (PDF) and (CDF) of the two-parameter Weibull probability density function are defined, respectively, as follows:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{k}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \text{ for } v \geq 0; \quad k, c > 0 \tag{1}$$

$$F(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

where v (m/s) represents wind speed, c (m/s) and k (dimensional) are called scale and shape Weibull parameters respectively, which have a precise role in referring to the characteristics of the regional winds. Both parameters are estimated using the following equations [7]:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad 1 \leq k \leq 10 \tag{3}$$

$$c = \frac{v_m}{\Gamma(1 + \frac{1}{k})} \tag{4}$$

Wind power density (WPD, in W/m^2), is an important indicator in determining the wind potential at a given location, calculated using the following equation:

$$WPD\ (v_m) = \frac{1}{2}\ \rho v_m^3 \tag{5}$$

where v_m is mean wind speed, ρ represents the air density.

The initial focus is within the framework of technical analysis to work on evaluating the expected production capacity of four wind turbines, taking into account the specifications of each type separately, which operate at a height of 100 meters, as specified in Table 1 below:

Table 1: Technical characteristics of the four selected wind generators [8], [9].

Turbine	Rated Power (MW)	Cut-in Speed (m/s)	Rated Speed (m/s)	Cut-out Speed (m/s)	Hub Height (m)	Type instalation
V90-3.0 MW	3.00	4	15	25	80-105	Onshore
	3.00	3.5	15	25	65-105	Offshore
Siemens SWT-3.6	3.60	3	13	25	80-96	Onshore
	3.60	4	13.5	25	80-96	Offshore
Gamesa G128-5.0MW	5.00	2	14	27	81-140	Onshore/Offshore
BARD VM - 5.28 MW	5.28	3	12.5	30	90	Onshore/Offshore

Figure 2 shows the power curves of the selected wind turbines. These power curves are obtained at a standard air density of ρ_0 =1.225 kg/m^3. The four wind turbines were selected in proportion to the wind potential, after analysing the average wind speed, as we will see later, as well as their spatial position.

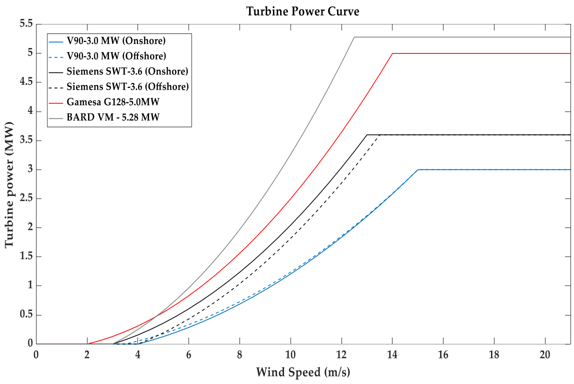

Figure 2: Turbine Power curves of the selected wind turbines

The annual wind energy production (AEP) of a particular wind turbine can be obtained as [10]:

$$AEP = T\int_{v_{in}}^{v_{out}} f(v)\, P(v) dv \tag{6}$$

Where AEP is in MWh, T is time average hours per year (8760h), *P(v)* is wind turbine power curve. The v_{in} and v_{out} values define the operational limits of a wind turbine.

The Capacity factor (Cf) is the ratio between wind average power generation P_{avg} from a turbine and the rated power generation P_{rated} [11].

$$Cf = \frac{P_{avg}}{P_{rated}} \tag{7}$$

The annual cost (AC) is obtained by multiplying the LCOE (in €/MWh) by the annual electricity production (E_t) (in MWh/year) using the following equation [12]:

$$AC = LCOE \times E_t \tag{8}$$

RESULTS

Taking a first look at the mean wind speed at 100 m altitude for the last 10 years in southern Morocco, the spatial distribution indicates the presence of the maximum value in the offshore domain, followed by the nearshore and onshore respectively, which reach the limits of 11 m/s in the offshore domain (Fig. 3a). The standard deviation is higher than the mean (up to 3.5 m/s), indicating a large variation in wind speeds for the three modes (Fig. 3b).

The mean wind speed in the offshore areas is relatively higher than in the onshore areas, and the wind speed values increase as one moves closer to the coast towards the sea, recording speeds of 8.29 and 9.59, and 10.12 m/s for onshore and nearshore and offshore, respectively, as shown in Table 2.

Drawing on a classification (Oh et al., 2012) [13] for wind energy regulation, the three proposed sites are very good, from category C5 (excellent) to C7 (superb), which makes the attractiveness of the southern region of Morocco for the development of wind energy projects very large.

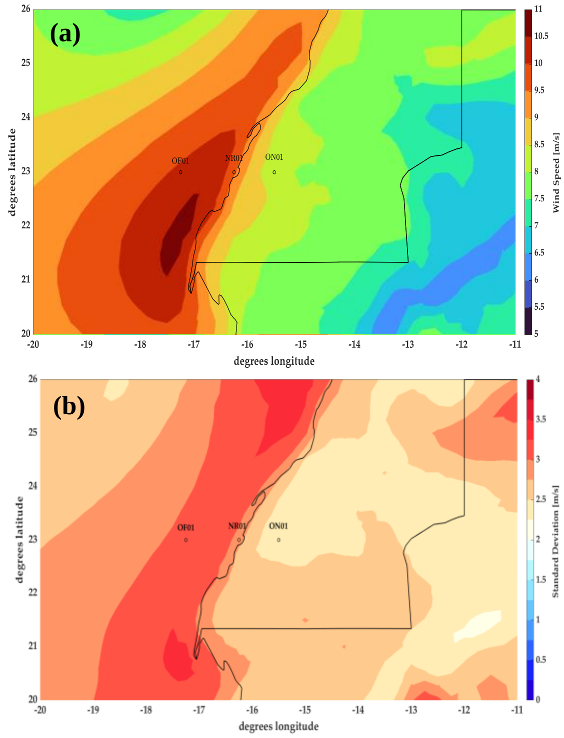

Figure 3: (a) The spatial distribution of the mean wind speed (m/s) at 100 m and, (b) standard deviation (m/s) at 100 m.

Table 2: Statistical values of the average wind speed estimated by the ERA5 dataset.

	Mean (m/s)	Max (m/s)	Std (m/s)	k	c (m/s)	Cv
Onshore	*8.29*	*16.95*	*2.39*	*4.00*	*9.14*	*0.29*
Nearshore	*9.59*	*20.73*	*2.84*	*3.90*	*10.58*	*0.29*
Offshore	*10.12*	*20.50*	*3.09*	*3.76*	*11.19*	*0.30*

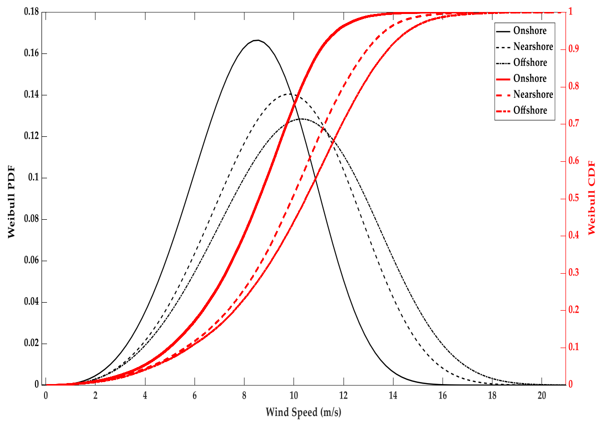

Figure 4: Weibull PDFs and CDFs distributions of the three spatial patterns from 2011 to 2020 at 100 m from the ground.

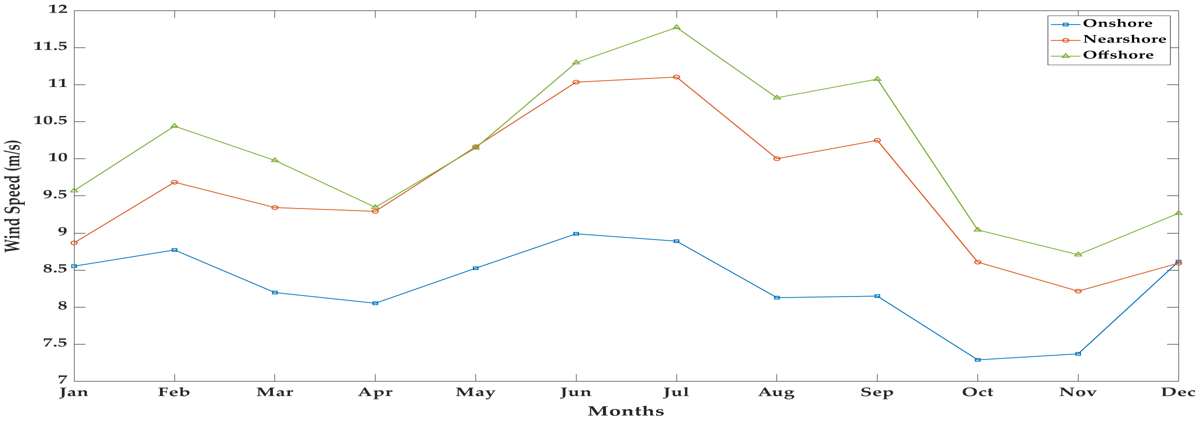

Figure 5: Average monthly wind speed for the 10-year interval (2011-2020) at an altitude of 100 m obtained from ERA5 dataset.

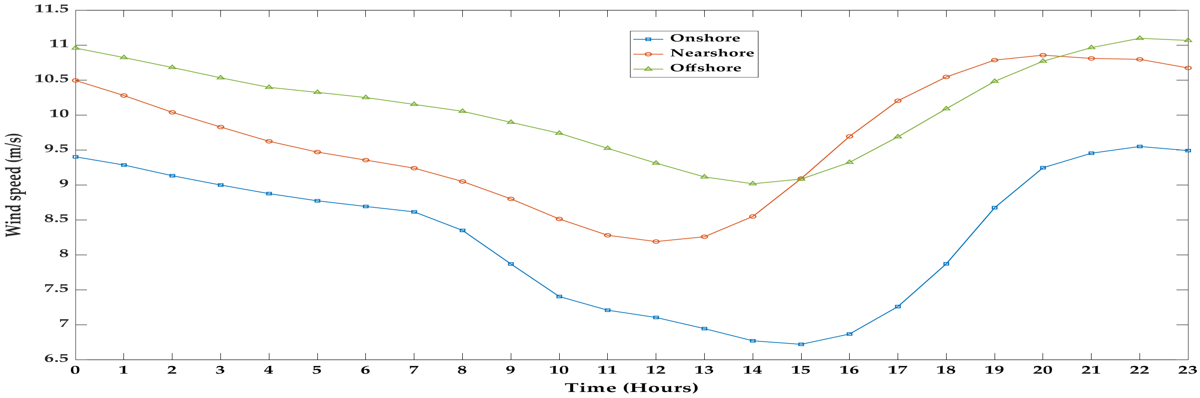

Figure 6: Diurnal cycle of mean wind speed for the three spatial modes of wind energy over the period 2011- 2020 at a height of 100 m from the ground based on ERA5 dataset.

Figure 4 shows the Weibull distribution of the PDFs and CDFs files as a function of wind speed for the three locations onshore, nearshore, and offshore for the same selected period. The figure shows that the wind speeds in the marine location followed by the nearshore location have a more concentrated PDF distribution than the onshore location, with an average speed of about 10 m/s. About the CDFs curves, it is evident that 50% of the total winds are above 10 m/s in the offshore and near-shore locations, compared to the onshore location, which represents only about 25% of the value.

Monthly average wind speeds shown in Figure 5 show a noticeable difference in terms of recorded peaks, as they are lower in onshore locations than those in nearshore and offshore locations, and they increase clearly during the summer with a difference of more than 2.90 m/s, while the winter season is less different by a difference of less than 1.70 m/s.

Figure 6 shows a representation of the curves of the diurnal cycle of the average wind speed, through which it can be said that the pattern of its change is somewhat similar, as the lowest value was recorded on onshore and offshore locations between 2h and 3h a.m. with an average of 6.5 and 9.3 m/s, respectively, while it differs for the nearshore where it notes the minimum value of 8.2 m/s between 11h and 12h a.m., and the reason for the difference is probably the effect of the land and sea breezes on the nearshore. As for the maximum values, they have the same timing between 11h and 12h p.m., with an average of 9.4, 10.7 and 11.1 m/s, respectively. Despite this similarity in the time sequence, the margin of difference between the maximum and minimum values gives a complete preference to the offshore site, as it does not exceed ±1.8 m/s compared to the land site which exceeds ±2.9 m/s, meaning that the marine site is more stable in energy production throughout the day than the land site.

The wind direction was analysed at a height of 100 m for the period 2011 to 2020. The wind rose indicates that the NNE-NE wind direction is the dominant regime in southern Morocco. The wind climate is similar for the three regimes in general, but a marginal difference is noted between them, where other sub-direction appears, caused by factors such as breezes and the influence of local winds (Fig. 7). It is also noted that wind speeds are higher in the marine and coastal areas reaching values of 15-20 m/s.

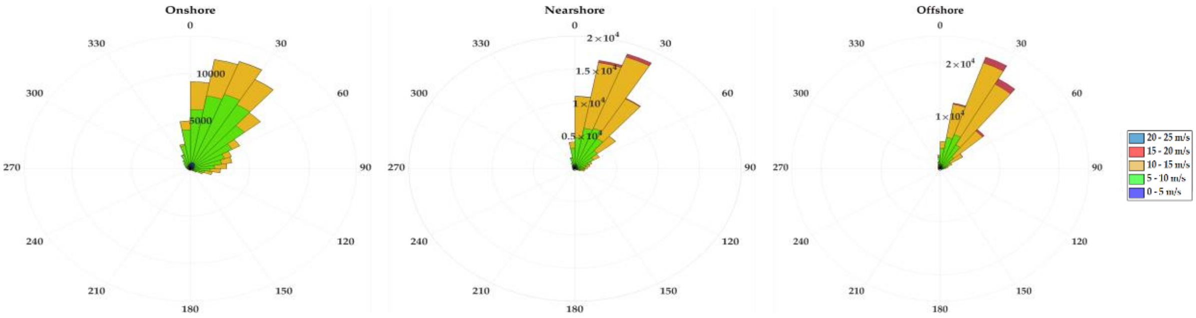

Figure 7: Wind rose diagrams for the three spatial modes of wind energy from at 100 m from ground related to the ERA5 dataset.

The seasonal wind power density graph shows significant differences in average wind energy in each of the three modes (Fig 8). The annual wind power density (WPD) varies between 432, 676 and 804 W/m^2 for onshore, nearshore and offshore, respectively. Across the monthly distribution, a discrepancy is observed in the density values in each of the three locations, as it is at offshore (1184 W/m^2) almost double the value recorded on onshore (538 W/m^2) during the summer, while it is slightly closer during the winter.

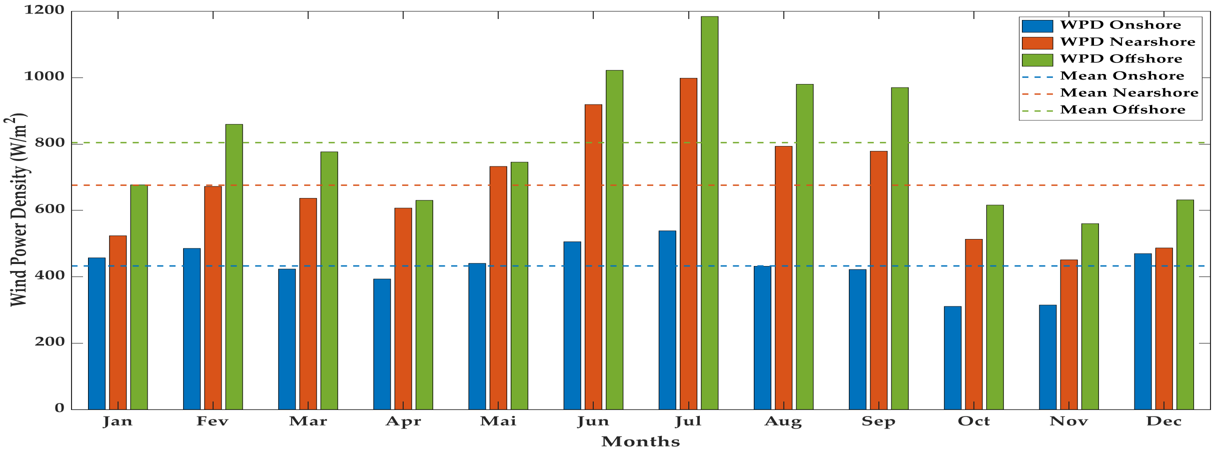

Figure 8: Histogram of seasonal wind power densities at 100 m height above the ground, the lines represent the annual mean WPD (W/m^2) over 10 years.

Table 3: Results of calculating average wind power (Pavg), capacity factory (Cf) and annual energy production (AEP) for the four wind turbine models proposed in this study.

	Onshore			**Nearshore**			**Offshore**		
	Avg (kW)	**Cf (%)**	**AEP (GWh)**	**Avg (kW)**	**Cf (%)**	**AEP (GWh)**	**Avg (kW)**	**Cf (%)**	**AEP (GWh)**
Vestas V90-3.0	*845*	*28.19*	*7.41*	*1208*	*40.29*	*10.59*	*1394*	*46.48*	*12.21*
Siemens SWT-3.6	*1472*	*40.90*	*12.90*	*1996*	*55.45*	*17.48*	*1997*	*55.48*	*17.50*
Gamesa G128-5.0MW	*1836*	*36.72*	*16.08*	*2482*	*49.63*	*21.74*	*2744*	*54.88*	*24.04*
BARD VM - 5.28 MW	*2338*	*44.31*	*20.48*	*3125*	*59.23*	*27.37*	*3387*	*64.19*	*29.67*

Using the technical data of the selected turbines (Table 1), the maximum capacity factor of each turbine was calculated, as well as the average annual maximum energy production at each location, as shown in Table 3, the four models in nearshore and offshore exceed the barrier of 40% in terms of capacity factor, while in the onshore this only happen for Siemens SWT-3.6 and BARD VM-5.28 MW. It can also be noted that the BARD VM-5.28 MW model produces the highest annual energy output for the three sites, but the production volume in the offshore area is very high at 35-65% and in the nearshore 34-43%, compared to the onshore.

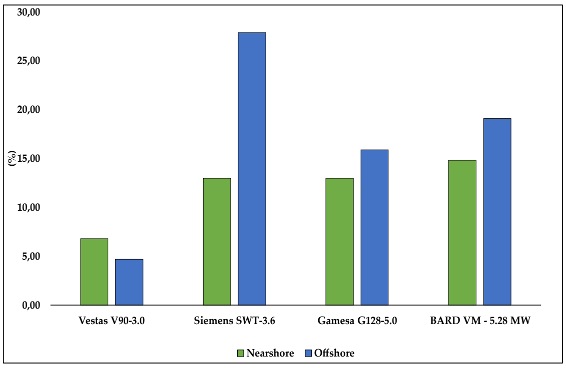

Figure 9: The percentage difference between the annual cost (AC) for each of the nearshore and offshore locations compared to the onshore.

Fig.9 using data from the IRENA Renewable Energy Cost Database 2020 [14], the annual cost (AC) of electricity generation for each individual turbine at the onshore and offshore site was calculated relative to the onshore site. Where it should be noted that despite the high annual productivity of the offshore, the annual cost also remains high at rates of more than 15%, except for the Vestas V90-3.0 which is less than 7%, but due to the rapid development of the offshore wind sector, these percentages could see a significant decrease in the coming years, according to estimates from (IRENA).

3. CONCLUSION

This paper analyses the technical and economic feasibility of the wind energy potential for three different wind energy installation sites in southern Morocco. Average wind speeds above 8 m/s were observed in both onshore and nearshore sites and exceeded 10 m/s in the offshore site at a height of 100 m for the period 2011-2020. It can be seen that the wind speed is more stable in the offshore area compared to the onshore and nearshore areas, and the monthly distribution shows a significant difference between the winter and summer seasons.

The selection of the most appropriate wind turbine in each of the three locations gave good results for the SWT-3.6 and BARD VM-5.28 models, where the capacity factor (Cf) exceeds 40% in all three locations. The maximum annual energy productivity (AEP) rates in nearshore and offshore reach over 34% to 65% compared to its onshore counterpart. The annual cost (AC) has decreased somewhat with the margin of AEP increase recorded in the offshore site compared to the onshore site.

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