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# Evaluation of wind energy potential and trends in Morocco

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ABSTRACT

In recent years, the use of wind energy has become increasingly attractive for the successful and economic development. Wind energy is one of the fastest-growing renewable energy technologies of electricity generation. Wind energy has proved its potential in combating environmental degradation while ensuring a renewable, efficient and clean energy source. Good wind sites can even be competitive with traditional energy sources. In this paper, we used statistical methods namely Weibull probability density function for evaluating the wind energy potential as a power source in Morocco's regions, in particular Taza and Dakhla cities. Various methods were explored as wind variability, power density, standard deviation, Moroccan and WAsP methods for calculating the Weibull parameters using mean wind speed data measured at one-hour intervals. The wind data have been extracted at the height of 50 m and over a three-year period 2015–2017. Furthermore, the variations of monthly and annual wind speed are studied and the power and energy densities are evaluated. The monthly values of the Weibull shape parameter are on average 5.01 m/s at Taza and 9.04 m/s at Dakhla. The results obtained showed that the highest values of wind potential occur during March, July, September and December in Dakhla and during the December to March in Taza.

## 1. Introduction

Energy is one of the important inputs for economic development and power generation. Fossil fuels are the main resources and play an important goal to supply world needs of energy. However fossil fuel reserves are limited, exhaustible and usage of fossil fuel sources have negative environmental effects and produces gaz emissions such as, carbon monoxide, hydrocarbons and ionization radiation. Therefore, the best use of renewable energy and the management of energy sources are essential [1].

The wind energy is currently considered as one of the most important energy source among the others renewable sources, it's fastest growing, commercially attractive source and commonly used to generate electrical energy because of the mature and cost effective energy conversation system technology [2].

Modern turbines have become an appropriate technique for extracting wind energy. Wind energy is economical, sustainable, renewable and a clean energy [3]. In addition, wind energy does not consume water, which makes it more efficient than thermal power. These last use a large amount of fresh water for cooling [4].

In recent decades, demand of energy has increased very rapidly in Africa region, due to demographic and economic growth and improved living standards [5].

The Moroccan government has a strategy for the development of renewable energies and energy efficiency. According of its energy strategy, the Moroccan government supports the development of renewable energies and their energy efficiency. Morocco's goal is to increase the installed wind energy capacity from 280 MW in 2010 to 2000 MW 2020 according to the Moroccan integrated wind energy project [6]. According to statistics, Morocco's energy demand is rapidly increasing by economic and demographic growth and is expected to triple by 2030.

In particular, Morocco has good climatic and geographic conditions for installation wind turbines with 17 selected regions for their use in wind power generation [7]. Morocco has 3500 km of coastline which mean wind speeds can reach up to 10 m/s. Therefore, the estimated total theoretical potential of wind power in Morocco is 25 GW. Currently, according to Moroccan integrated wind energy project, the installation of new wind farms is increasing in order to increase the wind energy capacity from 280 MW in 2010 to 2 000 MW in 2020 [8].

The wind energy is major concern and priority in the world, has become a very important research area and a motivational factor in scientific research. Because the demand increase of wind resources in power generation, efforts are created to predict the wind behavior and therefore the corresponding electrical energy production.

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Many research works have been conducted to improve the models for wind characteristics. Dabbaghiyan et al. [9] investigated the wind energy potential of sites locations in Bushehr province in Iran. The Weibull distribution function is employed to estimate the wind power density and energy for the regions. This analysis show that the annual average wind power density is identified about 265 W/m$^2$ at a height 40 m.

Ayodele and Ogunjuyigbe [10] studied the wind potential using the average wind speed data measured over a period ranging from 2001 to 2012 in Vesleskarvet region (Antarctica). Different wind turbines are simulated using HOMER software for selecting most suitable turbine. The average wind power and wind speed over a period (2001–2012) are respectively 1650 W/m$^2$ and 10.9 m/s.

Al-Abbadi et al. [11] analyzed wind energy resources for different sites in Saudi Arabia under various climatic conditions. It was shown that the wind speed distribution and proportion of events were important parameters in evaluating the wind energy potential at the sites considered. Akdag and Dinler [12] studied the wind potential at various sites of Turkey. They developed the power density method to estimate shape and scale Weibull parameters for wind turbine applications. In the literature, the moments, WAsP and maximum likelihood methods are most frequently used. Different quality of fit tests is used to determine the appropriate method for wind potential investigation at various geographical sites.

Katinas et al. [13] evaluated the wind energy efficiency for installed turbines using the capacity factor. The calculated results based on Weibull distribution and the scale and shape parameters investigated using the standard deviation method.

The wind energy potential for electricity generation using wind turbines at six sites of north Alegeria was investigated. The average wind speed was obtained at height 10 m and recorded over 10 years. The scale and shape Weibull parameters calculated for all months at various heights were extrapolated of the 10 m data. The WAsP algorithm was used for wind power density investigation and three commercial wind turbines were technically assessed for electricity generation by calculating the capacity factors and wind power and energy output. Also using the value cost method (PVC) for estimating the economic evaluation [14].

Ko et al. [15] studied the installation of meteorological observation for a good precision survey in Weno Islan, Chuuk State. The Rayleigh and Weibull distribution function are used for wind speed data fitting. The annual wind power density is about 157.08 W/m$^2$, and the highest value of power density was 345.91 W/m$^2$ in February 2013. The small - scale wind turbines with different rated power were used in estimating the annual energy generation.

Sedaghat et al. [16] determined the formulation to relate the power curves to the rated wind speed operating at maximum power coefficient to maximize the annual energy production. A capacity value is used to relates annual power production to the rated wind speed using an integral function of Weibull distribution.

Allouhi et al. [17] studied the wind energy of six coastal sites in Morocco. They used several methods for estimating the Weibull parameters of Weibull distribution function were applied based on wind speed measurement data. The numerical methods used in determining the Weibull parameters were more efficient in fitting the Weibull distribution curves. Therefore, the use of these methods is recommended for greater precision to provide more accurate results.

Costa Rocha et al. [18] applied seven methods for determining the shape and scale Weibull parameters for wind energy production in the northeast location of Brazil. They have concluded that the equivalent energy method gives accurate results for determining shape and scale Weibull parameters in the coastal zone of Brazil.

Chandra et al. [19] investigated the impact of Doubly Fed Induction Generator (DFIG) and Squirrel Cage Induction Generator (SCIG) on the transient stability of power system of the two types of wind generators. The study of sensitivity analysis and transient stability is conducted on a modified IEEE 14 bus system.

Reddy and Momoh [20] proposed an approach to solve an optimal power flow problem for minimization carbon oxides and nitrogen emissions. The cost of oxides and sulfur oxides play an important constraint for a wind-thermal power system. The Opposition based Bacterial Dynamics algorithm is used for solving proposed approach which implemented on IEEE 30 bus system with wind farm located at different buses.

Reddy [21] utilized three objective functions, which transmission losses, total generation cost, and voltage stability enhancement index to solve a novel multi-objective optimal power flow (MO-OPF) problem for a hybrid power system including the wind energy generators (WEGs), thermal generators and photovoltaic system (PV) units with battery energy storage (BES) system.

Reddy et al. [22, 23, 24] presented the optimal power flow techniques and expressions used in Renewable Energy Resources (RER). The choice of stochastic optimization was validated with advantage of this method over other methods. The Voltage VAR optimization problem was discussed in Stochastic Environment. Petković et al. [25, 26, 27, 28, 29, 30] applied several control techniques to evaluate the quality of produced energy from wind turbines, among these techniques such as adaptive neuro-fuzzy inference system (ANFIS) is used for estimating the optimal power coefficient. The neural network in ANFIS adapts the parameters in the fuzzy logic of the fuzzy inference system. This smart controller is executed with Matlab/Simulink. The main blessings of the ANFIS theme are: computationally economical, well-adaptable with improvement and accommodative techniques. ANFIS can also be employed with systems handling more complex parameters and its speed of operation, which is much faster than in other control strategies.

The theory of inventive problem solution (TRIZ) as an innovative concept design is used to investigate wind turbine innovative design [31]. The main goal was to detect conflicting situations using TRIZ methodology in wind turbine simulation. The thirteen inventive solutions of TRIZ were used in final design of wind turbine system. These inventive solutions in the following order: Partial or excessive actions, pneumatics and hydraulics, segmentation and others inventive.

The evaluation of wind turbine performance using CFD and BEM methods is conducted. In the first part of this study, the CFD study carried out S809 airfoil based on resolution Navier-Stokes equations coupled with turbulence models to calculate the aerodynamic coefficients [32, 33, 34]. In second part, we used a mathematical model (BEM) to calculate the loads applied on the blade and wind power output for optimizing blade geometry.

In this paper, the wind data extrated over a three years duration at Taza and Dakhla Moroccan sites are used for the analysis of wind power potential. We used five methods (wind variability, power density, standard deviation, Moroccan and WAsP) for predicting the wind power and energy output and select the most suitable wind turbines for each site location. The analysis results include monthly mean wind speed variation, methods used for estimation Weibull parameters, probability density distribution function, and wind energy and power density. The variation of monthly wind speed and wind power density and energy output at different heights is also determined.

## 2. Methodology

The study was carried out using the hourly wind speeds data extracted at the height of 50 m over a three-year period (2015–2017). The geographic coordinates for the two sites, is listed in Table 1.

**Table 1**
Geographic coordinates for the studied Moroccan sites.

| Site | Latitude | Longitude |
|---|---|---|
| Taza | 34°12′ | 4°00′ |
| Dakhla | 23°41′ | 15°57′ |

## 3. Theory

### 3.1. Probability density function

Various statistical distributions for describing and analyzing wind resource information, some of these include Rayleigh and Weibull distributions. However, among the statistical methods, the Weibull distribution proved to be accurate fitting method of measured wind speed data and its characteristics of prevailing wind speed variation. In this work, the Weibull probability density function was used in carrying out the analysis of wind speed potentials in the considered sites. This is given by Eq. (1) [35, 36]:

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

where k and c are the Weibull shape and scale parameters respectively, and f (v) is the probability of observing wind speed v (m/s).

The Weibull cumulative density function corresponding to the probability density function, Eq. (2) can be expressed [37]:

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

the k values vary from 1.5 to 3.0 for most wind conditions. In the case of shape parameter (k = 2), the Weibull distribution called Rayleigh distribution. The Rayleigh probability distribution function can be simplified by Eq. (3) [38]

$$f(v) = \left(\frac{2v}{c^2}\right)\exp\left(\left(-\frac{v}{c}\right)^{k}\right) \tag{3}$$

The mean speed $v_m$ and standard deviation σ of the Weibull distribution can be defined by the Eqs. (4) and (5) respectively [39].

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

and

$$\sigma = \sqrt{c^2\left\{\Gamma\left(1+\frac{2}{k}\right) - \left[\Gamma\left(1+\frac{1}{k}\right)\right]^2\right\}} \tag{5}$$

In the Eq. (5), where Γ is the gamma function.

There are several methods for estimating Weibull parameters. We go here discuss four commonly used methods. One of them, which is the most precise, will be used in this study.

### 3.2. Wind variability method

This empirical approach consists in estimating k, from the variability of the wind and the average wind speed.

The shape parameter is defined by Eq. (6) [40].

$$k = \begin{cases} 1.05v^{0.5} \; if \; v < 3 \\ 0.94v^{0.5} \; if \; 3 < v < 4 \\ 0.83v^{0.5} \; if \; v > 4 \end{cases} \tag{6}$$

and the scale parameter for all methods (variability, power density, standard deviation methods) is written by Eq. (7) [41].

$$c = \frac{\overline{v}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{7}$$

### 3.3. Standard deviation method

This method is suggested by Justus et al. If the standard deviation and the mean speed are available, the estimation of the parameters is done using the following two formulas [42]:

$$k = \left(\frac{\sigma}{\overline{v}}\right)^{-1.086} \tag{8}$$

In Eq. (8), the standard deviation and mean wind speed defined by the Eqs. (9) and (10) [42].

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(v_i - \overline{v})^2} \tag{9}$$

and

$$\overline{v} = \frac{1}{N}\sum_{i=1}^{N} v_i \tag{10}$$

### 3.4. Power density method

The value of k is determined using Eq. (11) [43]

$$k = 1 + \frac{3.69}{E_{pf}^2} \tag{11}$$

where

$$E_{pf} = \frac{\overline{v^3}}{\overline{v}^2}$$

### 3.5. Moroccan method

This method was used during the evaluation of the wind potential in Morocco by Mabchour [44]. The k given by Eq. (12):

$$k = 1 + (0.483(\overline{v} - 2))^{0.51} \tag{12}$$

### 3.6. WAsP method

This method has two requirements:

(i) The equality of mean power density between the adjusted Weibull distribution and the observed distribution
(ii) The proportion of values above the mean observed wind speed is the same for the adjusted Weibull distribution as to the observed distribution.

The scale parameter defined by first aspect is given by Eq. (13) [45]:

$$c = \left(\frac{\sum_{i=1}^{N} v_i^3}{N\Gamma\left(1+\frac{3}{k}\right)}\right)^{1/3} \tag{13}$$

Considering the second aspect and using cumulative Weibull distribution function, a proportion of the observed wind speeds X, that exceed the mean observed wind speed, X can be expressed by Eq. (14).

$$X = 1 - F(v) = \exp\left[-\left(\overline{v}/c\right)^{k}\right] \tag{14}$$

The following Eq. (14), such equation is written:

$$-\ln(X) = \left(\frac{\overline{v}}{c}\right)^{k} \tag{15}$$

Combination of Eqs. (13) and (15), an expression with one unknown (parameter k) is derived by Eq. (16) [45].

$$-\ln(X) = \left( v \left( \frac{N\Gamma(1+\frac{3}{k})}{\sum_{i=1}^{N} v_i^3} \right)^{1/3} \right)^k \tag{16}$$

### 3.7. Performance analysis

In this work, we are used various statistical test for validating goodness fit of Weibull parameters. The statistical tests are: etermination coefficient ($R^2$), root means square error (RMSE), chi-square test ($\chi^2$) and power density error were used [46, 47].

The determination coefficient is defined by the following Eq. (17)

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (y_i - x_i)^2}{\sum_{i=1}^{N} \left(y_i - \overline{y_i}\right)^2} \tag{17}$$

The higher values $R^2$ indicates that the calculated results describe better the observed results. The value of $R^2$ varies between 0 to 1.

The root mean square error is computing using Eq. (18)

$$RMSE = \left( \frac{1}{N} \sum_{i=1}^{N} (y_i - x_i)^2 \right)^{1/2} \tag{18}$$

where, $x_i$ the $i^{th}$ predicted data with Weibull or Rayleigh distribution, $y_i$ is the $i^{th}$ real data, n is the number of constants and N the number of observations.

The Weibull distribution describe better observed data when obtained smaller values of RMSE.

The chi-square tests were used to measure the reliability of predicted wind distribution with actual distribution. The expression for the chi-square test is defined by Eq. (19)

$$\chi^2 = \frac{\sum_{i=1}^{N} (y_i - x_i)^2}{N - n} \tag{19}$$

### 3.8. Evaluation of wind power density

The wind power density can be evaluated using two forms. One based on available power in the wind, it estimated directly from the wind speed v (m/s) and captured by the conversion system, and the other expression based on the Weibull distribution method [48]. The first approach is written by Eq. (20)

$$p(v) = \frac{1}{2}\rho A v^3 \tag{20}$$

And second approach, when Weibull method is applied, the wind power density is given by Eq. (21) [49].

$$P = \int_0^\infty \frac{p(v)}{A} f(v) = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{21}$$

The wind energy density is expressed as [50]:

$$E = \frac{1}{2}\rho c^3 \left(1 + \frac{3}{k}\right) T \tag{22}$$

In the Eq. (22), T is the number of days in the period considered.

### 3.9. Extrapolation of wind speed Weibull parameters

In general, wind speeds are measured using an anemometer at the height of 10 m. However, the energy estracted by the wind turbine is estimated using wind speed at the turbine hub height.

Wind speed increases with height. The extrapolation of the wind speed for different heights is expressed by the following equation [50]:

$$v = v_0 \left( \frac{z}{z_0} \right)^\alpha \tag{23}$$

In Eq. (23), $v_0$, the wind speed measured at height 10 m, v, the speed that must be calculated at height z, α, the power law exponent that is in function of the surface roughness, calculated by Eq. (24)

$$\alpha = \frac{0.37 - 0.088 \ln(v_0)}{1 - 0.088 \ln\left(\frac{z_0}{10}\right)} \tag{24}$$

The extrapolation of the Weibull parameters is obtained by Eqs. (25) and (26) [51, 52, 53, 54]:

$$k_z = \frac{k_0}{1 - 0.00881 \ln\left(\frac{z}{10}\right)} \tag{25}$$

$$c_z = c_0 \left( \frac{z}{z_0} \right)^\alpha \tag{26}$$

## 4. Results and discussion

Figs. 1 and 2 shows the monthly variations of mean wind speeds over three years and at two heights of the sites considered. From this figure, it can be seen, the two sites have a certain incompatibility of consistency of winds behavior.

At the height of 50 m, the wind speed varies between 3.94 m/s and 6.17 m/s at Taza. Also, the results show a good consistency of wind behavior. As a result, stable production of wind turbines can be achieved in this region. Dakhla has slightly higher wind speed values than Taza. The wind speed is between 6.69 m/s and 9.88 m/s at the height of 50 m and between 7.16 m/s and 10.77 m/s at the height of 100 m. In fact, at the Taza site, higher wind speeds are observed during the winter months but in summer for Dakhla site. Dakhla is windier than the Taza site and the wind speed have a highest value in summer. The maximum values of the wind speed are observed in July.

The monthly variation of the Weibull shape and scale parameters, which are estimated by the five methods used, is shown in Tables 2 and 3 for the studied sites. It can be deduced from these tables, that the monthly maximum scale parameter and mean wind speed are 10.55 m/s and 9.62 m/s respectively observed in July, while the minimum is observed in November as 6.75 m/s and 6.69 m/s respectively at Dakhla. In Taza, the monthly maximum scale parameter and mean wind speed are 5.95 m/s and 6.46 m/s are observed in February, while the minimum is found in July with values 4.2 m/s and 4.06 m/s in July. The tables further show that the variation of monthly maximum values of shape parameter is identified 9.16 in July while the minimum is observed in November as 2.04 at Dakhla. In Taza, the maximum is observed in November with value 3.49, while the minimum was identfied in July as 1.61.

The wind speed is more uniform in Taza and Dakhla during the months of February and July respectively, whereas it is less uniform during November. From this analyze we concluded that Dakhla is the windiest site.

Figs. 3 and 4 presents the measured and the estimated Weibull frequencies for two sites locations Dakhla and Taza at height 50 m. This figure also shows the comparison between the fitting distribution and actual data using the five methods: wind variability, power density, Moroccan, standard deviation and WAsP methods. The accuracy of the fit depends on the method used, the evaluation of fit quality was studied using determination coefficient $R^2$, RMSE and chi-square error $\chi^2$ statistic parameters. For each site, there is a large difference in the results obtained by the 5 methods, some of these methods were gave accurate results to adjust wind speeds in specific regions.

The results of annual Weibull parameters and performance tests using five methods for each site are given by Tables 4 and 5. Moreover, some of the methods were provided accurate results in fitting wind speeds in

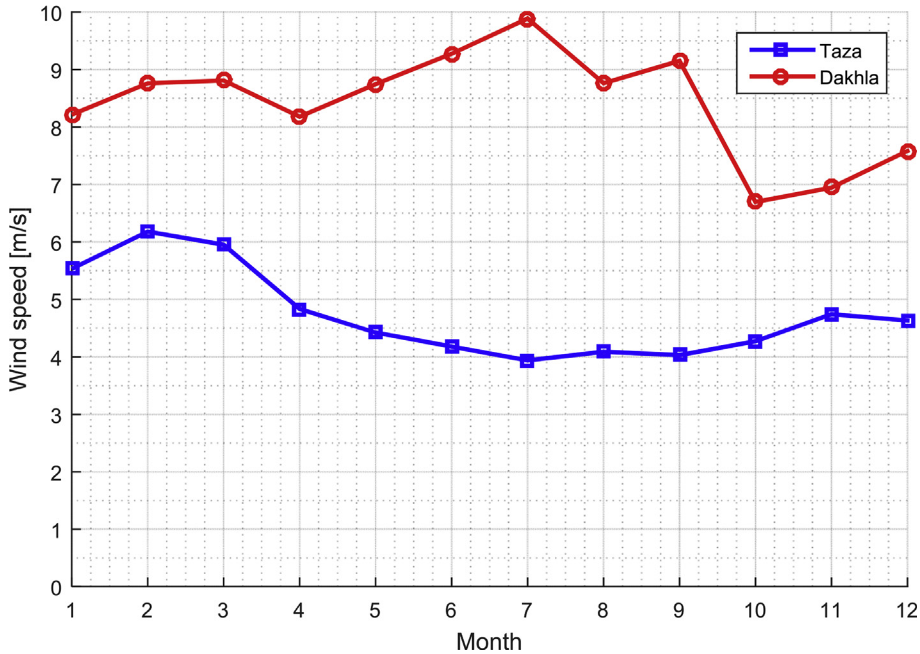


**Fig. 1.** Monthly mean wind speed at the height 50 m.

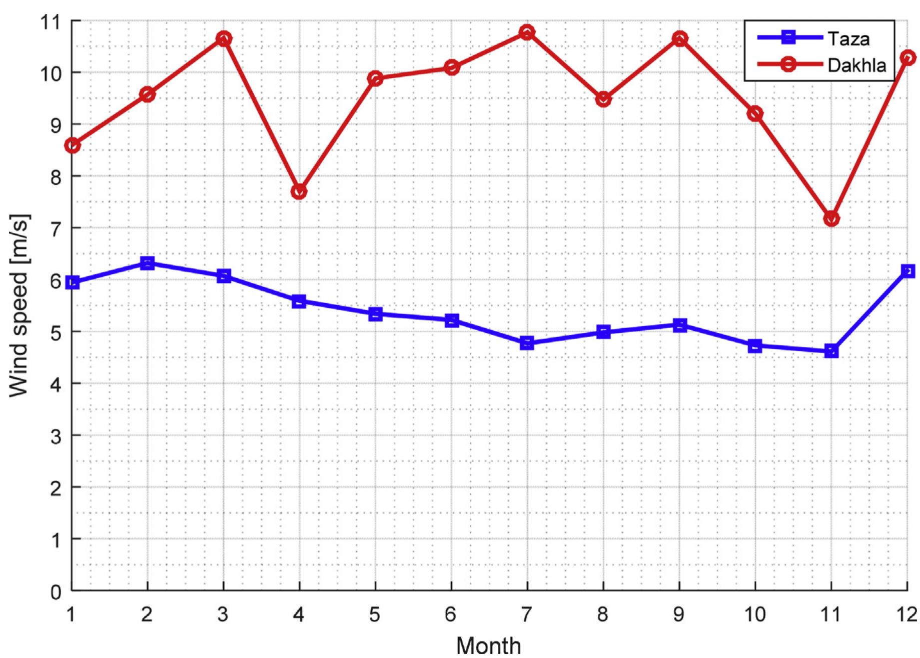


**Fig. 2.** Monthly mean wind speed at the height 100 m.

specific locations. Obviously, the best estimation of Weibull parameters is obtained by the lowest value of RMSE and chi-square test and the highest value of determination coefficient $R^2$. The results of shape and scale parameters calculated based on WAsP method show a better description of the wind speed density distribution for Taza site location. Moreover, the WAsP and wind variability methods presents satisfactory results when applied for Dakhla site.

The results analysis shows that the WAsP method can be used to evaluate Weibull parameters at the both locations. Because the WAsP method is calculated using the concept of equivalent energies. It is accepted that the wind energy density value, calculated from the actual wind data is equal to the energy density predicted using Weibull parameters.

However, the Weibull parameters calculated based on WAsP method give good description of wind speed density distribution during the conditions of low mean wind speed (Table 4, Fig. 3). The results indicated that WAsP method can be used for evaluation the Weibull parameters in both locations. The numerical methods (WAsP and Power density) that use mathematical iterations were more efficient in fitting Weibull distribution curves. Therefore, the use of these methods is recommended when a greater precision is required to provide more accurate results.

Tables 4 and 5 present the annual statistical indicators obtained for each site and for different methods. The $R^2$ was found between 0.88-0.96 for wind variability, power density and WAsP methods, showing that the highest correspondence between Weibull distribution and actual data.

**Table 2**
Monthly shape and scale parameters for Dakhla site using five methods.

| Months | Wind variability | | Standard deviation | | Power density | | Moroccan | | WAsP | |
|---|---|---|---|---|---|---|---|---|---|---|
| | k | c | k | c | k | c | k | c | k | c |
| Jan | 2.25 | 8.29 | 5.83 | 7.92 | 3.98 | 8.10 | 2.62 | 8.26 | 4.1 | 7.92 |
| Feb | 2.38 | 9.31 | 4.94 | 8.99 | 3.80 | 9.13 | 2.76 | 9.27 | 4.05 | 8.42 |
| Mar | 2.53 | 10.44 | 5.10 | 10.08 | 3.83 | 10.25 | 2.89 | 10.39 | 3.92 | 9.2 |
| Apr | 2.12 | 7.37 | 4.25 | 7.18 | 3.55 | 7.25 | 2.49 | 7.36 | 3.75 | 8.12 |
| May | 2.42 | 9.63 | 5.88 | 9.21 | 4.01 | 9.41 | 2.79 | 9.58 | 4.25 | 8.53 |
| Jun | 2.45 | 9.84 | 5.65 | 9.43 | 3.99 | 9.62 | 2.82 | 9.79 | 4.19 | 9.21 |
| Jul | 2.54 | 10.55 | 9.16 | 9.88 | 4.36 | 10.28 | 2.91 | 10.50 | 4.85 | 10.1 |
| Aug | 2.37 | 9.20 | 4.09 | 8.99 | 3.52 | 9.06 | 2.74 | 9.17 | 4.26 | 9.11 |
| Sep | 2.53 | 10.44 | 8.66 | 9.80 | 4.32 | 10.17 | 2.89 | 10.39 | 4.75 | 10.03 |
| Oct | 2.33 | 8.92 | 8.67 | 8.36 | 4.31 | 8.68 | 2.70 | 8.88 | 4.67 | 8.94 |
| Nov | 2.04 | 6.81 | 3.12 | 6.75 | 3.00 | 6.76 | 2.40 | 6.81 | 4.3 | 7.21 |
| Dec | 2.48 | 10.03 | 7.18 | 9.50 | 4.20 | 9.80 | 2.85 | 9.99 | 4.53 | 8.86 |
| Annual | **2.37** | **9.23** | **6.04** | **8.84** | **3.91** | **9.04** | **2.74** | **9.20** | **4.3** | **8.8** |

**Table 3**
Monthly shape and scale parameters for Taza site using five methods.

| Months | Wind variability | | Standard deviation | | Power density | | Moroccan | | WAsP | |
|---|---|---|---|---|---|---|---|---|---|---|
| | k | c | k | c | k | c | k | c | k | c |
| Jan | 1.84 | 5.55 | 2.08 | 5.57 | 2.11 | 5.57 | 2.19 | 5.57 | 1.83 | 5.52 |
| Feb | 1.91 | 5.94 | 2.52 | 5.94 | 2.49 | 5.94 | 2.26 | 5.95 | 1.90 | 5.85 |
| Mar | 1.86 | 5.69 | 2.47 | 5.69 | 2.38 | 5.70 | 2.22 | 5.71 | 1.87 | 5.7 |
| Apr | 1.78 | 5.19 | 2.81 | 5.19 | 2.71 | 5.20 | 2.12 | 5.22 | 1.77 | 5.35 |
| May | 1.74 | 4.93 | 3.33 | 4.89 | 3.06 | 4.92 | 2.07 | 4.96 | 1.75 | 4.89 |
| Jun | 1.72 | 4.82 | 3.60 | 4.76 | 3.27 | 4.78 | 2.05 | 4.88 | 1.73 | 4.75 |
| Jul | 1.64 | 4.36 | 3.49 | 4.34 | 3.08 | 4.36 | 1.96 | 4.40 | 1.65 | 4.2 |
| Aug | 1.68 | 4.57 | 2.93 | 4.57 | 2.78 | 4.58 | 2.00 | 4.60 | 1.68 | 4.38 |
| Sep | 1.70 | 4.72 | 2.92 | 4.72 | 2.68 | 4.74 | 2.03 | 4.75 | 1.73 | 4.53 |
| Oct | 1.63 | 4.31 | 2.06 | 4.35 | 1.90 | 4.35 | 1.94 | 4.35 | 1.67 | 4.22 |
| Nov | 1.61 | 4.19 | 1.92 | 4.23 | 1.78 | 4.22 | 1.92 | 4.23 | 1.65 | 4.05 |
| Dec | 1.88 | 5.79 | 1.98 | 5.79 | 1.94 | 5.79 | 2.24 | 5.80 | 1.9 | 4.97 |
| Annual | **1.75** | **5.01** | **2.68** | **5.01** | **2.51** | **5.01** | **2.09** | **5.03** | **1.75** | **4.8** |

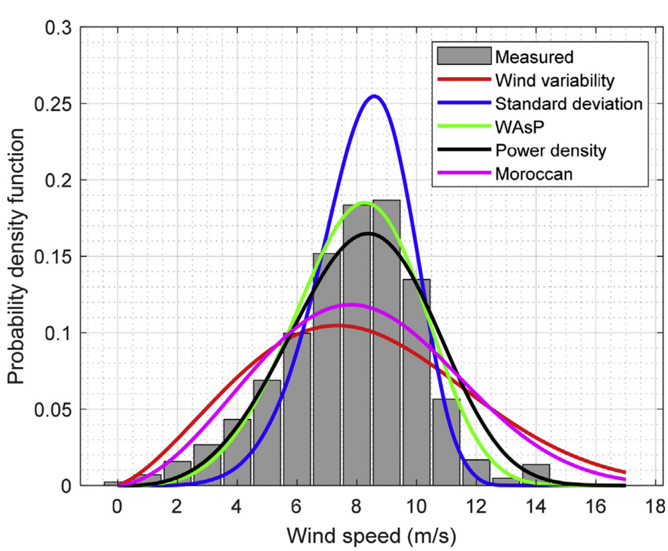


**Fig. 3.** Comparison of the frequency calculated by the four methods for Dakhla site.

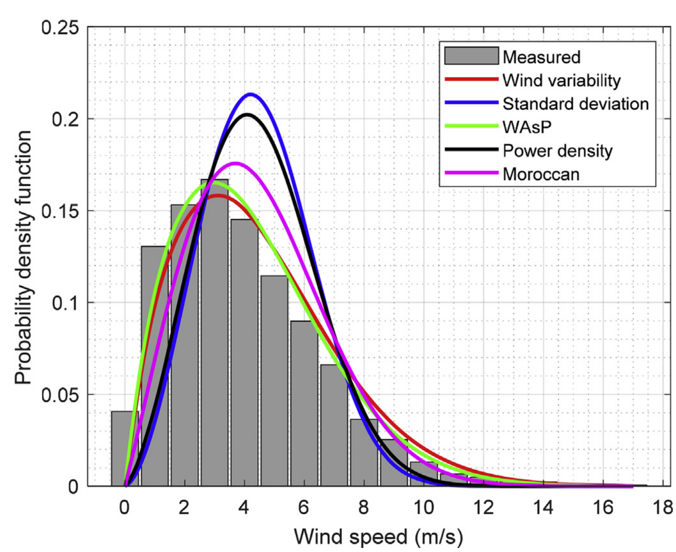


**Fig. 4.** Comparison of the frequency calculated by the four methods for Taza site.

Moreover, some of the methods were found more efficient to adjust wind speeds in specific locations. The results show that the WAsP method present the height values of determination coefficient $R^2$ and low values of RMSE and chi-square $\chi^2$. Moreover, it is further observed that WAsP method based on numerical iterations is fully adequate to estimate the Weibull parameters at the Dakhla and Taza. The power density method presents satisfactory results for Dakhla site. It is also seen that, wind variability method describes wind distribution better than power density, standard deviation and Moroccan methods in the case of Taza site.

Graphically, it is seen that the best fitting of actual data histogram is obtained using the methods based on numerical iterations i.e., WAsP and power density methods in determining the Weibull parameters.

Figs. 5 and 6 shows a wind rose diagram that gives the information about measured wind speed frequency and its corresponding wind

**Table 4**
Performance indicators of five methods for Dakhla site.

| Numerical methods | k | c | $R^2$ | RMSE | $\chi^2$ | % Error |
|---|---|---|---|---|---|---|
| Wind variability | 2.37 | 9.23 | 0.85 | 0.0380 | 0.002 | 10.2 |
| Standard deviation | 6.04 | 8.84 | 0.81 | 0.0300 | 0.00098 | 4.62 |
| Power density | 3.91 | 9.04 | 0.89 | 0.0146 | 0.00082 | 2.39 |
| Moroccan | 2.74 | 9.2 | 0.72 | 0.0317 | 0.0012 | 6.68 |
| WAsP | 4.3 | 8.8 | 0.96 | 0.0121 | 0.0006 | 1.86 |

**Table 5**
Performance indicators of five methods for Taza site.

| Numerical methods | k | c | $R^2$ | RMSE | $\chi^2$ | % Error |
|---|---|---|---|---|---|---|
| Wind variability | 1.75 | 5.01 | 0.88 | 0.0142 | 0.00072 | 2.32 |
| Standard deviation | 2.68 | 5.01 | 0.65 | 0.0300 | 0.0012 | 5.95 |
| Power density | 2.51 | 5.01 | 0.85 | 0.0146 | 0.00091 | 4.53 |
| Moroccan | 2.09 | 5.03 | 0.7 | 0.0317 | 0.00145 | 7.02 |
| WAsP | 1.75 | 4.8 | 0.92 | 0.0122 | 0.00055 | 2.28 |

direction over the period (2015–2017). From these figures, it can be seen that the most probable wind directions in Taza arrived from west. Next, the moderate to low wind speed is received from south-west, and south-east directions, in that order. Thus, the wind direction in Taza is arrived to be between east to west through south, for most part of the period. Moreover, Dakhla receives maximum winds from north, Further, it can be seen that Dakhla site does not receive any wind from south to east and south to west directions.

The monthly wind power density estimated using Weibull function are presented in Figs. 7 and 8 at two heights 50 m and 100 m. It will be expected that Dakhla site with annual wind speed of 8.18 m/s should have higher wind power density compared to Taza site. Dakhla site presents a very good wind power and wind energy potential with annual wind power density of 435.96 W/m$^2$ while Taza site shows poor wind power potential with annual wind power density of 122.91 W/m$^2$.

These figures also show, the highest value of monthly wind power density was identified in July at Dakhla with value of 565.26 W/m$^2$ and in February at Taza with value of 173.52 W/m$^2$ at the height of 50 m, and 803.49 W/m$^2$ and 265.79 W/m$^2$ in Dakhla and Taza at the height 100 m, respectively. We concluded that, the highest values of power density are seen in summer (June, July and August) for Dakhla and in winter for Taza (January, February and March). In Dakhla, the wind energy potential is most suitable for energy generation at two heights 50 m and 100 m while in Taza, the wind energy potential is suitable for energy generation at height 100 m but not suitable for any application at height 50 m.

The characteristic variations of typical monthly mean wind over three years (2015–2017) period is shown in Table 6. It is obvious that the highest values of mean wind speed and power density are visible in summer and they have the lowest values of wind speed in autumn and power density in winter for Dakhla site while the highest values of mean wind speed and power density are visible in winter and the have the lowest values in autumn for Taza site.

The wind speeds and annual wind energy density are presented in different wind classes according to Table 7. This Table show the wind energy resource at the height of 50 m in Taza belongs to class 1, the wind potential not suitable for any wind application. The wind power generation is most suitable from January to April at the height 100 m which power density more than 200 W/m$^2$. Moreover, Dakhla site with monthly power density more than 300 W/m$^2$ at two heights 50 m and 100 m was viable for wind power systems grid connected for electricity generation.

Three turbines with rated power vary from 750 – 1000 kW were selected for performance evaluation in Taza and Dakhla sites. The characteristics of the selected wind turbines are given in Table 8. Fig. 9 represent the power curves variation versus wind speed of the wind turbines. We are calculated the annual capacity factor and annual energy output of the selected wind turbines based on the Weibull probability distribution functions. The selected wind turbines are designed for operation at different hub heights. However, in this work, the efficiency of wind turbines is determined at height of 50 m.

The capacity factor and energy output estimated by each wind turbine model and in each location are shown in Table 9. The results indicate that the annual energy output and capacity factor increases with increasing the wind speed. As shown, the lowest value of annual energy output was

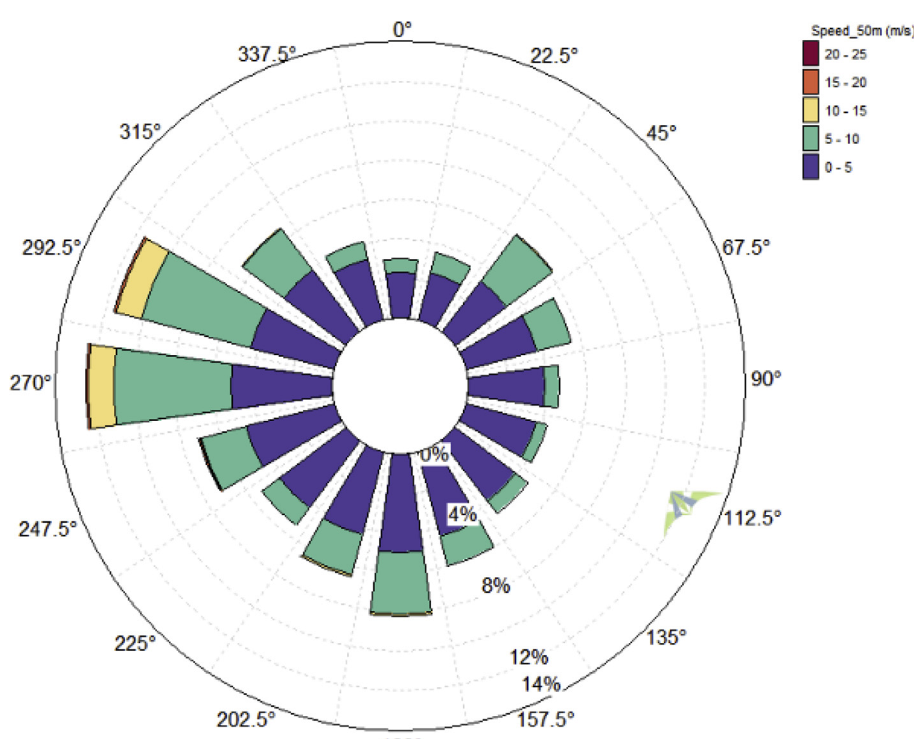


**Fig. 5.** Wind rose polar diagram for Taza site.

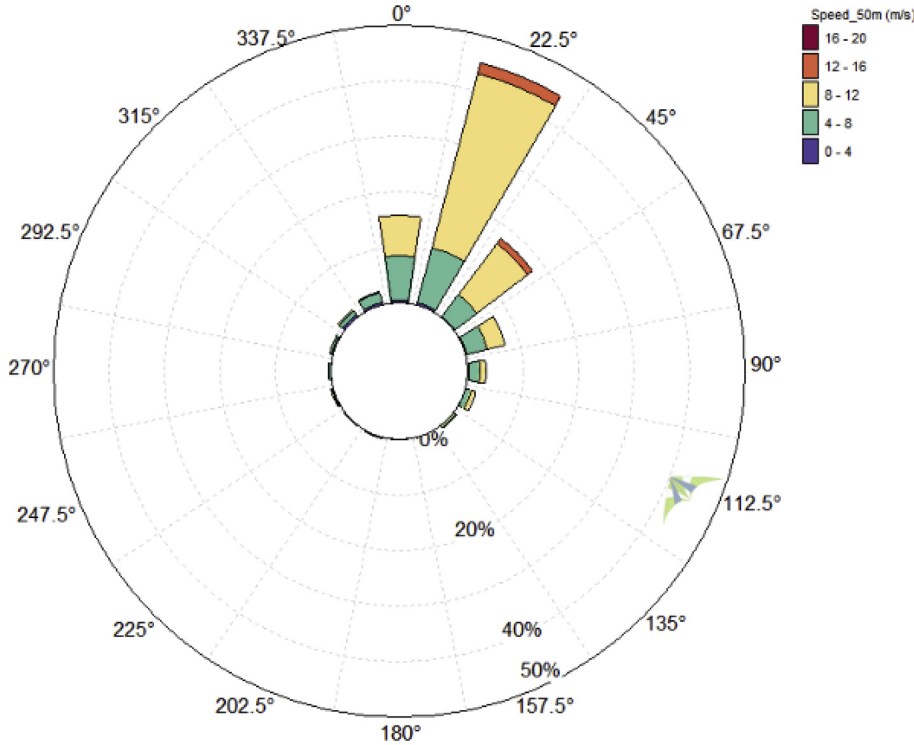


**Fig. 6.** Wind rose polar diagram for Dakhla site.

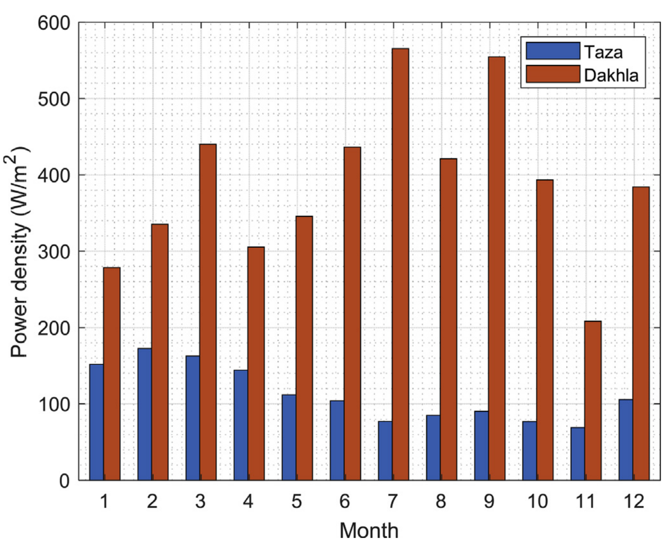


**Fig. 7.** Monthly wind power density from Weibull distribution of Dakhla and Taza sites at 50 m height.

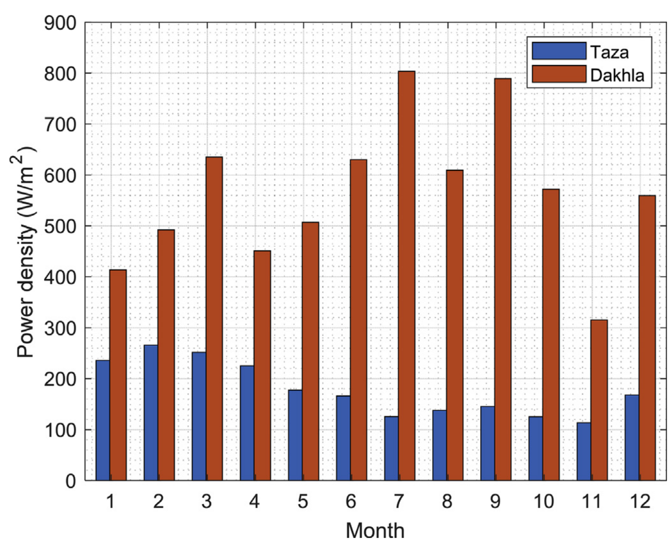


**Fig. 8.** Monthly wind power density from Weibull distribution of Dakhla and Taza sites at 100 m height.

predicted in Taza (less than 0.88 GWh for turbines with a hub height of 50 m). Dakhla showed a higher energy output (between 2.49 GWh and 3.61 GWh) compared with that of Taza (between 0.63 GWh and 0.87 GWh).

The Dakhla site has higher capacity factor and Taza has lower potential for installing wind turbines. Although, Mitsubishi MWT62/1.0 has the highest capacity factor in Dakhla, it most suitable in terms of annual energy generation.

Then, Dakhla was found to be most suitable and has sufficient wind potential for wind power generation. Moreover, we concluded from comparison of wind turbine models, that Mitsubishi MWT62/1.0 wind turbine showed slightly higher capacity factor performance compared with that of Unison U50. It was found to be most suitable turbine model with capacity factor of 41.3%.

**Table 6**
Seasonal variation in wind characteristics for the Moroccan sites.

| sites | | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|---|
| Dakhla | k | 4.23 | 3.97 | 4.43 | 4.57 |
| | c | 8.4 | 8.62 | 9.47 | 8.73 |
| | $v_m$ (m/s) | 8.16 | 8.11 | 8.74 | 7.73 |
| | P (W/m$^2$) | 332.657 | 363.757 | 474.233 | 385.528 |
| Taza | k | 1.88 | 1.79 | 1.68 | 1.65 |
| | c | 5.76 | 5.27 | 4.58 | 4.41 |
| | $v_m$ (m/s) | 5.11 | 4.69 | 4.06 | 3.94 |
| | P (W/m$^2$) | 143.38 | 139.63 | 88.91 | 78.87 |

**Table 7**
NREL classification by wind power density.

| Wind power class | Wind power density (W/m$^2$) | Resource potential |
|---|---|---|
| 1 | 0–200 | Not suitable |
| 2 | 200–300 | Probable for stand – alone applications |
| 3 | 300–400 | Good |
| 4 | 400–500 | Good |
| 5 | 500–600 | Excellent |
| 6 | 600–800 | Outstanding |
| 7 | 800–2000 | Superb |

**Table 8**
Technical specification of selected wind turbine at hub height 50 m.

| Wind turbine | Rated power (kW) | Rotor diameter (m) | Rated speed (m/s) | Cut – in speed (m/s) | Cut – out speed (m/s) |
|---|---|---|---|---|---|
| Hyosung HS50 | 750 | 50 | 14.5 | 3.5 | 25 |
| Unison U50 | 750 | 50 | 12.5 | 2.5 | 25 |
| Mitsubishi MWT62/1.0 | 1000 | 61.4 | 13.5 | 3.5 | 25 |

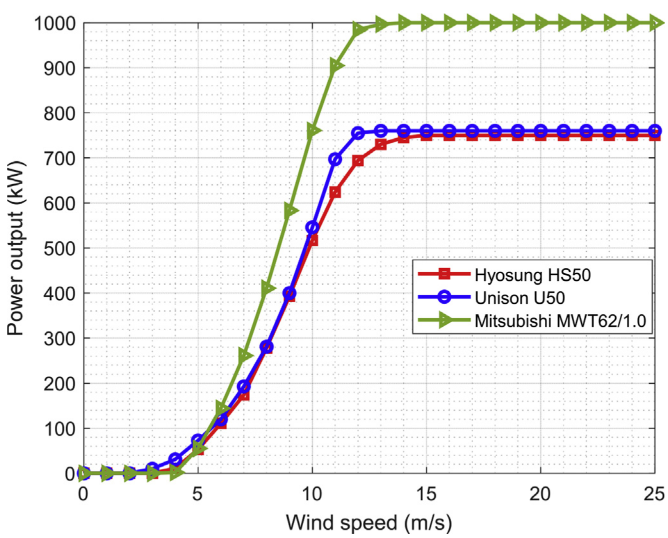


**Fig. 9.** Power curves of three turbines for a hub height of 50 m.

**Table 9**
Annual output energy and capacity factor for three wind turbines at height 50 m.

| Turbines | Taza | | Dakhla | |
|---|---|---|---|---|
| | $C_f$ (%) | $E_{out}$ (GWh) | $C_f$ (%) | $E_{out}$ (GWh) |
| Hyosung HS50 | 9.6 | 0.63 | 38 | 2.49 |
| Unison U50 | 11 | 0.72 | 40.5 | 2.65 |
| Mitsubishi MWT62/1.0 | 10 | 0.87 | 41.3 | 3.61 |

## 5. Conclusions

This article investigated a comparative evaluation of statistical distribution model for fitting wind speed distribution in the site areas of Morocco.

It was found from the goodness of fit test that WAsP and wind variability methods gives better fittings of scale and shape Weibull parameters. Weibull parameters vary over a wide range of values in the entire site. The annual shape parameter varies from 1.65 at Taza to 4.85 at Dakhla and the annual scale parameter ranges from 4.05 m/s in Taza to 10.03 m/s in Dakhla.

Dakhla site presents a very good wind power potential with annual wind power density of 435.96 W/m$^2$ while Taza site shows poor wind power potential with annual wind power density of 122.91 W/m$^2$.

Based on the NREL classification, Dakhla site was identified to be suitable for the grid-connected power generation. Whereas, Taza was not suitable for any wind power application at the height of 50 m.

## Declarations

### *Author contribution statement*

Younes El Khchine: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mohammed Sriti: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Nacer Eddine El Kadri Elyamani: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.


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### *Competing interest statement*

The authors declare no conflict of interest.

### *Additional information*

No additional information is available for this paper.

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