Evaluation of Wind Energy Utilisation and Analysis of Turbines in the Fes Meknes Region, Kingdom of Morocco

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Abstract: This article explores the feasibility of using wind energy to generate electricity in four sites distributed across different geographical provinces of the Kingdom of Morocco (Fes, El Hajeb, Ifrane, Taounate). The objective is to provide accurate scientific information to facilitate decision-making regarding optimal investments in wind technology for electricity production. The data used in this study are sourced from the Windographer software database, which catalogues locations in Morocco. It includes average wind speeds measured per hour at a height of 10 meters for 43 years, extrapolated to different sizes. The sites are selected based on their wind potential for various energy applications. The wind turbine is suitable for the viable site in terms of grid integration and is determined based on the estimation of their capacity factor. One of the study's key findings reveals that the studied sites have limited wind resources and are not viable for grid integration, except for the province of Fes. This information could serve as a basis for developing a renewable energy policy to expand wind energy in Morocco.

Keywords: Wind potential, capacity factor, wind turbine, electricity generation, grid integration.

1 Introduction

Ensuring a transition to green energies is paramount in avoiding devastating climate change. Wind energy is a significant player in accomplishing the emission reduction targets set by the 2015 Paris Agreement [1].

Over the last few decades, the Kingdom of Morocco has continued to develop and innovate its energy strategy in line with international agreements to increase investment in green energies and reduce its dependence on non-renewable fuels such as oil and coal as much as possible [2]. Given this context, one hundred and eleven renewable energy projects have been either finished or are in progress since 2009. Furthermore, the authorities in the
kingdom are actively striving to increase the share of alternative energies in the electricity grid capacity to exceed 52% by the year 2030 [3].

Morocco enjoys advantageous climate and geographical conditions ideal for installing wind turbines. Its coastline, extending over 3,500 km, allows for wind speeds of up to 10 m/s, making it an excellent location for harnessing wind energy [4]. The Kingdom's vision for wind energy [5] indicates a rising trend in establishing new wind projects, intending to enhance wind capacity from 280 MW in 2010 to a substantial 25,000 MW by 2030. To achieve these goals, the installed capacity of renewable sources has reached 3,950 MW, accounting for approximately 37% of the electricity mix (710 MW from solar sources, 1,430 MW from wind sources, and 1,770 MW from hydroelectric sources).

According to the article by Sunny et al. [6], wind technology currently enjoys global recognition as a highly efficient and widely adopted solution for harnessing wind energy. As a renewable energy source, wind energy brings numerous advantages: sustainability, inexhaustibility, cost-effectiveness, and environmental friendliness, with no associated pollution. A study conducted by Namahoro and al. [7] advocates that all nations should invest in exploring wind energy to bolster CO₂ emission reduction policies through its utilisation. Furthermore, investment in wind energy will promote the growth of green economies.

Elsener's article [8] highlights Morocco's substantial wind energy potential within Africa, which still needs to be explored. Consequently, this study focuses on evaluating wind resources and projecting future electricity production in four provinces of the Fes-Meknes region. Importantly, this specific region has yet to be subject to similar studies. While several research endeavours have already explored the wind potential and assessment in various locations across Morocco, this study aims to shed light on previously unexplored areas, for example:

In their study, Nouri and al. [9] conducted a comparative analysis of wind resources at two locations in Morocco: Safi and Essaouira. They primarily aimed to identify the site with favourable wind potential for accurate long-term weather forecasting. They utilised the Wasp software to optimise wind turbine placement and identify areas with strong wind potential to achieve this.

Allouhi and al. [10] examined the wind power potential in six coastal locations across Morocco. Their statistical analysis of wind data over five years revealed that Dakhla exhibited the most favourable conditions for wind energy exploitation, closely followed by Laayoune. These locations are well-suited for grid-connected wind power generation systems. However, Assila and Essaouira are more suitable for small-scale wind energy applications, such as domestic wind turbines.

El Khchine and al. [11] conducted a comprehensive assessment of the wind potential in coastal regions of Morocco, namely Laayoune, Al Hoceima, Boudjord, Essaouira, and Tantan, utilising wind speed data spanning from 2015 to 2018. They applied various methodologies to estimate the parameters of the Weibull distribution. Then, the monthly and annual power and energy densities were calculated at 40m and 50m from the hub height. The performance of five wind turbines with different power capacities was thoroughly evaluated. The study findings revealed that wind speeds are generally higher during winter in the northern regions and summer in the southern regions. Notably, the Boujdour and Essaouira regions showcased the highest power densities among the locations studied.

This study aims to evaluate the wind potential in four provinces within the Fes-Meknes region of Morocco. The initial part is dedicated to analysing wind characteristics and distribution parameters. Subsequently, the Weibull function is employed in the second part to model wind speeds at the four designated sites. An algorithm is utilised to estimate shape and scale parameters, enabling the calculation of power density and annual energy for various turbine heights. Lastly, the study's final section presents the capacity factor of the investigated sites, along with the distribution of dominant winds.
2 Methodology

In this section, we used the two-parameter Weibull distribution to model wind speed. Additionally, we presented various algorithms for estimating wind speed measurements. The data processing software Excel was used. Finally, we calculated the capacity factor at different hub heights.

2.1 Modelling the wind’s velocity.

Wind velocity distribution is commonly described using the Weibull function with two parameters, a widely recognised standard method for assessing local wind probabilities. It has shown accurate fitting with wind data from worldwide regions [12-13]. Studies have consistently highlighted the Weibull distribution's superior fitting capabilities to wind speed data and its comparatively simple mathematical expression compared to other distribution families [14].

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

(1)

Therefore, this article employs the Weibull distribution to depict the wind variation and adopts the parameters \( k \) and \( c \). The probability distribution function of the two-parameter Weibull distribution can be represented as follows, where \( c \) (m/s) is the scale parameter, is the dimensionless shape parameter, and \( v \) (m/s) is the wind speed. The cumulative function of formula (1) is [15]:

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

(2)

The techniques used in determining the parameters \( k \) and \( c \) are diverse and demonstrate their accuracy with minimal error [16]. Among these approaches, for example, are the Maximum Likelihood Method, the Graphical Method, the Least Squares Method of Moments, and others [17]. Empirical methods are often used in studies due to their simplicity in computation [18].

The calculation of variables \( k \) and \( c \) using the Justus empirical method [19] requires the gamma function, standard deviation (m/s), and average wind speed (m/s). Additionally, the most probable wind speed, denoted as \( v_{mp} \), and the wind speed \( v_{max} \), which represents the highest wind energy throughout the study period, are crucial as estimation parameters, and they are expressed as follows [20]:

\[
v_{mp} = c \left( 1 - \frac{1}{k} \right)^{1/k}
\]

(3)

\[
v_{max} = c \left( 1 + \frac{2}{k} \right)^{1/k}
\]

(4)

2.2 Energy modelling and wind power density

The wind power generated by a turbine, represented as \( P_{\text{Wind}} \) (W), varies in direct proportion to the product of the swept area of the turbine and the wind speed \( v^3 \) (m³/s³). This relationship is given, considering the surface area \( S \) (m²) and the air density \( \rho \) (kg/m³) [21], by:
\[ P_{\text{Wind}} = \frac{1}{2} \rho S \int_{0}^{\infty} v^3 f(v) \, dv \]  

Wind power density, denoted as \( P_{\text{density}} \) (W/m²), represents the wind power per unit of area. This essential parameter is crucial for analysing the wind power density of a specific location and it possible to be calculated using the following expression:

\[ P_{\text{density}} = \frac{P_{\text{Wind}}}{S} = \frac{1}{2} \rho \int_{0}^{\infty} v^3 f(v) \, dv \]  

Upon substituting equation (1) into equation (6), we arrive at:

\[ P_{\text{density}} = \frac{1}{2} \rho \int_{0}^{\infty} v^3 \left( \frac{k v^{k-1}}{c^k} \exp \left[ - \left( \frac{v}{c} \right)^k \right] \right) \, dv \]  

Upon integrating and rearranging equation (7), we arrive at the following expression, denoted as equation (8):

\[ P_{\text{density}} = \frac{1}{2} \rho v_m^2 \frac{\Gamma \left( 1 + \frac{3}{k} \right)}{\Gamma \left( 1 + \frac{1}{k} \right)} \]  

Finally, the power density can be written as [22]:

\[ P_{\text{density}} = \frac{1}{2} \rho c^3 \Gamma \left( 1 + \frac{3}{k} \right) \]  

Using this formula for a specific site, one can calculate the average power density, denoted as \( \bar{P}_{\text{density}} \), based on \( P_{\text{density}} \) across the entire range of wind speeds (\( N \)).

\[ \bar{P}_{\text{density}} = \frac{N}{2} \rho \sum_{i=1}^{N} c_i^3 \Gamma \left( 1 + \frac{3j}{\sum_{i=1}^{n} k_i} \right) \]  

The classification established by the National Renewable Energy Laboratory (NREL), at the height of 10 meters, allows sites to be categorised based on the wind power density value. Table 1 presents the wind power classes corresponding to the studied wind speeds [22].

<table>
<thead>
<tr>
<th>Class</th>
<th>( v_m ) (m/s)</th>
<th>( P_{\text{density}} ) (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[0.0, 4.4]</td>
<td>[0, 100]</td>
</tr>
<tr>
<td>2</td>
<td>[4.4, 5.1]</td>
<td>[100, 150]</td>
</tr>
<tr>
<td>3</td>
<td>[5.1, 5.6]</td>
<td>[150, 200]</td>
</tr>
<tr>
<td>4</td>
<td>[5.6, 6.0]</td>
<td>[200, 250]</td>
</tr>
<tr>
<td>5</td>
<td>[6.0, 6.4]</td>
<td>[250, 300]</td>
</tr>
<tr>
<td>6</td>
<td>[6.4, 7.0]</td>
<td>[300, 400]</td>
</tr>
<tr>
<td>7</td>
<td>[7.0, 9.4]</td>
<td>[400, 1000]</td>
</tr>
</tbody>
</table>
Wind power classes 4 and higher are well-suited for grid-integrated applications, offering significant potential for harnessing wind energy. Class 3 sites could be considered for wind energy applications but would require tall tower heights. Class 2 sites demand comprehensive assessment, while class 1 sites rarely are suitable for harnessing wind energy. To calculate the energy density in J/m² and the power density in W/m², it is necessary to include the time variable $t$ in seconds. The formula is expressed as follows [23]:

$$E_{density} = P_{density} t = \frac{1}{2} \rho c^3 \Gamma \left(1 + \frac{3}{k}\right) t$$  \hspace{1cm} (11)

Similarly, and for any given site, the average energy density, denoted as $\bar{E}_{density}$, can be determined by evaluating $E_{density}$ for the $(N)$ wind speeds. It can then be estimated using the following equation:

$$\bar{E}_{density} = \frac{N t}{2} \rho \sum_{i=1}^{N} c_i^3 \Gamma \left(1 + \frac{3N}{\sum_{i=1}^{n} k_i}\right)$$  \hspace{1cm} (12)

2.3 Process of wind speed extrapolation and determination of new parameters $k$ and $c$

Calculating wind power requires a crucial step of measuring the wind speed at the hub height of the wind turbine. However, in numerous instances, wind speeds are estimated or extrapolated to the hub height. In such scenarios, the power law is commonly employed. The following equation establishes a relationship between $v_H$ at the extrapolated height $h$ and $v_0$ at the reference height $h_0$:

$$\frac{v_H}{v_0} = \left(\frac{H}{h_0}\right)^{a}\hspace{1cm} (13)$$

Several extrapolation models have been investigated, notably the Justus and Mikhail model developed in 1979, followed by the power law with an exponent of $1/7$, denoted as “$a$”. Thanks to this approach, we can extrapolate the scale parameter $c_0$ to the reference height $h_0$, allowing us to estimate $c_H$ using the following formula [24]:

$$\frac{c_H}{c_0} = \left(\frac{H}{h_0}\right)^{q}\hspace{1cm} (14)$$

$$q = \frac{0.38 - 0.088 \ln c_0}{1 - 0.088 \ln \left(\frac{H}{10}\right)}\hspace{1cm} (15)$$

Additionally, the shape at a specific height $H$:

$$k_H = k_0 \frac{1 - 0.088 \ln \left(\frac{h_0}{10}\right)}{1 - 0.088 \ln \left(\frac{H}{10}\right)}\hspace{1cm} (16)$$
2.4 Modelling the efficiency rate of wind turbines.

The capacity factor of a power plant, by definition, corresponds to the ratio "x / y" between the actual electrical energy production "x" provided by the installation during a specific period and the theoretical energy production "y" that would have been generated if the installation had operated continuously at full nominal power over the same period. Within the scope of our study, the capacity factor of a wind turbine installed at a specific site represents the amount of energy produced during a given period, divided by its nominal energy generated when it operates continuously at total capacity [25]:

\[ C_f = \frac{\bar{P}}{P_r} \] (17)

This crucial indicator provides an overall view of the performance. A high-capacity factor indicates efficient exploitation of the wind turbine, with a significant energy production compared to its theoretical capacity, whereas a lower capacity factor indicates the opposite. The average power \( \bar{P} \) can be calculated using the Weibull distribution as follows [26]:

\[ \bar{P} = \int_{V_c}^{V_r} P(v)f(v) \, dv \] (18)

To perform the calculation of the previous integral, it is necessary to use the Weibull function \( f(v) \) as indicated in formula (1), as well as the turbine power denoted by \( P(v) \). This power can be modelled either by an exponential curve or a quadratic curve. In the context of this study, we simplify by using the quadratic model with a fixed value for \( k \) (shape parameter) equal to 2. Thus, formula (18) is now [25]:

\[
P(v) = \begin{cases} 
  P_r \frac{v^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} & (v_{ci} \leq v_i \leq v_r) \\
  P_r = \frac{1}{2} \rho ACP v_i^3 & (v_r \leq v_i \leq v_{co}) \\
  0 & (v_i \leq v \text{ and } v_i \geq v_{co})
\end{cases}
\] (19)

\( ci, co \) and \( r \) respectively signify the start-up, shutdown, and nominal speed.

By replacing \( P(v) \) in formula (18), we will have:

\[
\bar{P} = P_r \left[ \int_{V_{ci}}^{V_r} \frac{v_i^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} f(v) \, dv + \int_{V_r}^{V_{co}} f(v) \, dv \right] (20)
\]

The equation (20) can be solved as follows [27]:

\[
\bar{P} = P_r \left( \frac{-\left(\frac{V_{ci}}{c}\right)^k}{\left(\frac{V_r}{c}\right)^k} - \exp\left[-\left(\frac{V_r}{c}\right)^k\right] - \exp\left[-\left(\frac{V_{co}}{c}\right)^k\right] \right) (21)
\]

Thus, \( C_f \) is obtained as follows [27]:
\[
C_f = \frac{\bar{p}}{P_r} = \exp\left(-\left(\frac{v_{ci}}{c}\right)^k\right) - \exp\left(-\left(\frac{v_{ri}}{c}\right)^k\right) - \exp\left(-\left(\frac{v_{co}}{c}\right)^k\right) - \exp\left(-\left(\frac{v_{re}}{c}\right)^k\right)
\]  

(22)

3 Experimental data

This section presents a comprehensive summary of the data utilised, the methodologies employed for data collection, the duration of the data observation period, and the specific geographical locations where the data were recorded. The study focuses on four distinct sites across four provinces within the Fes-Meknes region, as depicted in Figure 1.

Wind velocities were recorded at an elevation of 10 meters and gathered from a txt file sourced from Windographer, covering the period from 1980 to 2022. Table 2 summarises the pertinent information, including population data [28], the standard for location, and the duration of data collection.

Table 2. Information about the examined sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Designate</th>
<th>Population</th>
<th>Altitude(m)</th>
<th>Latitude(°N)</th>
<th>Longitude(°W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fes</td>
<td>L1</td>
<td>1 265 648</td>
<td>406</td>
<td>34.01</td>
<td>5.00</td>
</tr>
<tr>
<td>Ifrane</td>
<td>L2</td>
<td>299 218</td>
<td>1720</td>
<td>33.20</td>
<td>5.15</td>
</tr>
<tr>
<td>El Hajeb</td>
<td>L3</td>
<td>266 642</td>
<td>514</td>
<td>34.00</td>
<td>4.41</td>
</tr>
<tr>
<td>Taounate</td>
<td>L4</td>
<td>637 742</td>
<td>181</td>
<td>34.30</td>
<td>4.50</td>
</tr>
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</table>
4 Results and discussion

This section provides the results obtained from our analysis and includes an in-depth discussion of these findings across various subsections. Subsection 4.1 examines the wind characteristics and computes the distribution parameters for the four studied locations. The potential for electricity production at these sites is assessed in subsection 4.2. Moreover, subsection 4.3 features wind rose diagrams depicting the wind directions at the studied locations. Lastly, in subsection 4.4, we assess the capacity performance factor of various wind turbines available in the market, aiding in the optimal selection of turbines for each location.

4.1 Wind speed characteristics: statistical analysis and Weibull fitting

The wind velocities at the sites have been simulated using the Weibull distribution, as shown in Figure 2 for the selected locations. The wind characteristics $v_m$ and $\sigma$, the power density at 10 m $P_{density,10m}$ for different algorithms, the statistical analysis $R^2$ and $R_{MSE}^2$, as well as the Weibull distribution parameters $k$ and $c$ for each site, were calculated using the data collected throughout the entire observation period. The results are presented in Table 3. The algorithms mentioned in the table below are abbreviated as follows: Empirical Method of Jestus (E.M.J.), Maximum Likelihood Method (M.L.M.) Energy Pattern Factor Method (E.P.F.M.), Empirical Method of Lysen (E.M.L.) Moroccan Method (M.M.) and Graphical Method (G.M.).

<table>
<thead>
<tr>
<th>SITES</th>
<th>$v_m$</th>
<th>$\sigma$</th>
<th>$k$</th>
<th>$c$</th>
<th>$P_{density,10m}$</th>
<th>$R^2$</th>
<th>$R_{MSE}^2$</th>
<th>$v_{mp}$</th>
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<td>L1: Fes</td>
<td>3.8831</td>
<td>2.0123</td>
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<td>4.3830</td>
<td>67.1066</td>
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<td>0.0054</td>
<td>3.1526</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>E.P.F.M.</td>
<td>2.0026</td>
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<td>0.0060</td>
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<td>70.1769</td>
<td>0.9896</td>
<td>0.0073</td>
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<td>0.0057</td>
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<td>0.9942</td>
<td>0.0054</td>
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<td>0.9949</td>
<td>0.0051</td>
<td>3.2136</td>
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<td>68.7995</td>
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<td>1.8680</td>
<td>E.M.J.</td>
<td>2.0791</td>
<td>4.1379</td>
<td>55.4621</td>
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<td>55.3563</td>
<td>0.9907</td>
<td>0.0069</td>
<td>2.4421</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>M.M.</td>
<td>1.8381</td>
<td>3.8994</td>
<td>53.2000</td>
<td>0.9849</td>
<td>0.0088</td>
<td>2.5436</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>M.L.M.</td>
<td>1.7651</td>
<td>3.8949</td>
<td>55.8893</td>
<td>0.9914</td>
<td>0.0066</td>
<td>2.4255</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E.M.L.</td>
<td>1.7839</td>
<td>3.8969</td>
<td>55.1829</td>
<td>0.9902</td>
<td>0.0070</td>
<td>2.4577</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>G.M.</td>
<td>1.7910</td>
<td>3.8770</td>
<td>54.0577</td>
<td>0.9894</td>
<td>0.0073</td>
<td>2.4566</td>
</tr>
<tr>
<td></td>
<td>Real</td>
<td></td>
<td></td>
<td>55.5454</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The table provides valuable insights into the variation of shape parameters $k$ among different locations. The values range from 1.7651 at L4 to 2.1704 at L3. The scale parameters $c$ also show significant variability, ranging from 3.877 m/s at L4 to 4.3858 m/s at L1.
Furthermore, the analysis of wind speeds reveals interesting patterns. The average wind speeds $v_m$ range from 4.34 m/s at L4 to 4.86 m/s at L1. The most probable wind speeds $v_{mp}$ also exhibit fluctuations, ranging from 3.4644 m/s at L4 to 3.8831 m/s at L1. Moreover, the wind speed carrying the maximum energy $v_{mp}$ attains its highest value at L1, with a velocity of 6.2840 m/s, while its lowest value is recorded at L3, measuring 5.4968 m/s.

Before entering this section, it is important to emphasize that higher values of the Weibull $c$ and $k$ parameters indicate a significant potential for wind energy application. Figure 2 presents these parameters evaluated monthly. A noteworthy observation from the figure is that location L1 (Fès) consistently displays the highest Weibull scale parameter throughout the year, closely followed by station L2 (Ifrane). This distinction can be attributed to their higher altitudes, 406 m for L1 and 1720 m for L2, compared to the other sites.

Location L4 (Taounate) exhibits the lowest Weibull parameter, while location L3 (El Hajeb) follows closely, signifying that they are the least windy locations in comparison to the other sites.

![Fig. 2. Monthly estimation of the scale (a) and shape (b) factors using the best algorithm.](image-url)
4.2 Wind data adjustment

The wind power densities for each site were assessed using data collected from 1980 to 2022 and classified according to NREL standards. The comprehensive results are presented in Table 4.

Table 4. Classification of sites for wind energy application according to NREL standards.

<table>
<thead>
<tr>
<th>Location</th>
<th>$v_m$ (m/s)</th>
<th>$P_{density}$ (W/m²)</th>
<th>Class</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>3.8831</td>
<td>64.9102</td>
<td>1</td>
<td>Low</td>
</tr>
<tr>
<td>L2</td>
<td>3.6652</td>
<td>55.4621</td>
<td>1</td>
<td>Low</td>
</tr>
<tr>
<td>L3</td>
<td>3.6030</td>
<td>50.6473</td>
<td>1</td>
<td>Low</td>
</tr>
<tr>
<td>L4</td>
<td>3.4645</td>
<td>55.8896</td>
<td>1</td>
<td>Low</td>
</tr>
</tbody>
</table>

According to the table, it can be observed that sites L1 and L2 exhibit average wind speeds of 3.8831 m/s and 3.6652 m/s, respectively, corresponding to power densities of 64.9102 W/m² and 55.4621 W/m². These sites fall into class 1 based on NREL’s classification, indicating a low wind energy potential. Consequently, these sites are unsuitable for grid integration applications but are well-suited for standalone wind applications such as battery charging and other mechanical uses.

The power densities of the sites were also assessed monthly, and the results are illustrated in Figure 4. Thanks to this analysis, we understand the wind power by season at each location, which is crucial for the planning and operation of wind systems in the studied region.

The graph highlights the variations in monthly power density for the studied sites. Site L1 exhibits the highest power density compared to the average. Additionally, the curves show fluctuations. Regarding seasonal variations, the months from November to March are characterized by higher power densities (strong winds), while the months from June to September show lower power densities (calmer winds).

For example, site L1 has the highest power density in February and December and the lowest from June to September. Site L2 exhibits a power density like the average (black curve). Site L3 is below the average power density, while site L4 has power density values like the average, except for November to February.
4.3 Wind Rose

The wind rose is a more visually accessible graphical representation than numbers. It displays the wind direction based on various parameters the researcher chose, such as output energy, minimum and maximum wind speed, and wind frequency. Additionally, the circular graph aids in determining the most suitable location for a wind farm [30]. This visual tool is vital in selecting the appropriate turbine type and orientation relative to the prevailing wind flow, ensuring optimal performance and efficiency.

The graphs depicted in Figure 5, from (a) to (d), show the wind rose plots at a height of 50m, based on wind direction. They are presented in a polar format with 16 sectors, each representing an angle of 22.5°, considering the wind speed frequency as well. The plots reveal significant variations in the distribution of predominant wind directions at the studied sites. For instance, Ifrane and Taounate sites exhibit similar wind directions ranging clockwise from south to north, with wind frequencies ranging from 7 to 8%. On the other hand, the Fes site experiences strong winds from the northeast, with a frequency of 10-11%. Meanwhile, the El Hajeb site is characterized by a predominant wind direction of west-northwest, with a frequency of 19% and wind speeds reaching up to 12 m/s.

The wind rose plots offer valuable insights into the local wind patterns, crucial for making informed decisions in wind farm planning and design. The diverse wind directions and speeds observed among the sites underscore the significance of site-specific considerations when implementing wind energy projects. Understanding the unique wind characteristics of a location enables optimal turbine placement, maximizing the energy production in the studied region. By leveraging this information, wind energy projects can be developed more efficiently and effectively, leading to more significant sustainable energy generation.
4.4 Assessment of the performance coefficient for wind turbine selection

The capacity factor is used to assess the suitability of a wind turbine for a specific site. A thorough investigation of wind turbines available in the international market is meticulously conducted. The approach is to choose the turbines with nominal rated power from 15 kW to 3 MW. The chosen wind turbines from different manufacturers and available on the market are categorized into four groups based on their power: domestic, small commercial, medium commercial, and large commercial wind turbines, as indicated in Table 5. Subsequently, a calculation is performed to determine the appropriate capacity factor for each site.

Table 5. Studied wind turbines with power ranging from 15 to 3000 kW and their characteristics

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Abbreviation</th>
<th>Rated power output</th>
<th>Hub(m)</th>
<th>(v_{ce}(m/s))</th>
<th>(v_{m}(m/s))</th>
<th>(v_{cof}(m/s))</th>
<th>Area(m²)</th>
<th>Survival Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proven 15 kw</td>
<td>Tr1</td>
<td>15 KW</td>
<td>25</td>
<td>2.5</td>
<td>12</td>
<td>54</td>
<td>72</td>
<td>54</td>
</tr>
<tr>
<td>Small business wind turbine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seaforth AOC 15/50 50Hz</td>
<td>Tr2</td>
<td>50 KW</td>
<td>30</td>
<td>4.6</td>
<td>12.5</td>
<td>22.4</td>
<td>177</td>
<td>59.5</td>
</tr>
<tr>
<td>Northern power 60/23</td>
<td>Tr3</td>
<td>60 KW</td>
<td>37</td>
<td>3</td>
<td>11</td>
<td>25</td>
<td>468</td>
<td>52.5</td>
</tr>
<tr>
<td>Commercial average wind turbine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Wind rose diagrams of sites (a) Fes (b) Ifrane (c) Taounate (d) El Hajeb.
Previous research has established that the reasonable range for the capacity factor should be above 0.25 and below 0.40. The closer this value is to 0.40, the better the results. The adaptation of each wind turbine to the selected site is presented in Table 6. This table summarizes the study's findings. The first observation indicates that site L1 has a capacity factor higher than 0.25. This site is compatible with two types of wind turbines, namely Tr1 and Tr10. The obtained results are illustrated in the table below.

According to the data in the table, we can observe that the Tr1 turbine (Proven 15 kW) from the Domestic Wind Turbine category, with a nominal power of 15 kW, and the T10 turbine (Wind to Energy W2E-120/3fc) from the Large Commercial Wind Turbine category, with a nominal power of 3000 kW, best match the wind characteristics of site L1. No Small or Medium Commercial Wind Turbine turbine is suitable for the studied sites. For sites L2 and L3, the Domestic Wind Turbine category is the most appropriate, with the Tr1 turbine exhibiting marginal capacity factors of 21.69% and 21.46%, respectively. As for site L4, it is recommended to install a Tr1 turbine from the Domestic Wind Turbine category, as well as the Tr9 and Tr10 turbines from the Large Commercial category, which display marginal capacity factors of 22.95%, 20.17% and 21.79%, respectively.

### Table 6. Estimated Capacity Factor ($C_f$).

<table>
<thead>
<tr>
<th>Location</th>
<th>Tr1</th>
<th>Tr2</th>
<th>Tr3</th>
<th>Tr4</th>
<th>Tr5</th>
<th>Tr6</th>
<th>Tr7</th>
<th>Tr8</th>
<th>Tr9</th>
<th>Tr10</th>
<th>Tr11</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>26.50</td>
<td>20.11</td>
<td>22.22</td>
<td>22.10</td>
<td>20.12</td>
<td>13.98</td>
<td>18.39</td>
<td>24.18</td>
<td>23.43</td>
<td>25.32</td>
<td>22.87</td>
</tr>
<tr>
<td>L2</td>
<td>21.69</td>
<td>16.19</td>
<td>17.94</td>
<td>17.54</td>
<td>15.75</td>
<td>16.08</td>
<td>14.52</td>
<td>19.50</td>
<td>18.75</td>
<td>20.55</td>
<td>13.33</td>
</tr>
<tr>
<td>L3</td>
<td>21.46</td>
<td>15.81</td>
<td>17.59</td>
<td>16.78</td>
<td>15.01</td>
<td>10.11</td>
<td>13.91</td>
<td>18.77</td>
<td>18.05</td>
<td>19.82</td>
<td>17.58</td>
</tr>
<tr>
<td>L4</td>
<td>22.95</td>
<td>17.27</td>
<td>19.17</td>
<td>18.89</td>
<td>17.14</td>
<td>11.75</td>
<td>15.65</td>
<td>20.83</td>
<td>20.17</td>
<td>21.79</td>
<td>19.62</td>
</tr>
</tbody>
</table>

### 5 Conclusion

This study assessed the feasibility of wind energy at four sites in the Fes-Meknes region in the Kingdom of Morocco. In summary, Taounate, Ifrane, and El Hajeb sites are more suitable for small-scale wind turbines rather than integration into the national electrical grid. However, the Fes site shows potential for using large-capacity commercial turbines to establish a wind farm. The specific findings are as follows:

Site L1 (Fes) has an average wind speed of 3.8831 m/s. This site has a decent wind resource and is viable for grid integration of wind energy. As for the other sites' average wind speeds were generally between 3.66 and 3.46 m/s.
The Weibull distribution parameters, estimated using different methods, varied across the sites. The variations of the shape \((k)\) and scale \((c)\) parameters were estimated in the range of 1.7651 to 2.0990 and 3.8949 to 4.3858 m/s, respectively, at the height of 10 meters.

The Fes site exhibited an acceptable wind power density compared to the other sites. The maximum power density at Fes in December was 93.5 W/m² at the height of 10 meters and 283.7 W/m² at a height of 140 meters.

The wind direction distributions are diverse across the studied sites. Ifrane and Taounate exhibit similar wind directions, moving clockwise from south to north, with a wind speed frequency of 7 to 8%. Fes experiences strong winds from the northeast, with a frequency of 10 to 11%. El Hajeb, on the other hand, is characterized by a predominant wind direction from the west-northwest, with a frequency of 19% and speeds reaching up to 12 m/s. The main points regarding limitations, validation of results and prospects are as follows:

We only assessed four sites in the Fès-Meknès region, which limits the generalisation of the results to the whole region or Morocco. In addition, the modelling was based on the Weibull distribution. However, other distribution functions such as Rayleigh, Gamma and Log-Normal could be considered to improve the accuracy of our forecasts.

To validate our predictions, in situ measurements at several sites and over an extended period would be required to compare our predictions with actual wind generation data. A comparison with other wind forecasting models, such as ERA-Interim from the European Centre, MERRA-2 from NASA and JRA-55 from the Japan Meteorological Agency, could increase the reliability of our results. Including additional meteorological data, such as atmospheric pressure and temperature, could also improve our model's accuracy.

An in-depth economic study would be an essential complement to our research. For a more global perspective on energy sustainability, examining how wind energy could be integrated with other renewable energy sources, such as solar energy, would be relevant to meet Morocco's energy needs.

By considering these limitations, proposing methods for validating the results and exploring future perspectives, we hope to improve the quality and applicability of our research in the context of wind energy in Morocco.

References

6. K. A. Sunny, P. Kumar, and N. M. Kumar, Experimental study on novel curved blade vertical axis wind turbines, Results Eng., 7, 100-149, (2020)
9. A. Nouri, M. Ait Babram, E. Elwarraki, and M. Enzili, Moroccan wind farm potential
16. A. Aslan, Comparison based on the technical and economical analysis of wind energy potential at onshore, coastal, and offshore locations in Comparison based on the technical and economical analysis of wind energy potential at onshore, coastal, and offshore local, J. Renewable Sustainable Energy, 12, 063-306 (2020)

