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Research Article

Site suitability analysis of wind energy resources in different regions of Algeria's southwestern highland

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Abstract. This paper presents a site suitability analysis for a 20 MW wind farm project in western Algeria's highlands. The aim is to improve the quality of the electricity grid's service and increase Algeria's renewable energy utilization. The wind potential of three regions, Mecheria, El Kheiter, and Naâma, was evaluated using the Weibull function and the wind atlas analysis and application program (WAsP) with a ten-year database (2011-2021) at 10 m hub height. The assessment encompassed a comprehensive analysis of various wind resource parameters, including mean wind speed, prevailing direction, and power densities. In comparison to other sites, the Mecheria region has the best wind potential, with a mean annual wind speed of 6.31 m/s, a power density of 283 W/m^2, and Weibull parameters A = 7.1 m/s and k = 2.02. These promising results prompted us to design a wind farm in this region using Power Wind 90/2000 kW turbine technology facing the predominant wind directions of the site, producing 103.91 GWh of total annual gross energy produced (gross AEP) and 103.75 GWh of total annual net energy produced (net AEP). Finally, it appears that the wind resources in the selected region are well-suited for electricity generation, offering a promising opportunity to reduce the country's dependence on fossil fuels.

Keywords: Wind resource assessment, Site suitability analysis, Weibull distribution, WAsP, Power density, Algeria

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1. Introduction

Wind energy is now widely regarded as the most promising renewable energy source for replacing coal, oil, gas, and even nuclear power (Solarin & Bello, 2021). In Algeria, a North African country, electricity generation is almost entirely based on the extraction and transformation of fossil fuels. Algeria has significant solar and wind potential due to its geographical location, particularly in the South. A large program to promote renewable energy is currently underway with the goal of producing 22,000 MW of clean electrical energy by 2030, 5010 MW of which will be generated by wind energy (Stambouli *et al.*, 2012). (Said.,1984) published the first Algerian work on wind potential, which was followed by (Bensaid 1985), (Abdeladim *et al.*,1996), and (Merzouk, 2000). In comparison to previous work, the most recent studies have used recent meteorological data and a large number of measurement points (Boudia & Guerri., 2015; Abdeslame *et al.*, 2017).

Only hybrid systems with good energy integration and optimization can currently solve the problem of climate intermittency, increase the penetration of renewable energies, and lower storage system costs (Liu *et al.*,2022). The work presented in this paper only addresses the first stage of our project, which is to find a suitable location for the construction of a wind farm and to connect it in the future to the Naâma photovoltaic power plant, which was completed in May 2016 (Chabani *et al.*, 2018), by designing a hybrid system connected to the grid.

The availability of wind power databases, the presence of an electrical network to collect power, the absence of exclusion zones, and suitable terrain are the primary criteria for site selection (Asadi & Pourhossein., 2021). Our prospecting has led us to the southwest Algerian highlands, specifically Mecheria, El Kheiter, and Naâma. Thus, it meets these conditions in particular, as well as several other favorable conditions, such as the proximity of the NAÂMA photovoltaic plant, the presence of a weather station to measure wind speed, and the presence of a central grid disturbance. Some research has been done to determine wind data recorded at Mecheria, which shows a very promising mean wind speed of 5.6 m/s in the dominant southeast direction, 4.9 m/s and 4.4 m/s at El Kheiter and Naâma sites, respectively (Nedjari *et al.*, 2017).

In addition, the WAsP (Wind Atlas Analysis and Application Program) was used to aid in the analysis and diagnosis of each site. Several researchers have used it to assess the wind potential of many regions and conduct wind resource analyses, demonstrating that WAsP is a robust and reliable tool for wind assessment (De Araujo *et al.,* 2012). The methodology for sizing a wind farm generally consists of several steps. It starts with a statistical analysis of measurements and determining the mean wind speed. The optimal configuration and compatible wind turbine technology are then determined (Cetinay *et al.*, 2017).

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Few studies have employed extended time series data in Algeria (Meziane *et al*., 2021) (Diaf & Notton, 2013), and only a few works have reported on the assessment of wind potential in the Highlands, with no reports evaluating the Mecheria site. The current study aims to introduce a scientifically rigorous approach with an international standards-compliant methodology to assess wind potential in Algeria's southwestern highlands, which include three regions: Mecheria, El Kheiter, and Naâma, using WAsP software with the latest wind speed and wind direction data collected at the National Meteorological Office (ONM) network between 2011 and 2021. The WAsP tool was used to compute the mean wind speed and mean power density for each site, allowing us to select the best location for a wind farm project to contribute to Algeria's vision for renewable energy development.

2. Method and theory

2.1. Overview of method

The study's methodology for selecting a favorable wind farm location consists of four steps. Because wind speed is the most important factor in the construction of a wind power plant, the first step is to analyze wind data. The second stage of our process entails using WAsP software to estimate wind climatology based on three-hour data of wind speed and direction recorded at 10 m a.g.l for each of the three sites. Following that, in the third step, we enter the topographical information for each site as input into the WAsP map editor tool, which generates a contour map and wind atlases that represent the wind field of the studied areas. The fourth and final step necessitates the use of previous steps for site selection decision-making and, thus, wind farm siting analysis, where types and quantities of turbines, installation location, and energy output are identified for the chosen site.

2.2. Wind data collection

A minimum of one year of observational data is necessary to quantify the available wind resources and to assess wind potential energy development (Ko *et al*., 2015).In order to mitigate any seasonal biases and make analysis less influenced by the specific conditions of a single year, this study collected wind speed and wind direction data at 10 m a.g.l from three weather stations situated in Southwestern Highlands Algeria obtained from the National Meteorological Office of Algeria (ONM) over a period of 10 years. The geographical coordinates of the meteorological stations and measurement duration of the three sites are shown in Table 1.

2.3 Wind Data Adjustment

Adjusting wind speed across different heights, locations, and times is a crucial process for wind resource assessment ensuring its suitability and accuracy for the analysis. To achieve this, it is necessary to adjust the collected wind data through the application of extrapolation methods in the following steps (Jourdier, 2015).

Table 1
Geographical coordinates of the measurement sites.

Station	Latitude (°	Longitude (°)	Altitude (m)	Measurement period
Mecheria	33.580	-0.280	1150.00	2011-2021
El Kheiter	34.149	0.067	1080.82	2011-2021
Naàma	33.263	-0.309	1174.39	2011-2021

2.3.1 Vertical extrapolation

One of the main objectives during site assessment is to estimate the wind resource at the hub height of a wind turbine because the Meteorological mast used for collecting wind data is generally positioned at lower heights than the turbine hub. Therefore, it is necessary to employ a mathematical model to extrapolate the measured wind to the turbine hub. In this study, the logarithmic law expression was used, as it stands as the primary function employed by WAsP software, defined by Eq. (1) (Petersen *et al*., 1998):

$$V(z) = \frac{V_*}{0.4} ln\left(\frac{z}{z_0}\right) \quad (1)$$

WAsP uses a single height measurement as well as a local roughness map to determine the z_0 parameter upstream of the mast for each wind direction. The friction velocity V_* is then calculated, which characterizes the flow at a higher altitude unaffected by the surface. Then, it descends from the upper-level wind to the wind near the surface at the desired height and location (Petersen *et al*., 1998).

2.3.2 Temporal extrapolation

"Long-term adjustment" is another term for temporal extrapolation, which involves extending data from a limited period to a longer period. To address this, another set of wind data collected over many years (long-term reference data) from a nearby location is essential. These reference data serve as a basis for making a more precise estimation of wind conditions at the study site. Methods such as MCP (measurement-correlation-prediction) are widely used in this step (Janie,2015). Their principle is to establish a relationship between the measurement taken at the site V_{site} and reference measurement V_{ref}. As shown in Eq. (2), linear regression is an improved version of the Klint and Langreder method (Carta *et al.,* 2013) is employed to achieve this adjustment, incorporating a random term Є that follows a normal distribution, thereby addressing the issue of decreasing variance and ultimately yielding improved results.

$$\hat{V}_{site} = \beta_0 + \beta_1 V_{ref} + \epsilon \quad (2)$$

2.3.3 Horizontal extrapolation and wake effect

Horizontal extrapolation accounts for the fact that wind turbines will not be installed exactly where the measurement mast is. This step is also used to test the various wind farm configurations, allowing the wind turbines to be placed in the windiest locations while minimizing the wake effects of the turbines on each other (Abdel-Rahman *et al*., 2022). Horizontal extrapolation is never performed alone. In most cases, it is combined with the steps of calculating gross output and wake-adjusted output. The WAsP is the best software for this step.

2.4. Weibull distribution

The observed time series is not typically kept during the wind extrapolation steps. Its distribution is frequently modeled by the Weibull distribution, which is widely used due to its high flexibility and precision (Pishgar *et al*., 2015). It represents a statistical distribution that is determined by two (strictly positive) parameters:

- *A*, scale factor that is close to the mean wind speed,
- *k*, shape factor.

The probability density function (*PDF*) as a function of wind speed *V* is written as follows (Wadi *et al*., 2021):

$$p(V) = \frac{k}{A}\left(\frac{V}{A}\right)^{k-1} exp\left[-\left(\frac{V}{A}\right)^{K}\right] \quad (3)$$

The cumulative distribution function (*CDF)* is given by Eq. (4) (Wadi *et al.,* 2021) :

$$F(V) = 1 - exp\left[-\left(\frac{V}{A}\right)^{K}\right] \quad (4)$$

For calculating the mean wind speed $\bar{v}$, following expressions can be used:

$$\bar{v} = \frac{1}{n}\left[\sum_{i=1}^{n} v_i\right] \quad (5)$$

Weibull parameters can be determined using a variety of methods, including simple analytical expressions and numerical approaches. Among these are the moments method (Justus *et al.,* 1978), the least squares method based on the cumulative Weibull function, and the Energy Factor method (Akdag & Dinler., 2009). We chose the moment's method because it stems as the predominant method utilized by WAsP, where the probability equation of the above-average winds is (Pryor *et al*., 2004):

$$\hat{p} = \frac{1}{n}\sum_{i=1}^{n} 1\left\{V_i \rhd \overline{V}\right\} \quad (6)$$

The result is Eq. (7):

$$ln(-ln(\hat{p})) - k\left[ln\left(\frac{1}{n}\sum_{i=1}^{n} V_i\right) - \frac{1}{3}ln\left(\frac{1}{n}\sum_{i=1}^{n} V_i^3\right) + \frac{1}{3}\Gamma\left(1 + \frac{3}{k}\right)\right] = 0 \quad (7)$$

Eq. (7) is solved iteratively to determine *k,* and then, as with the method of moments, *A* is calculated with Eq. (8):

$$A = \left(\frac{\frac{1}{n}\sum_{i=1}^{n} V_i^3}{\Gamma\left(1+\frac{3}{k}\right)}\right)^{\frac{1}{3}} \quad (8)$$

Where Γ is the gamma function given as follows:

$$\Gamma(x) = \int_0^{\infty} e^t\, t^{x-1}\, dt \quad (9)$$

2.5. Power curve and gross production

A wind turbine's power curve is the function that gives the power delivered by the machine as a function of wind speed V called Power density. It is expressed as follows (Candona *et al.*, 2018):

$$p(V) = \frac{1}{2}\rho S c_p(V) V^3 \quad (10)$$

where P is the power delivered in W,ρ is the air density in $kg{\cdot}m^{-3}$, S is the area swept by the rotor (πR^2 for a wind turbine with radius R) in $m^{2,}$ and C_p is the power coefficient, a characteristic of the turbine.

The function curve's general form has two parts with different shapes: a parabolic part and a constant linear part. The first nonlinear portion of the power curve causes significant differentiation between users and manufacturers (Carrillo *et al.*, 2013).

3. Results and Discussion

In this section, we present the key findings and delve into a comprehensive discussion of the results obtained from the comparative assessment at Mecheria, El Kheiter, and Naâma, using a ten-year database. The assessment covered various aspects of wind resource evaluation, such as the mean wind speed, the prevailing direction, their duration, and availability. Additionally, the assessment delved into the resulting power density, detailed wind farm design considerations, and meticulous analysis of the potential energy output, shedding light on the viability and potential for sustainable wind energy generation at the suitable selected location.

3.1 Wind speed variation

Wind speed serves as a pivotal factor in accurately assessing the potential for harnessing wind energy via turbines to generate electricity. Evaluating the variability in wind speed, including its daily, monthly, seasonal, and annual fluctuations, is of utmost significance in determining the anticipated energy production over specific timeframes (Abdelrahman *et al*., 2022). Fig. 1 shows the daily average wind speed of Mecheria, El Kheiter, and Naâma at 10 m a.g.l and Fig. 2 illustrates the monthly mean wind speeds of the three sites met mast at 10 m height.

The evaluation of hourly mean wind speed variations, conducted using Eq. (5), revealed that the maximum values of wind speed were recorded in the afternoon, while the lowest values were recorded in the early hours of the day for the three sites. This can be attributed to the diurnal wind patterns

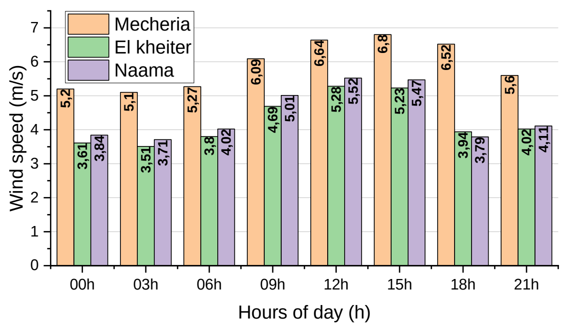


Fig. 1. Hourly mean wind speed variations of the three sites at 10 m a.g.l.

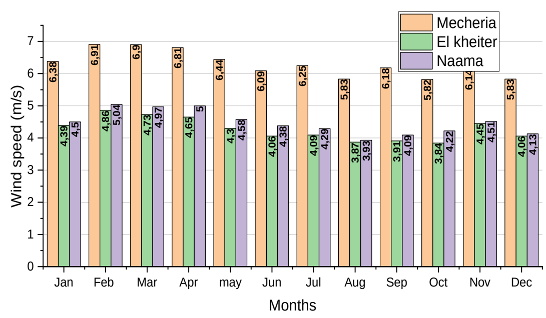


Fig. 2. Monthly mean wind speed variations of the three sites at 10 m a.g.l.

influenced by the heating and cooling of the Earth's surface (Schmid *et al.*, 2020). Although the hourly wind speed data shows that wind speeds start to increase around 06h (6 a.m.). This is likely due to the initial warming of the surface as the day begins. The peak wind speed occurs at around 15h (3 p.m.), aligning with the time of maximum surface heating, which leads to the most significant convective activity and stronger winds. As the day progresses and the surface starts to cool, the wind speeds begin to decrease, as shown in Fig. 1.

Monthly wind speed fluctuations were determined through the application of Eq. (5), revealing significant congruities in the wind speed patterns across the three sites., These patterns reveal higher wind speeds during spring and a corresponding decrease in wind speed during autumn (Fig. 2). This is because Spring and autumn mark transitional periods between the extremes of winter and summer. During these transitions, weather patterns tend to be less stable, and temperature and pressure gradients change. In spring, as temperatures rise, pressure systems may become more dynamic, leading to increased wind speeds. Conversely, in autumn, temperatures begin to cool, resulting in decreased wind speeds (Wooten, 2011)

Thus, the analysis of hourly and monthly variations in wind speed at the three sites (Figs. 1 and 2) indicates that the Mecheria site experiences higher wind speed values during colder months of the year compared to El Kheiter and Naâma and that the site's consistent wind resources in these periods could position it as a promising candidate for a hybrid system. This potential system would combine both wind and solar energy generation, potentially improving the reliability and efficiency of renewable energy production throughout the year and optimizing the system's output.

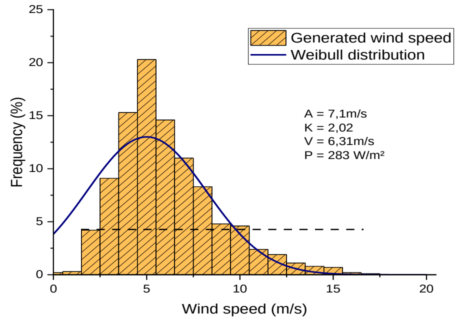
3.2 Weibull Distribution and Power Density

There are many distribution functions proposed in the literature for evaluating wind data around the world such as Weibull (Wan *et al.*, 2021), Rayleigh (Serban *et al.*, 2020), Gamma (Lo Brano *et al.*, 2011) Burr (Soukissian, 2013), Normal, truncated normal (Carta, 2009), Loglogistic (Wu *et al.*, 2013), and lognormal (Calif & Schmitt., 2012). The main function of the WAsP software is the Weibull distribution. Fig. 3 shows the probability density function of the annual wind speed distribution for Mecheria, El Kheiter, and Naâma at 10 m a.g.l using Weibull models Eq. (3).

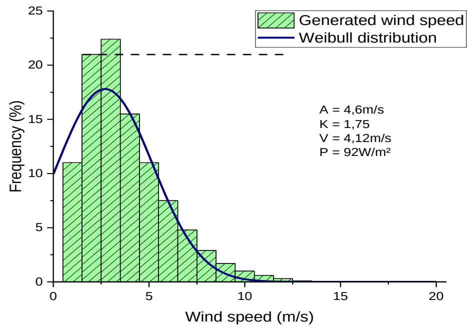
The wind power density can be divided into seven categories on the basis of windspeed and annual wind power density, as illustrated in Table 2. The analysis of Weibull distribution histograms for the three different sites reveals distinct wind speed and annual wind power density classifications as shown in Fig. 3. The annual mean wind speed and mean power density with the highest value of 6.31 m/s and 283 W/m² was found in Mecheria, which belongs to wind class 5, followed by Naâma (4.28 m/s and 103 W/m²) with a wind

Table 2
Wind Power classification at 10 m a.g.l (Dayal *et al.*, 2021).

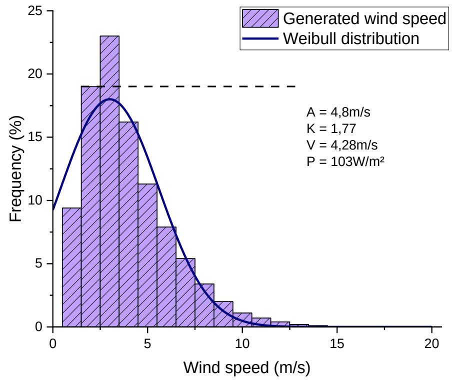
Wind Power Class	Mean wind speed (m/s)	Wind Power Density (W/m²)
1	0-4.4	0-100
2	4.4-5.1	100-150
3	5.1-5.6	150-200
4	5.6-6.0	200-250
5	6.0-6.4	250-300
6	6.4-7.0	300-400
7	7.0-9.4	400-1000



(a)Mecheria



(b)El Kheiter



(c) Naama

Fig. 3. Annual wind speed frequencies fitted by Weibull distribution for the three sites.

class 2 and El Kheiter (4.12 m/s and 92 W/m²) classifying it as a wind class 1. Dayal et al (Dayal *et al.*, 2021) reported that a Wind Power Class of 3 or higher is typically deemed appropriate for most utility-scale wind power developments which compare favorably to similar studies in Algeria's highlands. El Bayadh for example boasts a mean wind speed of 4.73 m/s and a power density of 157.49 w/m2, while Djelfa records a mean wind speed of 3.88 m/s with a power density of 81.57 w/m2 (Merzouk & Merzouk, 2012). Furthermore, in the far East the annual mean wind speed values for three highlands stations Ksar-Chellala, Tiaret and M'sila were 3.94 m/s, 5.07 m/s, and 4.03 m/s, respectively, with power densities of 144 w/m², 238 w/m², and 142.13 w/m² (Louassa *et al.,* 2017) (Belabes *et al.*, 2015) (Boudia *et al.*, 2012). Thus, findings clearly show that the Mecheria site exhibits a higher level of wind resources in comparison to other highlands sites and possesses great potential for wind farm development.

Table 3
Seasonal Weibull parameters.

Site	Parameters	Winter	Spring	Summer	Autumn	Annual
Mecheria	A m/s	7.1	7.5	6.8	6.8	7.1
	K	1.88	2.04	2.17	2.09	2.02
ElKheiter	A m/s	4.6	5	4.4	4.3	4.6
	K	1.61	1.83	2.04	1.65	1.75
Naâma	A m/s	4.7	5,3	4.6	4.4	4.8
	K	1.57	1.87	2.12	1.69	1.77

Table 3 lists the seasonal and annual Weibull K and A parameters for the three locations. The shape factor K can be used to predict wind stability and wind distribution at a specific location, whereas the scale factor A can predict wind strength (Al-Ghriybah, 2022).

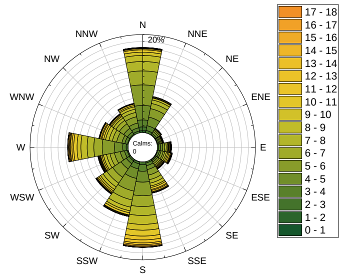
The variations of standard deviation, shape and scale factors are calculated using Eq. (7) and (8). The Mecheria site has the highest annual values for k and A, with values of 2.02 and 7.1 m/s, respectively, while the El Kheiter site has the lowest values of 1.75 and 4.6 m/s. This observation aligns with the principles of Weibull parameters, where higher A values correspond to elevated mean wind speeds, simultaneously, a higher K value surpassing the 2 value signifies reduced variation and a more stable wind in the location (Manwell *et al.*, 2006).

The investigation of seasonal variation of shape and scale factors leads to the conclusion that wind speed is more uniform in Summer than in Winter across the three sites. These findings are consistent with the expected seasonal weather patterns, as summer typically brings about stronger and more stable winds, while winter experiences more variable and subdued wind conditions.

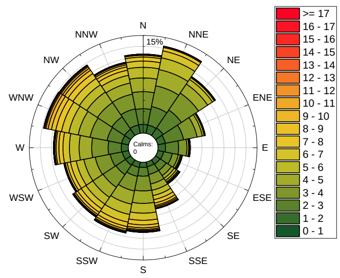
When we compare the obtained values to those found in other studies in the country's highlands, we find that the shape factor in the Ksar-Chellala region falls between 1.5 and 1.24 (Louassa *et al.*, 2017). Furthermore, in Tiaret and M'Sila, the shape factor is 1.48 and 1.41, respectively (Belabes *et al.*, 2015) (Abdeslame *et al.*, 2017), and in Djelfa and El Bayadh, the shape factor is 1.71 and 1.62, respectively (Merzouk & Merzouk, 2012). This finding demonstrates that Mecheria has large, stable winds at high speeds, whereas other locations have smaller, less stable winds at low speeds. Thus, we believe that the shape factor values in our study area validate our choice.

3.3 Dominant wind directions (Wind Roses)

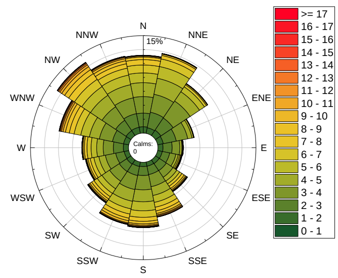
Wind direction assessment identifies the predominant direction and amplitude of the most common wind (Meziane *et al.,* 2021). WAsP software was used to generate wind roses for all three sites. The annual wind direction polar diagram is shown in Fig.4. Wind speed frequencies are shown in 16 frequency sectors on this diagram. Each sector represents a wind direction interval ranging from 1° to 380°. The dominant direction can be seen to vary from one location to another, as well as within the same location. Wind roses analysis reveals that the dominant wind directions for the three sites are from the northwest and south sides of the area. Regarding the other directions, we observed a significant variation in the dominant directions of the El Kheiter and Naâma sites across the sixteen sectors Fig. 4(b, c). On the other hand, Fig. 4(a) shows that the Mecheria region recorded the most stable direction from North to South, forming a good index favoring wind turbine planting. Therefore, it is better for a wind turbine to face this direction.



(a) Mecheria



(b) El Kheiter

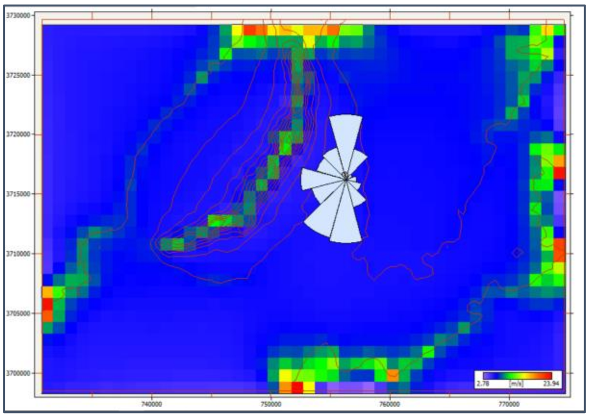


(c) Naama

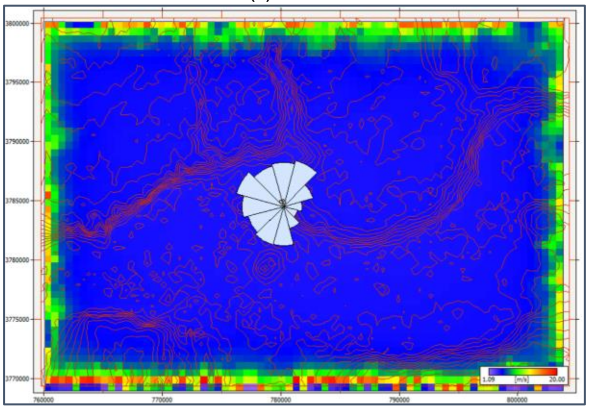
Fig. 4: Annual Wind rose for the three sites

3.4 Wind resource map

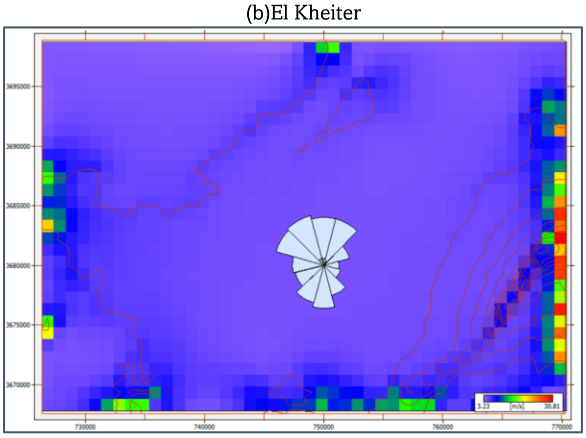
The Wind Atlas for the three regions was drawn at a 10 m altitude to represent the wind field in the entire area (Fig. 5), with a roughness length of 0.003 m used in this study (Holmes, 2001). Mountain peaks (indicated in red shading) exhibit the highest wind speeds, while flat land areas (highlighted in blue shading) experience lower wind speeds which means that the wind speed varies according to the site topographies. According to the Mecheria wind map, a large portion of the region is swept by winds ranging from 5 m/s to 6.8 m/s, with gusts reaching 11



(a)Mecheria



(b)El Kheiter



(c)Naama

Fig. 5. Wind resource map of the three sites

m/s in mountainous areas. On the other hand, the west of the eastern region corresponds to the highest speeds, which can be a good location for wind farm installation if the region's mountainous areas above 1100 m elevation are avoided. El Kheiter maps show that the region is swept by a speed ranging from 3.5 m/s to 5.5 m/s across the entire region. The maps of the Naâma site are swept at speeds ranging from 3.21 m/s to 5 m/s. The measurement mast site was marked by the wind rose frequency distribution as shown in the center of the wind resource map. The differentiation in Mecheria's wind characteristics is influenced by the presence of mountains in the western part of the measurement mast placement. This underscores the importance of considering local topography when planning wind turbine installations."

3.5 Wind Farm Design and Energy Output

Based on the promising results obtained in the first part of the analysis favoring the Mecheria site, the second part of this analysis consists of designing a wind farm with a capacity of 20 MW and analyzing its feasibility in order to connect it in the future to the 20 MW Naâma photovoltaic power plant (GPVN) and realize a multi-sources system that helps to improve the quality of the central power grid and increase the penetration of renewable energy. For the experiment, we chose the Power Wind 2 MW turbine. Fig. 6 depicts its power distribution as a function of speed with 80 m hub height extrapolated using Eq.(1). Our decision was influenced by a comparative study conducted for the Arzew area (Marih *et al.,* 2020).

The site's turbines were installed in two rows facing the predominant wind directions (Fig.7). Tables 4 and 5 show the

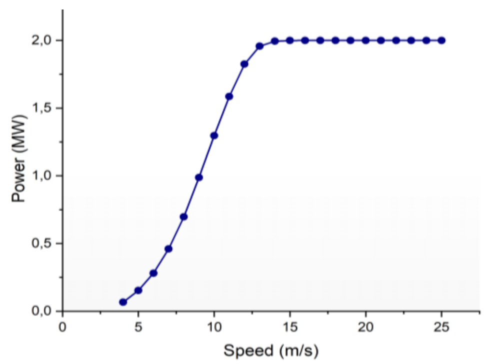


Fig. 6. Power curve of Power Wind 2 MW turbine.

Table 4
Result parameters produced by the farm.

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U [m/s]	Gross [GWh]	Net AEP [GWh]	Loss [%]
Turbine site 001	760050.2	3705107	1120.8	80	9.65	10.603	10.584	0.18
Turbine site 002	748528.6	3708564	1139.6	80	9.73	10.862	10.856	0.06
Turbine site 003	756824.1	3705050	1082	80	9.5	10.443	10.424	0.18
Turbine site 004	751869.9	3708564	1056.6	80	9.25	10.236	10.222	0.14
Turbine site 005	755326.3	3708506	1069.6	80	9.27	10.215	10.194	0.2
Turbine site 006	750314.4	3705107	878.7	80	9.29	10.239	10.228	0.11
Turbine site 007	758782.8	3708621	1100	80	9.37	10.246	10.225	0.21
Turbine site 008	761893.6	3708564	1100	80	9.41	10.257	10.239	0.18
Turbine site 009	753713.3	3705165	1003.5	80	9.36	10.329	10.308	0.21
Turbine site 010	765119.6	3708621	1111.7	80	9.58	10.479	10.471	0.08

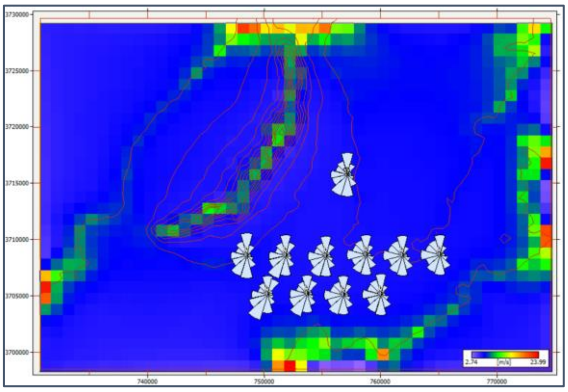


Fig. 7. Wind turbines (PowerWind 2 MW) layout over the Annual Energy Production (AEP) map of the site at 80 m above ground level.

simulation results of the installation, where (*x.y* location) represents the location of the wind turbines, (Elev. [m]) is the wind turbine altitude, (Ht [m]) is the height of the wind turbine above ground level, (U[m/s]) is the wind speed of each wind turbine, (Gross [GWh]) is the gross annual energy produced, (Net AEP [GWh]) is the net annual energy produced (%-loss) is the wake loss effect which means the loss index of each wind turbine. Finally, it should be noted that the measuring mast is located on the 11th wind rose depicted above the ten wind turbines.

The study region offers several advantages that enhance the viability of the wind farm. It benefits from its proximity to the electrical network, the presence of gentle hills, and the occupation of larger areas characterized by high wind velocities and medium density. The simulation results not only underscore the potential but also provide strong evidence of the wind farm's effectiveness.

In examining the results presented in Table 4, which details the performance of 10 wind turbines configured in two rows as illustrated in Fig. 7, a comprehensive analysis reveals noteworthy insights into turbine wake loss and the spatial distribution of each turbine in terms of both location and elevation. The turbine locations exhibit a deliberate arrangement, showcasing varying spacing and patterns that demand attention. Notably, the highest Annual Energy Production (AEP) values coincide with turbines positioned at the highest elevation of 1139.6 m (Turbine site 002) as shown in Table 4, highlighting a direct correlation between elevation and energy output. This underscores the significance of topography in wind farm layout considerations, offering valuable insights for optimizing energy yield in future wind farm designs.

The results summarized in Table 5 clearly show that the gross annual energy production is estimated at 103.91 GWh, with a net energy production of 103.75 GWh, resulting in a minimal loss of 0.16 GWh attributed to a minor wake loss effect of just 0.15%. Moreover, the mean wind speed at the wind turbine hub is an impressive 9.44 m/s, accompanied by a power density of 831W/m^2. The selection of an 80 m hub height wind turbine type, taking advantage of this high-speed value, holds great promise for the Mecheria region. This speed ensures that the turbines operate with produced energies that are very close to their nominal values. In comparison to the El Kheiter and Naâma regions, the findings of this study strongly indicate that a 20 MW wind farm in the Mecheria region is significantly more feasible, affirming its potential as a prime location for wind energy development

Table 5
Simulation results of the wind farm's total annual production.

Variable	Total	Mean	Min	Max
Total gross AEP[GWh]	103.91	10.391	10.215	10.862
Total net AEP[GWh]	103.75	10.375	10.194	10.856
Proportional wake loss [%]	0.15	-	0.06	0.21
Mean speed [m/s]	-	9.44	9.25	9.73
Power density [W/m^2]	-	831	764	895

These results further strengthen the case for wind farm installation and underscore the region's suitability for wind energy projects, corroborated by favorable comparisons to previous studies (Dayal *et al.,* 2021) (Meziane *et al.*, 2021) (Boudia & Guerri, 2015).

4. Conclusion

In response to the growing energy demand and with a commitment to environmental preservation in Algeria, a country traditionally reliant on fossil fuel production, this study assesses the wind potential of Mecheria, El Kheiter, and Naâma located in the western highlands of Algeria using WAsP software.

Comparing the potential of the three sites in terms of variation in average wind speed on a daily, seasonal, monthly, and annual basis, the wind indicators strongly favor the Mecheria site. Daily mean wind speed variations reveal a noteworthy wind pattern occurs in the afternoon at 3 a.m. influenced by the maximum heating of the earth's surface attributed to the diurnal wind patterns. Moreover, monthly fluctuations are highest in colder months of the year, presenting an ideal opportunity for hybridization with a solar system which can be a good index favoring the hybridization of the system with a solar system typically thrives during the hotter months of the year.

Furthermore, when comparing the annual wind speed and power density across the three sites, the Mecheria site prevails with a wind power rating of Class 5, whereas Naâma and El Kheiter are classified as Class 2 and Class 1, respectively. This classification not only underscores the superior wind energy potential of the Mecheria site but also highlights its suitability for the establishment of a robust and efficient wind energy project.

Wind data have been instrumental in the creation of the regional wind atlases of each site, shedding light on the significant impact of site topography on wind speed variations. Notably, In the case of the Mecheria region, wind characteristics clearly reveal a remarkable consistency from North to South direction making it highly advantageous for turbines to be oriented in this direction to harness the region's optimal wind resources.

Encouraged by these relevant indices favoring Mecheria's wind potential, a 20 MW wind turbine installation was designed in this space with a prudent choice of machines, taking into account the dimensions of the site and the configuration, the power wind 90/2 MW is the turbine technology chosen for this study. The wind potential of this site at 80 m hub height presented a mean wind speed of 9.44 m/s and a power density of 350 W/m^2 for the preferred direction. The installation of ten turbines on the site resulted in a gross AEP of 103.91 GWh and a net energy of 103.75 GWh, resulting in a wake loss effect of 0.15%.

The fruitful results of this analysis will lead the team to design a multi-source system in the future, connecting the 20 MW Naâma photovoltaic power plant (GPVN) with the wind farm reported in our study to improve energy distribution quality while respecting the environment and increasing the penetration of renewable energies in Algerian territory.

Abbreviations

a.g.l	Above Ground Level
AEP	Annual Energy Production
CDF	Cumulative Distribution Function
Cp	Power Coefficient
Elev	Elevation
GPVN	Naâma Photovoltaic Power Plant
Gross AEP	Gross Annual Energy Production
Ht	Heights
Loss	Losses (Wake loss effect)
MCP	Measurement-Correlation-Prediction
Net AEP	Net Annual Energy Production
NPV	Net Present Value
ONM	National Meteorological Office
PDF	Probability Density Function
WAsP	Wind Atlas Analysis and Application Program

Symbols

A	Scale factor (m.s-1)
K	Shape factor
V	Wind speed (m.s-1)
V*	Friction velocity
$\bar{V}$	Mean wind speed (m.s-1)
Vi	Initial wind speed value (m.s-1)
z	Turbine altitude
z0	Mast altitude
$\hat{V}$ site	Site wind speed
V ref	Reference wind speed
β 0, β 1	Regression parameters
ϵ	Random term following a normal distribution
P(V)	Probability density function
F(V)	Cumulative distribution function
P	Power delivered (W)
$\hat{p}$	Probability of the above-average wind
Γ	Gamma function
p(V)	Power output of turbine (W)
S	Sweep area of turbine rotor (m^2)
R	Radius (m^2)
ρ	Air density (kg.m3)
t	Time(s)

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