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Assessment of using wind energy for pumping water: a case study from Ténès (Algeria)

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ABSTRACT

This work assesses the feasibility of using wind energy for pumping water to supply the Ténès region in Algeria. The assessment starts with taking the velocity data and the direction of the wind acquired at 10 m height to establish a statistical analysis model using the Weibull distribution. This developed wind power model is then correlated to the water flows via data collected in two local turbine pumps. The Weibull parameters were derived monthly through water pumping data from the Ténès water pump stations and the results are extrapolated to 45 m AGL (i.e. the wind turbine height) empirically. The wind direction variation is recorded and incorporated into the model. In addition, the efficiency of the pumping systems is also evaluated. The results obtained suggest that water flow predicted by this model can supply the needs of population of Ténès.

Keyword: Wind power; Weibull distribution; Wind turbine and water flow

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1. Introduction

Water is the main source of life, but this natural wealth is distributed very unevenly in the world. It is the most basic need for sustainable development of rural areas [1]. Water demand in these regions for crop irrigation and domestic water supply is rising sharply. However, decreasing rainfall in many arid countries causes rarefaction of surface water [2]. Groundwater is an alternative to this dilemma. Nonetheless, through the years, the ground water had decreased to a point that it requires mechanicals pumps to access water. Generally, these pumps use fossil energy that contributes to pollution. Wind turbines thus can serve as a viable alternative at the wake of environmental conscientiousness. Wind-driven pumps are expanding rapidly in rural areas in Algeria. Wind turbines are attractive since they can be used in very far locations where fuel supply is scarce [3].

The population grows rapidly in Algeria; between years 2000 and 2010, the Algerian population has grown from 32 to 39 million and is projected to grow

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to 46 million in 2020. Water consumption to accommodate the upcoming population could be of the order of 5 billion m^3 per year [4]. Moreover, Algeria is located in an arid region, and needs the development of its water distribution network. The challenge has been to ensure sufficient water supply for the growing population, the agricultural, and the industrial needs. In the case of Ténès city, water is mainly from dam Sidi Yaakoub, but only covers about 40% of the population [5]. As a result, pumping ground water with renewable energy is an inevitable choice.

In fact, Algeria has ambitious quantitative targets for developing renewable energy, particularly when electricity demand is growing annually at 5–7% (based on the national society of electricity and gas, the Sonelgaz) [6]. Algeria, in association with the European community, has set a goal of a renewable energy production rate between 10 and 12% for the year 2025 [7].

Using wind as an energy source could encounter various challenges. Many research works concerning wind resources have been investigated. Takle and Brown [8] have published a work dealing with the use of Weibull statistics to characterize the data of the wind velocity. Peterson [9] has computed the wind energy potential by the estimation of the power laws. The variation of the wind speed as a function of the height has been studied by Justus and Mikhail [10]. They also investigated different extrapolation models to calculate the wind velocity [11]. Lalas [12] has worked on the estimation of wind velocity in a complex terrain.

Some researchers have investigated the coupling of the wind energy with the water pumping. Saiful Rehman [13] presented a comparative study dealing with the use of the wind, the solar, and the gasoline engines for pumping water in India. Gipe [14] has shown that the wind technology system is reliable and economically competitive compared to the conventional system in California (USA) and Denmark. In Denmark, the use of wind energy for pumping hot water has been studied by Hedegaard et al. [15,16]. Rehman and Sahin [17] investigated a techno-economic study on the use of wind energy for pumping water using small wind turbines in Saudi Arabia. Mustafa Omer [18] and Badran [19] worked on wind energy use for pumping water in rural areas in Sudan and Jordan, respectively. Recently, Genç [20] has studied the viability of pumping systems for water supplied by wind energy in northern central Anatolia in Turkey. Kose et al. [21] have evaluated the potential of wind energy and economic feasibility to meet electricity demand in Konya in Turkey.

In Algeria, initial works on the assessment of the wind resources have begun in 1984 by Said and Ibrahim [22] followed by Bensaid in 1985 [23]. They proposed a classification of the wind velocity depending on the topography of the country. In 1990, Hammouche [24] established a wind map for Algeria. Later, Kasbadji Merzouk [25,26] updated this map of wind velocity with new data. Himri et al. [27–29] applied the Weibull model and extracted the relevant parameters using the wind for fifteen sites in Algeria. They also worked on the economic analysis of wind farms in three different sites [30] and the wind power in rural area [31]. Abdesselame et al. [32] evaluate the electric energy production of a farm wind for supplying a station of seawater desalination in Ténès. Boukli Hacène et al. [33] determined the wind energy potential by the mass consistent model in the same region.

This paper aims to assess potential use of wind energy for pumping water to supply the Ténès region in Algeria. Ténès region can make use of wind energy from the Cheliff valley [34] to pump ground water to feed the local agriculture industry. Assessment of the wind energy, particularly its critical parameters such as monthly average of wind speed and its dependence on height, etc., is crucial for operating wind-pumped water supply. The purpose of this study is to evaluate the critical parameters using the well-known Weibull model.

This paper first discusses the water inventory in the studied area, followed by description of the methodology used, in which a statistical analysis of wind velocities and directions is applied to model the data from daily flow of water pumped by two wind turbines. The derived parameters are used to simulate water pumping data and compared with those obtained from the WAsP software. Lastly, the conclusions and future works are presented.

2. Numerical calculation of wind resources

2.1. The study area—Ténès region

Ténès area is located in the coastal region at about 200 km at the west of Algiers (capital of the country). It has a latitude and a longitude of 36˚31´47´´N and 1˚9´16´´E, respectively. The city of Ténès is bounded by the Mediterranean Sea to the north and the mountains of Dahra chain to the east, west, and south. The topography of this area is complex since it is classified as a mountainous zone. Indeed, the altitude varies between 0 and 700 m with abrupt variations [27]. The site is characterized by an interesting wind potential. It is also known for its needs of water for agricultural purposes.

2.2. Statistical analysis of the measured wind velocities

In the region of Ténès, a measurement station provides the wind velocity and direction every three hours. Hence, acquired measurements by the meteorological national office since five years are available for treatment. This treatment is based on the statistical method of the distribution [35]:

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

with $f(V)$ being the occurrence frequency of the wind velocity V. k and c are Weibull parameters. Determination of these parameters using measured data allows adequate modeling of the wind for the investigated site. To find the Weibull parameters, one can use the Lvenberg-Marquart optimization method, [36]:

$$C^k = \frac{1}{N}\sum_{i=1}^{N} V_i^k \tag{2}$$

and

$$\frac{1}{k} = \frac{1}{N}\left[\frac{1}{c^k}\sum_{i=1}^{N} V_i^k \ln(V_i) - \sum_{i=1}^{N} \ln(V_i)\right] \tag{3}$$

where N is the total number of observations.

The mean wind speed, $\langle V\rangle$, mean cubic wind speed, $\langle V^3\rangle$, and the available energy power $\langle P\rangle$ are given by [25]:

$$\langle V\rangle = c\,\Gamma\left(1+\frac{1}{k}\right) \tag{4}$$

$$\langle V^3\rangle = c^3\,\Gamma\left(1+\frac{3}{k}\right) \tag{5}$$

$$\langle P\rangle = \frac{1}{2}\rho_{\text{air}}\langle V^3\rangle \tag{6}$$

Where ρ_{air} is air density (kg/m^3). Note that the wind velocity measurements used in the modeling are acquired at a height of 10 m. Since wind velocities at 45 m are needed in an actual setting (where the wind turbines are), an extrapolation method developed by Justus and Mikhail is used to obtain the desired velocities. It is written in the following form [10]:

$$k_1 = k\left[\frac{1 - 0.088\ln\frac{Z}{10}}{1 - 0.0881\ln\frac{Z_1}{10}}\right] \tag{7}$$

With

$$c_1 = c\left(\frac{Z_1}{Z}\right)^{\alpha} \tag{8}$$

where Z and Z_1 are the height of the measured data (10 m) and the height of the generator rotor, respectively. c and c_1 are the scale parameters of Weibull distribution at 10 m and wind turbine height, AGL, respectively. k and k_1 are the shape parameters of Weibull distribution at 10 m and wind turbine height AGL, respectively. The α exponent is written as:

$$\alpha = \left[\frac{0.37 - 0.088\ln c}{1 - 0.0881\ln\frac{Z}{10}}\right] \tag{9}$$

2.3. Estimation of the water flow pumped by wind turbines

Water flow is a measure of the wind turbine power, and provides information about whether the wind turbines can sustain the overall water needs, in terms of the needs from the population, the industrial operations, and the agriculture crops. The daily water flow (Q_d) can be expressed as [37]:

$$Q_d = 3{,}600.24\,\frac{\eta_p\langle P_e\rangle}{\rho g H_t} \tag{10}$$

where η_p is the hydraulic pump performance given by the constructor, ρ is the water density assumed to be constant, g is the gravity, and H_t is the total monometric height, and $\langle P_e\rangle$ is the mean electric extraction power, [38]:

$$\langle P_e\rangle = \eta\langle P_u\rangle, \tag{11}$$

Depending on the mean useful wind power $\langle P_u\rangle$ and the wind turbine performance η given by:

$$\eta = \frac{\langle P_n\rangle}{\langle P_{th}\rangle}. \tag{12}$$

where P_n is the rated power of the wind turbine given by the constructor. $\langle P_{th}\rangle$ is the theoretical power of the wind turbine:

$$\langle P_{th} \rangle = \frac{1}{2} \rho A \langle V_n^3 \rangle \tag{13}$$

with $A = \pi \frac{D_r^2}{4}$ being the swept area of rotor function of the rotor diameter D_r. V_n is the rated velocity of the wind turbine and given by the constructor.

The density of useful wind power is calculated by, [37]:

$$P_u = \begin{cases} 0 & \text{for} \quad V < V_i \\ \frac{1}{2} \rho V^3 & \text{for} \quad V_i \leq V < V_n \\ \frac{1}{2} \rho V_n^3 & \text{for} \quad V_n \leq V < V_s \\ 0 & \text{for} \quad V \geq V_s \end{cases} \tag{14}$$

where V_i and V_s are cut-in-wind and cut-out-wind speed given by the constructor, respectively.

To calculate a usable wind power density, the frequency curve of Weibull distribution is used. The frequency requires a double truncation. First, only frequencies of a wind speed up to cut-in-wind speed V_i are used. Secondly, when the wind turbine reaches its rated wind speed value V_n, the increase of the wind speed has no consequence. Finally, when speed reaches cut-in speed V_s, the power density is null. The usable wind power density under such circumstance can be written as:

$$P_u = \frac{1}{2} \rho \overline{V_u^3} \tag{15}$$

where:

$$\overline{V_u^3} = \int_{V_i}^{V_n} V^3 f(V)\, dV) + V_n^3 \int_{V_n}^{V_s} f(V) dV \tag{16}$$

The integration gives, [37]:

$$\begin{aligned} \overline{V_u^3} = & \left[\Gamma_n \left(\left(\frac{V_n}{c} \right)^k, 1 + \frac{3}{k} \right) - \Gamma_n \left(\left(\frac{V_i}{c} \right)^k, 1 + \frac{3}{k} \right) \right] \overline{V^3} \\ & + V_n^3 \left[\exp\left(- \left(\frac{V_n}{c} \right)^k \right) - \exp\left(- \left(\frac{V_s}{c} \right)^k \right) \right] \end{aligned} \tag{17}$$

where Γ_n is the normalized incomplete Gamma function.

3. Results and discussion

This section presents the results of the analysis for potentially using the wind powder to feed the water need of the Ténès area. The results are compared with those obtained by the WAsP software [32]. The aim is to determine the daily flow of the pumped water with wind turbine. In this analysis, two wind turbines with 600 and 850 kW power were investigated. The characteristics of these wind turbines are given in the Table 1 [38].

3.1. Annual speed distribution

The results of the statistical analysis per methodology described in Section 2 and the wind speed data at 10 m AGL are given in Table 2.

Note that the average values of the wind speed and the available energy power are 5.4 m/s and 150.9 W/m^2, respectively. This recorded data are somewhat biased from the annual average given below.

A classification of the wind frequencies carried out on an annual basis for the Ténès site is shown in Fig. 1.

The average annual wind speed is equal to 3.69 m/s and density of available wind power is 95 W/m^2; both numbers are lower than we recorded. The frequency of zero wind is equal to about 39%. To incorporate the zero wind in the modeling, hybrid Weibull distribution was adopted.

3.2. The wind rise

Fig. 2 shows the wind speeds distribution according to various sectors. Apparently, the southwest wind is the dominant one (20.7% of the observed winds are

Table 1
Characteristic of wind turbine, [38]

	1st wind turbine	2nd wind turbine
Diameter D_r, (m)	44	52
Height Z, (m)	45	45
Rated power, P_n (kW)	600	850
Cut-in-wind speed, V_i (m/s)	3	4
Rated wind speed, V_n (m/s)	15	16
Cut-out-wind speed, V_s (m/s)	25	25

Table 2
Annual statistical parameters at 10 m AGL

Site	k	c (m/s)	$\langle V \rangle$ (m/s)	$\langle P \rangle$ (W/m^2)
Ténès	2.47	6.08	5.4	150.9

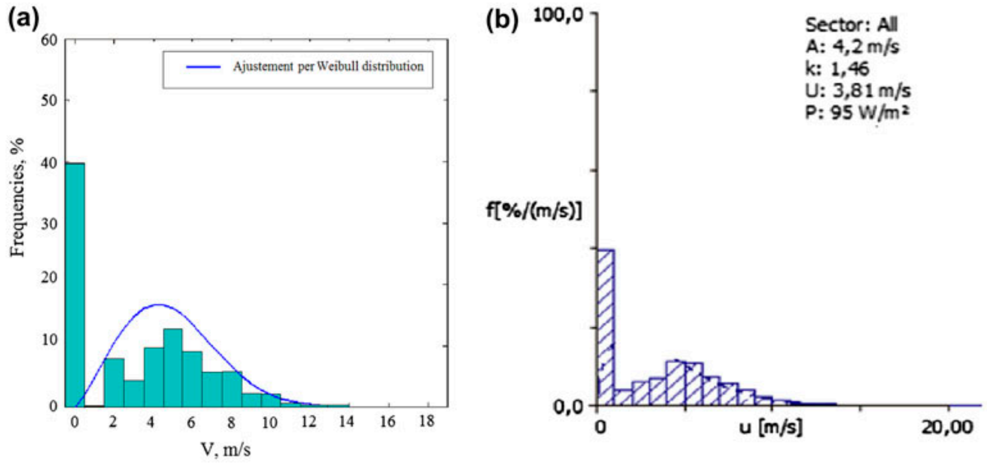

Fig. 1. Wind frequencies classification. (a) Developed Software and (b) WAsP [34].

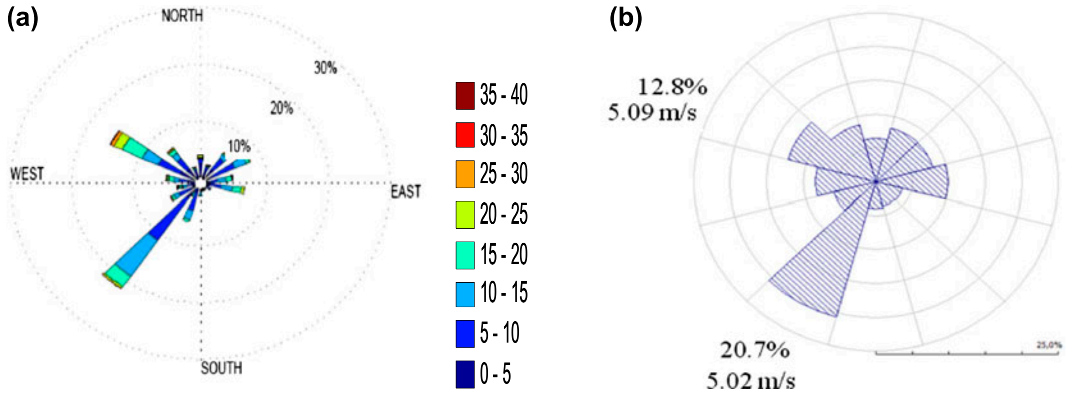

Fig. 2. Wind speeds distribution. (a) Developed Software and (b) WAsP [34].

Table 3
Monthly statistical parameters at 10 m AGL

Month	k	Mean velocity c (m/s)	$\langle V \rangle$ (m/s)	$\langle P \rangle$ (W/m^2)
January	1.30	5.08	4.7	217.18
April	1.09	4.06	3.93	181.81
July	0.9	2.91	3.06	139.77
October	0.94	3.36	3.45	178.22

of sector 210° with a mean velocity of 5.02 m/s, indicative of the dominant annual scale at 210°).

In a parallel analysis, using the WAsP software [33] showed similar results to the developed program in our case. It is noted that the main direction is the southwest sector.

3.3. Monthly speed distribution

The drinking water largely comes from underground water, which was subsequently desalinated. Farmers also use the well water for irrigation of agricultural land. Since irrigation is critical in spring

Table 4
Monthly statistical parameters at 45 m AGL

Month	k_1	c_1 (m/s)	$\langle V \rangle$ (m/s)	$\langle P \rangle$ (W/m^2)
January	1.37	8.07	7.37	761.34
April	1.15	6.53	6.20	630
July	0.95	4.77	4.87	478.99
October	0.99	5.46	5.47	606.37

and summer, it is necessary to establish a monthly study scheme and use it for designing the pumping systems. The simulation provided here is critical for establishing a monthly trend of the demand. As such, the distribution of the wind velocity was measured on a monthly basis, and the Weibull parameters were extracted for that specific month. Table 3 shows data and the Weibull extracted parameters from several months.

3.4. Extrapolation to higher elevation

Wind speeds were measured by the stations of the National Office of Meteorology, at a standardized height of 10 m AGL. However, realistic outputs for the two chosen wind turbines should be at a higher elevation; the Weibull parameters were thus extrapolated to 45 m AGL. The results are carried in Table 4.

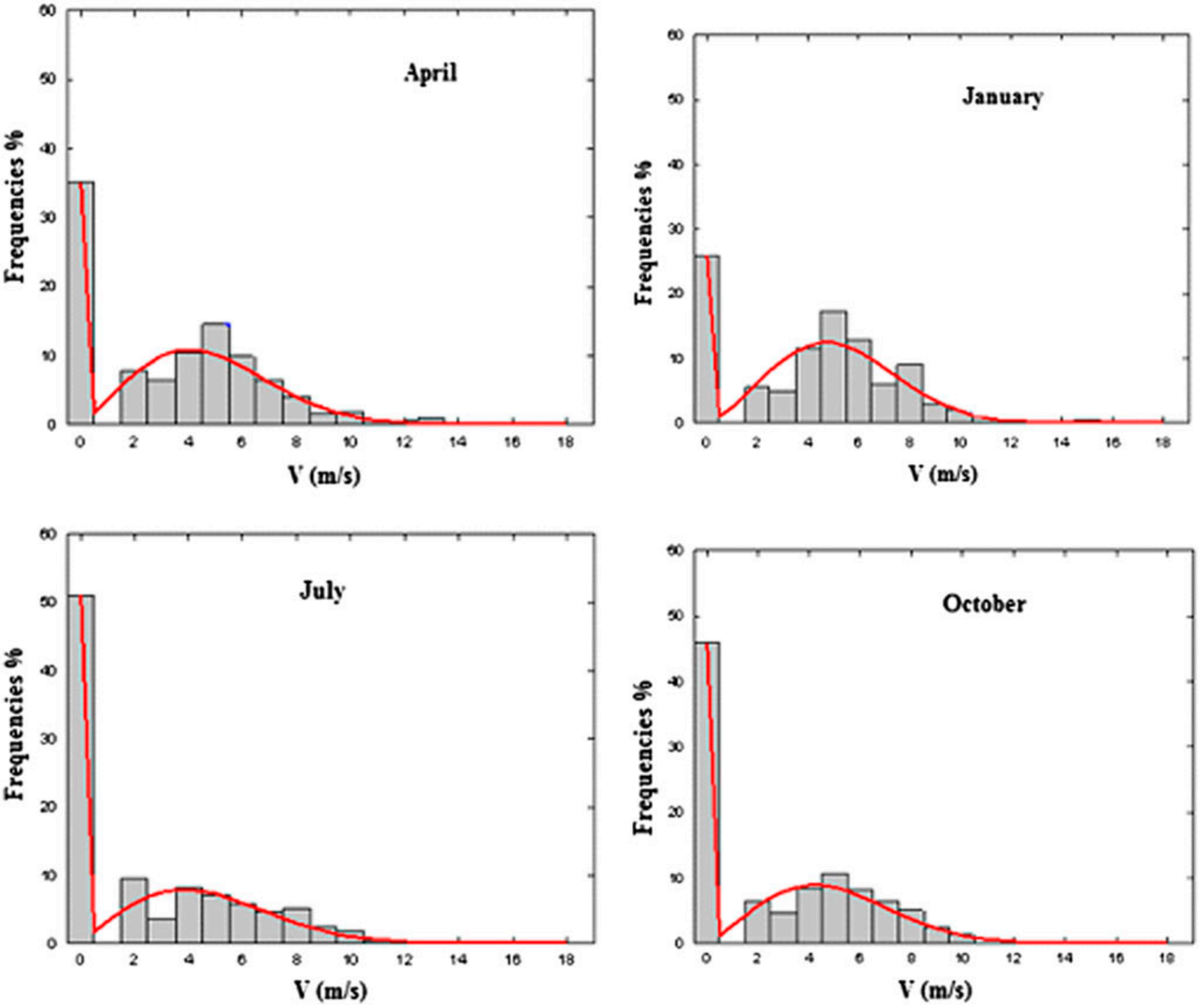

Fig. 3. Speed histograms and monthly adjustment curves for the months of January, April, July, and October for the site of Ténès.

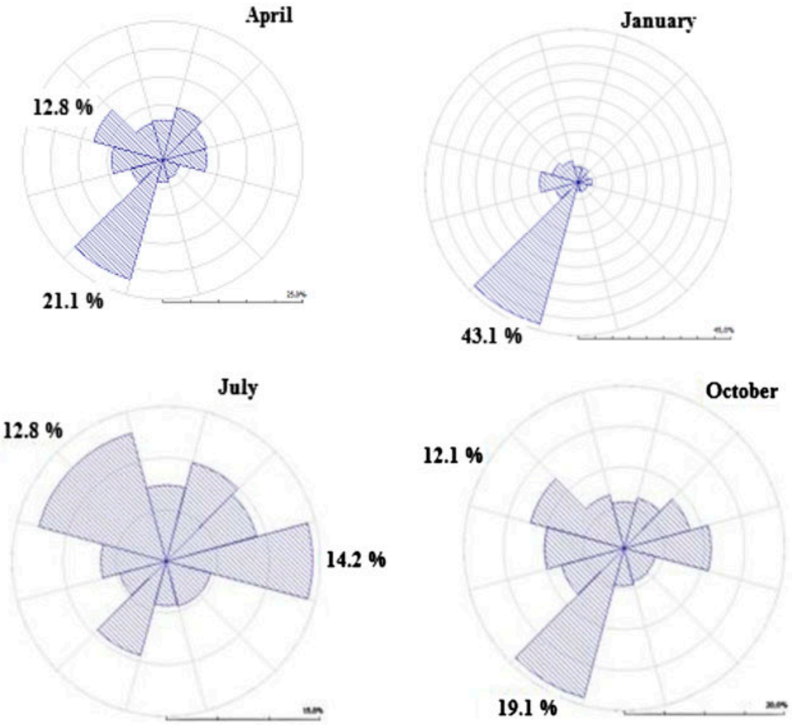

Fig. 4. Monthly wind rise.

Fig. 3 shows data and the fitted Weibull distributions of the chosen months.

Note that the Weibull parameters differ appreciably from one month to another. The winter months show stronger winds. Fig. 4 are the monthly wind rises.

For the months January, April, and October, the prevailing direction is 210˚, meaning that the Southwest area is identical to the annual data. In contrast, for the month of July, the dominant direction becomes 90˚, meaning a dominant East wind.

3.5. Monthly variation of the Weibull parameters

Fig. 5 shows the monthly variations of each shape parameter k at 10 and 45 m AGL. We notice the same

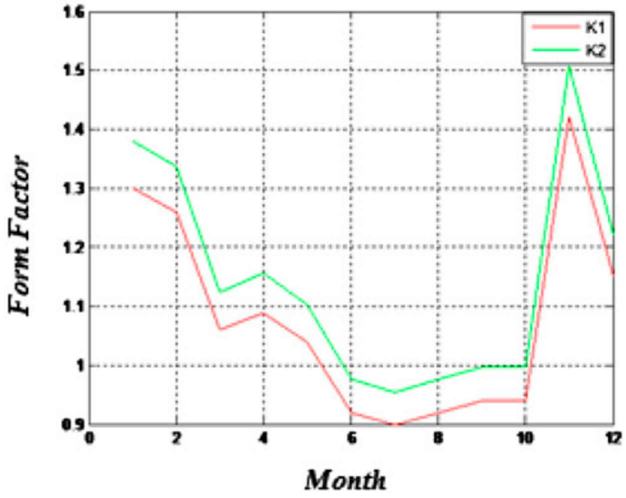

Fig. 5. Monthly evolution of the form factor at 10 and 45 m from the ground.

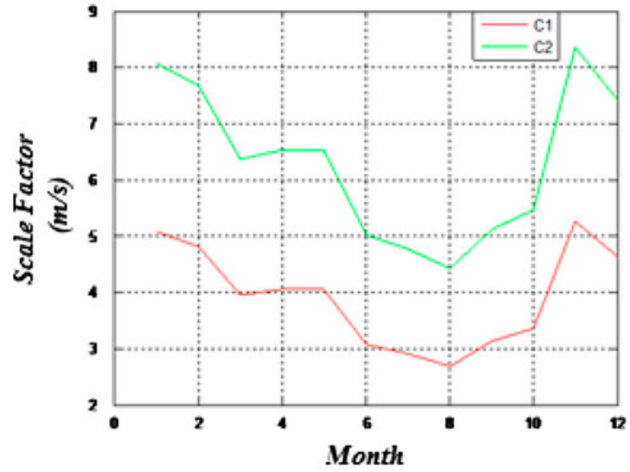

Fig. 6. Monthly evolution of the scale to 10 and 45 m AGL.

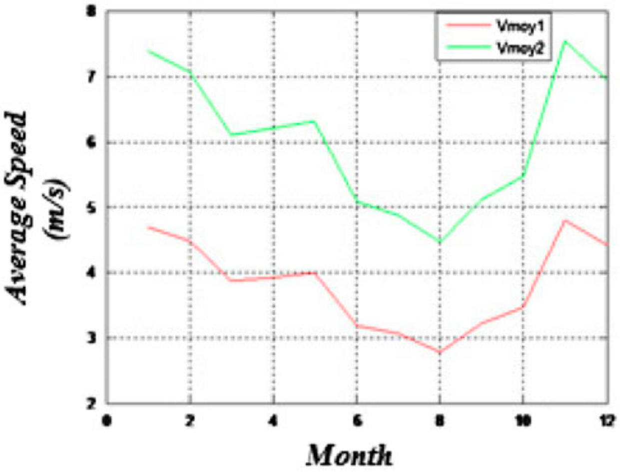

Fig. 7. Evolution of the monthly average speed 10 and 45 m ground.

monthly evolution for both altitudes. We see the same evolution curves of the shape parameter at different heights. Thus, in January, the form factor k is equal to 1.3 and 1.38, respectively, at 10 and 45 m AGL. It gradually decreases during the months of February and March, but increases in the month of April and then drops sharply during the months of May, June, and July. Subsequently, it increases again and reaches the maximum value of the order 1.42 and 1.5, respectively, 10 and 45 m AGL in November.

The same pattern applies to the scale factor at 10 and 45 m AGL throughout the year. Since the range of variation is more important for the scale factor, Fig. 6 shows the monthly changes of the scale at 10 and 45 m.

Overall, it is apparent that the maximum wind arrives on the months of November and January, and the minimum in August. Similar trend is shown in the evolution of the variation of the average monthly wind speed—4.7 m/s and 4.79 m/s, respectively, in January and November for 10 m height and 7.37 m/s and 7.53 m/s in January and November for 45 m AGL (Fig. 7).

Power density available for a single data series for 10 and 45 m above the ground is shown in Fig. 8.

In January, the available power density is equal to 219 W/m^2 at 10 m AGL. It gradually decreases until August with the exception of May when it reaches 212 W/m^2. The minimum is in August (99.5 W/m^2) and the maximum in December (229 W/m^2). At 45 m AGL, 777.13 W/m^2 was found in January. The trend resembles the 10 m elevation. The density decreases to April and increases for the month of May before decreasing to the minimum of 354.76 W/m^2 in

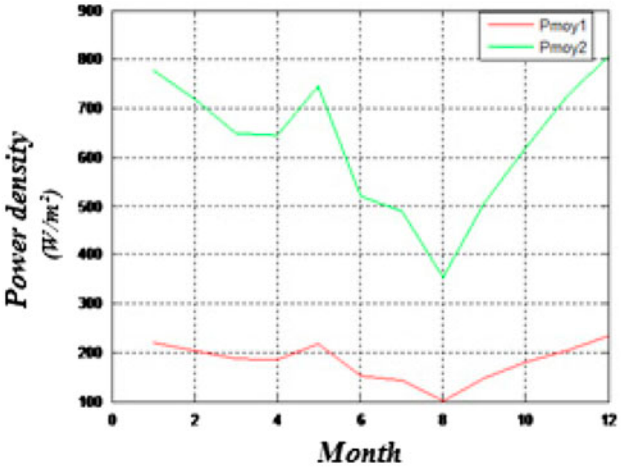

Fig. 8. Evolution of the power density available in 10 and 45 m from the ground.

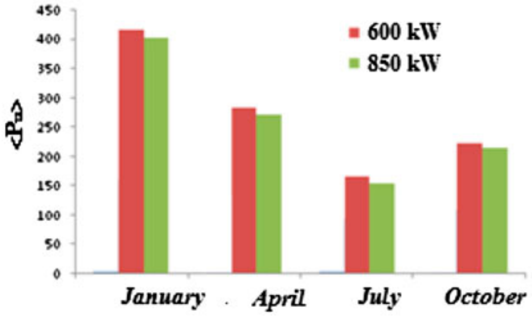

Fig. 9. Distribution of the average power used for both machines.

Fig. 10. Amount of water pumped daily for wind turbines with rated outputs, respectively, 600 and 850 kW at 45 m AGL.

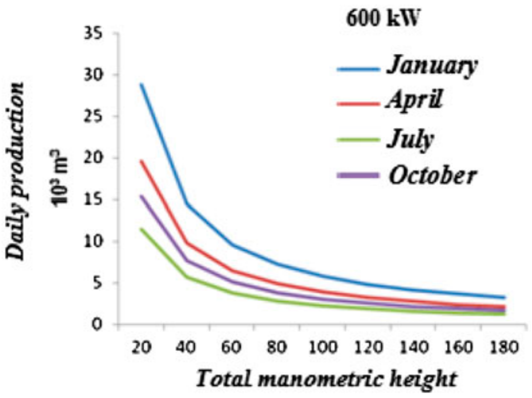

Fig. 11. Daily water flow pumped by season 600KW.

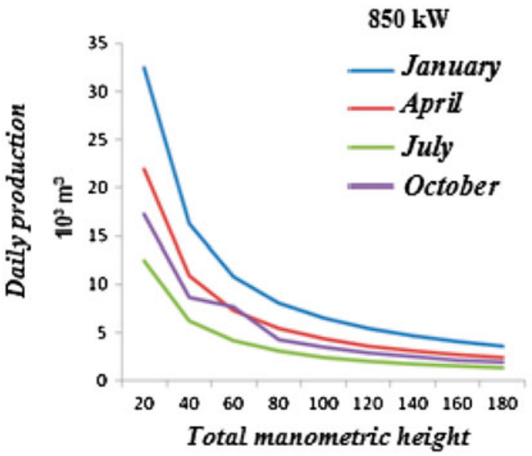

Fig. 12. Flow of water pumped daily seasonally 850 kW.

August; it increases to reach the maximum of over 800 W/m^2 in December.

Fig. 9 shows the histogram averages of the usable power for the month of January, April, July, and October for two selected wind turbines.

Note that the use of wind-generated power of 600 and 850 kW are generally considered the same order of magnitude, even though it varies from one month to another. We can see that the power demand is the highest in January and lowest in July.

3.6. Amount of water pumped

Fig. 10 shows the calculation of the average amount of water pumped daily, demonstrating the seasonal effect and the wind turbine performance. The variation of the amount of water pumped heavily depends on the total wind turbine outputs at 45 m, especially for the months January, April, July, and October. The estimation is performed for a total manometric height H_t equal to 45 m and a pump efficiency of 0.55.

The data suggest that the most important daily flow is in January, and the least in July. The mean daily pumping water with the two turbines for different manometric heights is calculated (Figs. 11 and 12).

The daily flow decreases with height, showing the same manometic height trend within a month. Fig. 12 gives the results for 850 kW case.

4. Conclusion

Wind power has its commercial potential in the area of Ténès, Algeria, though it varies from month to month. This study shows great potential of using this wind power to pump water for the population, agricultural uses, as long as one carefully chooses the wind turbine and accurate interactive wind measurement stations. This study recommends conduction of all relevant measurements on a monthly basis and proper modeling of the data before settling with any turbine power and installation. In conclusion, the wind potential in the Ténès area varies monthly; thus, a daily water supply from wind pumping should be closely monitored. The supply is highly dependent on the season and on the nature of the wind turbine used.

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