Wind pumping assessment as source of renewable energy

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Abstract

The socio-economic development of the rural and desert zones is related to the presence of drinking water and the availability of energy. The wind, among renewable energies, can play an important role for the water supply, irrigation of agricultural land and the generation of electrical energy. In fact, groundwater can be pumped by using wind energy. This paper presents the perspectives of wind mechanical pumping in eight synoptic sites distributed in the Tunisian south. The wind resource analysis, based on meteorological data recorded during five years, shows that the south of the country has a good wind potential. The annual mean wind speed is between 2.7 and 5.08 m/s. The map of water resources showed that the south Tunisia (deserted area) is characterized by its aridity and vulnerability of the soil. Indeed, the pluviometry is random and varies from 100 to 200 mm/year. In this paper, we are also interested in the study of the energetic performances of the wind turbine SEN 5000 P8. Based on its curve characteristic of power, we studied this energy profitability (efficiency, use factor, availability rate and water volume pumped) in the eight selected sites (Kebili, Tozeur, Elborma, Djerba, Tataouine, Ramada, Gabes, and Medenine).

Keywords

Wind energy; Multi-blade rotor; Wind water pump; Efficiency; Use factor; Availability rate

Introduction

The current decade has been marked by a decline in the interest in the urgent but complex problems that are linked to our very survival such as global warming, threats to the ozone layer, and desertification of agricultural land.

Several countries around the world are facing great problems to cover drinking water supply and irrigation in rural and desert areas, especially in the developing countries both in Asia and Africa. Indeed, South Africa has been experiencing its worst drought for 130 years as well as water and energy scarcity. To deal with this crisis, these countries have set a priority to improve the supply of water that would greatly contribute to meeting basic needs of the most disadvantaged populations [1-3].

In order to contribute to a regional balance of development, the preservation of the ecosystems in these regions can be obtained only with the attachment of the population to their regions by means of the improvement and development of their standard of living. The socio-economic development of these regions is closely related to two main factors, which are the presence of water and energy availability.

Many pumping systems exist according to their source: human power, conventional network, diesel generator, wind systems, photovoltaic systems, and hybrid systems. The current problem lies in a judicious choice between conventional pumping (mechanical, thermal and electrical) and pumping to renewable energy (wind and solar). This choice is determined on the one hand by operational constraints, and on the other hand, by investment cost parameters [4-7].

Currently, the pumping of water by renewable energy sources could be a more economically competitive alternative than conventional methods. Indeed, it is well suited for most of the arid and semi-arid areas because of the existence of shallow underground water potential, inferior to 30 meters in the majority of the desert areas, and a great renewable energy potential. Similarly, it is the most cost effective way to ensure regular water supply in remote and/or isolated areas of electricity and road networks. However, site characteristics are decisive in the choice of the solution (photovoltaic solar and wind) [8-11].

In particular, the wind pumping is a financially attractive alternative in situations where the total head is relatively small (10 to 20m) and where wind speeds are greater than 3 m/s. This technology is well suited for pumping water using mechanical systems for low wind sites and electrical systems for strong wind sites [12-14].

Our work is conducted to quantify the wind potential available in the south of Tunisia represented by eight synoptic sites and the analysis of wind water pumping process, based on the mechanical pumping model using wind turbine multi-blade SEN 5000 P8.

Regional annual average pluviometry

Tunisia is the smallest Maghreb country. It occupies a geographical zone between 30 and 37°N latitude and between 8 and 12°E longitude. It opens largely on the Mediterranean with 1298 km of coasts, delimited of the West by Algeria and the south by Libya.

Because of its geographical situation between the Mediterranean and the Sahara, Tunisia is an arid country on the major part of its territory. This aridity, combined with the variability of the Mediterranean climate, makes water a resource both scarce and unevenly distributed in time and space. Its climate is Mediterranean while going from the wet to the north extreme at desert in the south extreme. Taking into account the climatic and geomorphologic conditions, three great agro-ecological zones are distinguished (Figure 1).

The North, with an average pluviometry between 400-600 mm/year, of relief is marked by the mountainous masses in the North-West and the fertile plains in the North-East.

The Center, with an average pluviometry between 200-400 mm/year, is characterized by a morphology constituted by a low steppe in the East with fertile plains interrupted by depressions and a high steppe with a mountainous mass and plains.

The South, with a random pluviometry from 100 to 200 mm/year, is characterized by its aridity and vulnerability of its land to desertification. It is a pastoral farming zone with oases around the water points.

The precipitations in all the country bring on average a water quantity of about 37 billion m^3, that is to say the equivalent of an average pluviometry of 230 mm/year.

Of this quantity, on average only 2.7 billion m^3 are annually mobilizable, thanks to the existence of a developed hydrographic network, of a topography favoring the flow and an impermeable geological foundation limiting the infiltrations, which explains the poverty of septentrional Tunisia in aquifers.

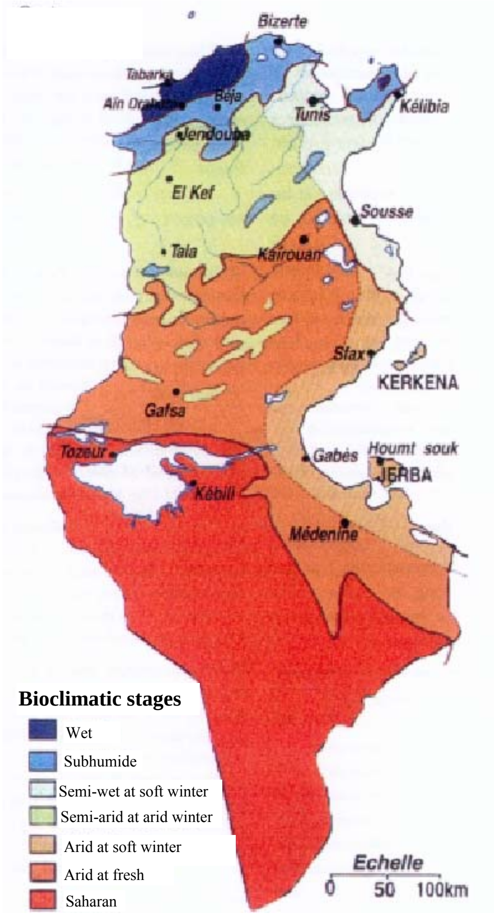

Figure 1. *Bioclimatic chart of Tunisia* [15]

The surface water resources are very variable in time and space. The inter-annual average of the contributions in surface water is estimated at 2.7 billion m^3, of which 80 % come from the North areas (Figure 2).

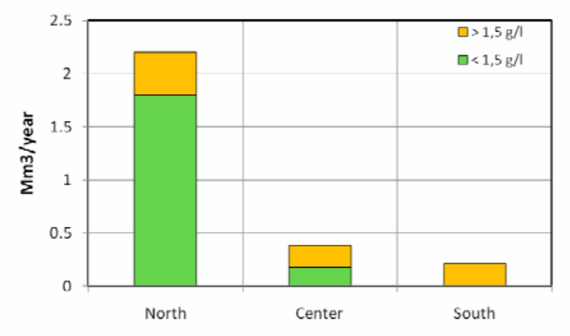

Figure 2. *Surface water resources by area*

The annual average of underground water resources is estimated at 2.1 billion m^3, of which 43.5% come from the south of the country (Figure 3).

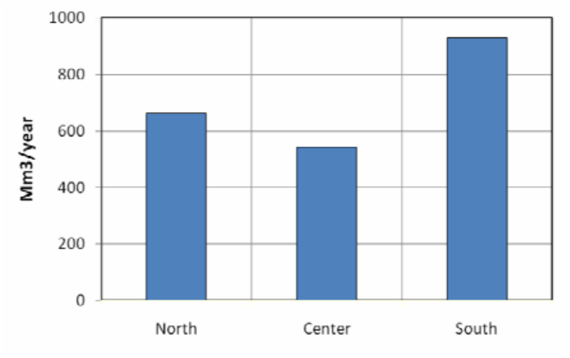

***Figure 3**. Underground water resources by area*

Thus, the total water resources of Tunisia are estimated on average of 4,836 billion m^3, of which 44.2% are underground waters and 55.8% are surface waters [15].

Wind characteristics of selected sites

To use the wind as source of energy, it is necessary to know the available wind energy of the site. In this study, we are interested in the south of the country which is characterized by its aridity and desertification, but which presents good underground water resources.

The selected sites (Kebili, Tozeur, Elborma, Djerba, Tataouine, Ramada, Gabes and Medenine) represent synoptic sites of the I.N.M. (National Institute of Meteorology) distributed in the south of Tunisia (Figure 4). The measured meteorological data of the wind are gathered during five years 2004-2009 (in open area at 11m height above ground level).

***Figure 4**. Geographical positions of selected sites*

In this study, we use two distribution methods [16-17] for computation of wind characteristics:

Meteorological distribution method

From the wind speeds cumulative frequencies, one defines the occurrence frequencies by Eq(1):

$$f(\overline{V}) = F(\overline{V}) - F(\overline{V}+1) \quad (1)$$

where: $\overline{V}$ is the classified speed, $f(\overline{V})$ is the occurrence frequency, F is the cumulated frequency.

The available annual energy of the wind E, per unit area, is estimated by Eq(2):

$$E = \frac{1}{2} \cdot \frac{24 \times 365}{1000} \cdot \rho \cdot \sum_{i=1}^{n} \overline{V}_i^3 f(\overline{V}_i) \quad (2)$$

$(kWh/m^2/year)$

where: ρ is the air density (1.225 kg/m^3).

Weibull distribution method

The Weibull distribution of the wind speed is given by the function provided by Eq(3):

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

where: A is Weibull scale parameter (*m/s*), K is the dimensionless Weibull shape parameter.

The annual energy production of the wind E, per unit area, is estimated by Eq(4):

$$E = \frac{1}{2} \cdot \frac{24 \times 365}{1000} \cdot \rho \cdot A^3 \cdot \Gamma\left(1 + \frac{3}{K}\right) \quad (4)$$

(W/m^2)

where Γ is the defined gamma function.

The statistical treatment of these data has enabled us to estimate the available wind energy E and the characteristic annual and seasonal speeds (mean speed V_m, frequent speed V_f and energetic speed V_e) of each site (Table 1 and Figure 5).

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Table 1. Annual wind characteristics in various sites

Ranking	Sites	Meteorological method				Weibull method			
		V_m (m/s)	V_f (m/s)	V_e (m/s)	E (kWh/m²/year)	V_m (m/s)	V_f (m/s)	V_e (m/s)	E (kWh/m²/year)
1	Kebili	5.08	2	12	1997.21	4.98	2.74	9.58	1758.31
2	Tozeur	4.66	3	8	1215.41	4.60	3.29	7.84	1117.50
3	Elborma	4.73	5	7	1151.97	4.91	3.59	8.28	1335.45
4	Djerba	4.64	3	7	1149.58	4.79	3.33	8.29	1298.58
5	Tataouine	3.50	2	6	645.53	3.50	1.97	6.68	601.70
6	Ramada	3.43	3	6	564.00	3.48	2.04	6.51	571.20
7	Gabes	3.15	3	5	393.85	3.19	3.02	5.76	413.17
8	Mednine	2.70	2	5	302.48	2.70	1.04	5.84	346.82

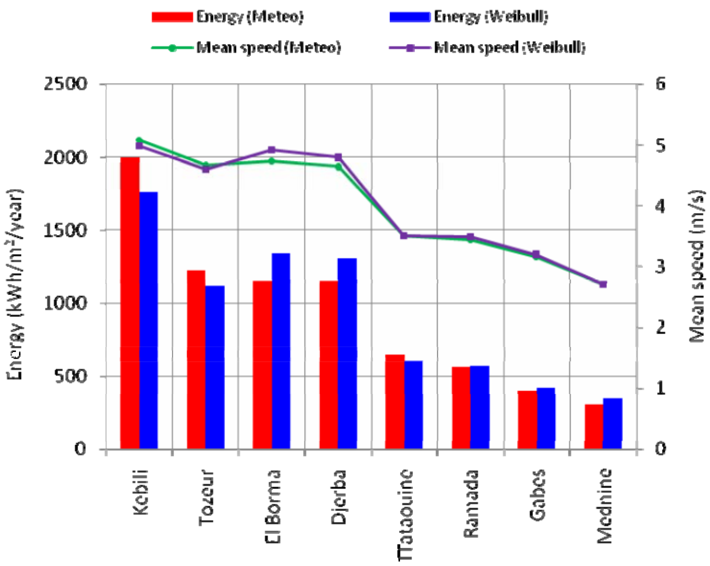

Figure 5. *Annual wind energy and mean speed of each site*

The analysis of table 1 leads to the following remarks:

- The numerical results obtained by the two methods (meteorological and Weibull) are comparable. However, a light difference on the values of frequent speed and the most energetic speed is noticed.
- At the height 11 m above ground level, the mean speed in the south exceeds 3 m/s except in Medenine, the frequent speed is lower or equal to 5 m/s and the energy wind speed varies from 5 to 12m/s. These encouraging results enable us to install wind pumping turbine which start at low wind speed.
- Compared to other sites, the Kebili site has a very high wind potential and represents 27% of the available total energy in the eight selected sites.

- The sites of Tozeur, Elborma and Djerba have a good wind potential, whose energy is about 1200 kWh/m^2/ year. They present 47.3% of total energy. The annual mean speed is approximately equal to 4.6 m/s.
- The last four sites (Tataouine, Remada, Gabes and Mednine) cover only 25.7% of the total energy. Their wind energy is inferior to 700 kWh/m^2/year. The annual mean wind speed lies between 3.5 and 2.7 m/s.

Similarly, to reveal the promising season, we plotted the seasonal wind characteristics with the two distribution methods, namely the mean wind speed and the available wind energy (Figure 6 and Table 2). These wind characteristics are maximums in spring in all the sites (the energy rate is superior at 30%). On the other hand, autumn is the least windy season (the energy rate is inferior at 20%).

Finally, we note that the south of the country represents a diversity of wind potential distribution. Indeed, the annual mean speed (respectively available energy) varies from 2.7 to 3.5 m/s in south-east (respectively 300 to 650 kWh/m^2/year) and varies from 4.6 to 5 m/s in south-west (respectively 1150 to 2000 kWh/m^2/year).

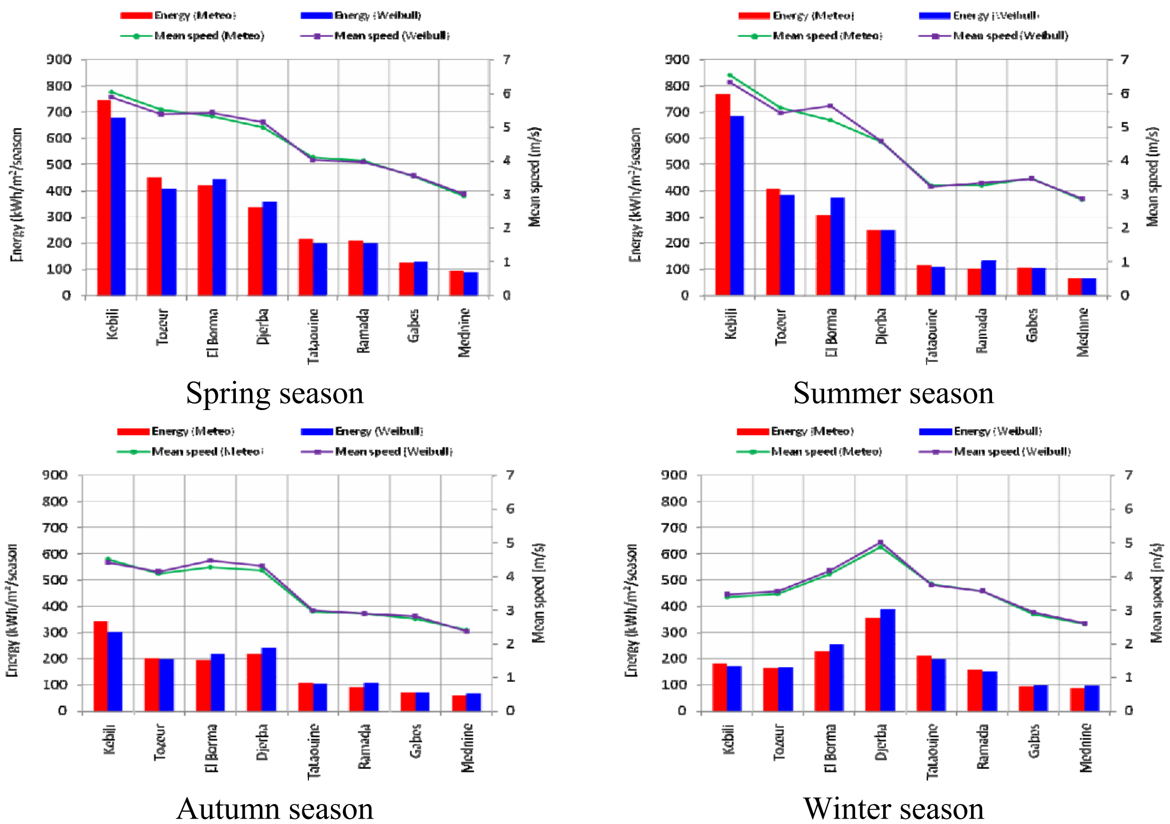

Figure 6. *Seasonal wind energy and mean speed of each site*

Table 2. Annual and seasonal percentage of available wind energy of each site

Sites	Spring (%)	Summer (%)	Autumn (%)	Winter (%)	Annual (kWh/m^2/year)
Kebili	37.27	38.38	17.16	8.99	1997.21
Tozeur	37.05	33.25	16.37	13.36	1215.41
Elborma	36.35	26.47	16.77	19.68	1151.97
Djerba	29.10	21.55	18.88	30.90	1149.58
Tataouine	33.31	17.90	16.49	32.70	645.53
Ramada	37.01	17.80	16.25	27.91	564.00
Gabes	31.66	26.30	18.15	23.89	393.85
Mednine	39.39	21.79	18.88	28.48	302.48

Wind pump technology development

For generations, wind has been used as a reliable energy and economic source in the water pumping systems. In rural or remote areas, the installation of a mechanical or electrical wind pumping system may be the best way to ensure the water needs of livestock, irrigation, household or even the community.

The performance of pumping wind turbine depends on several factors; the most important ones are: the depth of pumping, and the wind potential of each site. The mechanical pumping systems with wind turbine are generally machines of simple design and craftsmanship or skilled workmanship (Figure 7). They agree rather well for low wind potential zones, with daily needs for water not exceeding the 20 m^3 and depths of the wells not exceeding 50 m. Generally, they start for low speeds of about 2.5 to 3 m/s and adapt well to the characteristics of submerged piston pump, which require a low displacement speed, and they allow an important discharge height [11-14].

System design features

Rotor: its diameter can vary from 1.8 to 5 m. It comprises between 8 and 18 blades of galvanized sheet steel. The curve of the blades ensures the rotor an easy starting at a weak wind speed, and best efficiency.

Movement transformation system: The rotational movement of the rotor is transformed into vertical alternative movement by intermediary of a rod-crank system which actuates a piston pump.

Rudder and protection system: Rotor orientation opposite the wind is obtained by rudder. The machine functions by modifying the surface exposed to the wind which allows the wind turbine to turn regularly. A small pallet is fixed on the side of the wheel of the wind turbine and prevents the rotor from generally exceeding the speed of 80 rpm. In case of storm, it allows feathering machine, i.e. its stop in directing parallel to the wind direction.

Pump: It is a volumetric piston pump. It aspires and ascends water until about 5 meters above ground level. The pump is in steel treated against corrosion.

Pylon: It is conceived to resist a wind of 50 m/s (180 km/h). It is a structure of lattice bolted and assembled on tilting hinges. The pylon height varies from from 6 to 20 meters.

Technical characteristics of model SEN 5000 P8

In this study, the selected wind turbine SEN 5000 P8 is a multi-blade rotor with horizontal axis, manufactured in Tunisia (Serept Renewable Energies) in collaboration with Holland (Figure 8).

According to the manufacturer's technical document [18-19], the technical characteristics of the machine are given in Table 3.

***Figure 7**. Wind pump installation*

Table 3. Technical characteristics of model SEN 5000 P8

Rotor diameter (m)	5.0
Blade number	8.0
Maximum speed of rotation (rpm)	85.0
Speed of starting (m/s)	2.5
Nominal speed (m/s)	10.0
Speed automatic stop (m/s)	13.5
Piston diameter (m)	0.15
Stroke length of piston (m)	0.14
Total head (m)	22.0

Figure 8. *Wind turbine SEN 5000 P8*

Coupling Wind Turbine-Pump [20-25]

The hydraulic power necessary to produce a water quantity per time unit, under a height H, is expressed in Eq(5):

$$P_h = \rho_e . g . H_{mt} . Q_v \quad (5)$$

with ρ_e: Water density (kg/m^3), g: Gravitational constant (m/s^2), Q_v: Volumetric flow rate (m^3/s), H_{mt} is the sum of the geometrical height H_g and the linear pressure losses H_j (m). $H_{mt}=H_g+H_j$

The volumetric flow rate of the pump is directly related to the rotational speed of the turbine (see Eq(6)):

$$Q_v = \frac{S_p . c . N}{60} \quad (6)$$

with S_p: Piston area of pump (m^2), c: Piston stroke (m), N: Piston cycles number per minute (C/mn).

This number N corresponds to the rotational speed of the wind turbine rotor in the case of a direct connection of the rotor with the piston rod.

The specific speed λ is defined by Eq(7):

$$\lambda = \frac{\omega \cdot R}{V} \tag{7}$$

The available power of the wind is given in Eq(8):

$$P = \frac{1}{2}.\rho.S\,V^{3} \tag{8}$$

where S: Rotor area of wind turbine (m^2), ρ: Air density (kg/m^3).

The available energy of the wind is deduced by:

$$E=8.76\ P \tag{9}$$

The global efficiency of the wind pumping system is the ratio of the hydraulic power and the wind power:

$$\eta_G = \frac{P_h}{P} = \frac{2 \cdot \rho_e \cdot g \cdot H_{ml} \cdot Q_v}{\rho \cdot S \cdot V^{3}} \tag{10}$$

This efficiency corresponds to the product of the aerodynamic efficiency, the mechanical efficiency of the transmission chain and the pump efficiency.

Global efficiency of the wind pumping system

Figure 9 illustrates the experimental curve of the variation of volumetric flow rate of pumped water in function of the wind speed and the hydraulic power curve defined by the expression (5). The wind turbine SEN starts to supply water at a speed of 3 m/s and stops at 13 m/s. The water flow reaches its maximum of 3.5 liters per second at the wind nominal speed equal to 10 m/s corresponding to the nominal power of machine 755 W. Beyond this speed, we observe a fast fall of the water flow and the power due to the intervention of the regulation system. The rotor is equipped with an auxiliary rudder, which causes its progressive deviation from the wind direction (Figure 8).

Figure 10 describes the variation of the specific speed λ with the wind speed. This speed varies little between 2.1 and 2.4 for a wind speed inferior or equal to 10 m/s. Beyond this speed, λ decreases quickly until the stopping of the wind turbine.

The efficiency of the pumping system at each wind speed is represented by Figure 11. It is maximum at startup and decreases according to a hyperbolic curve until the stopping of the machine.

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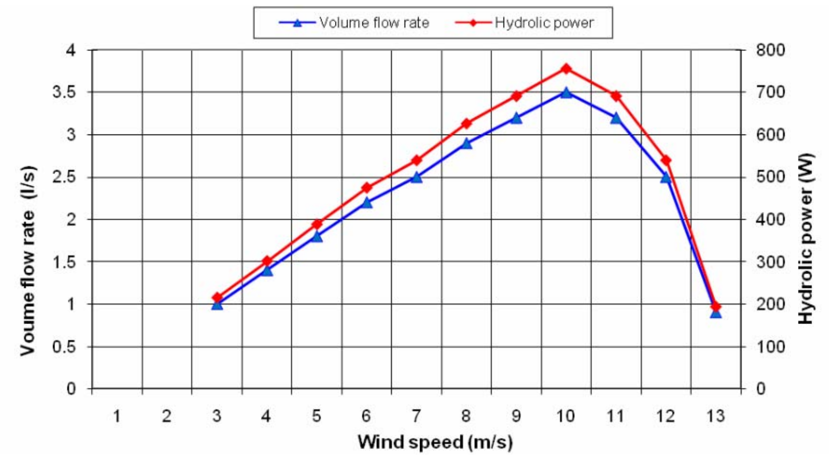

***Figure 9**. Variation curves of the water flow and the hydraulic power*

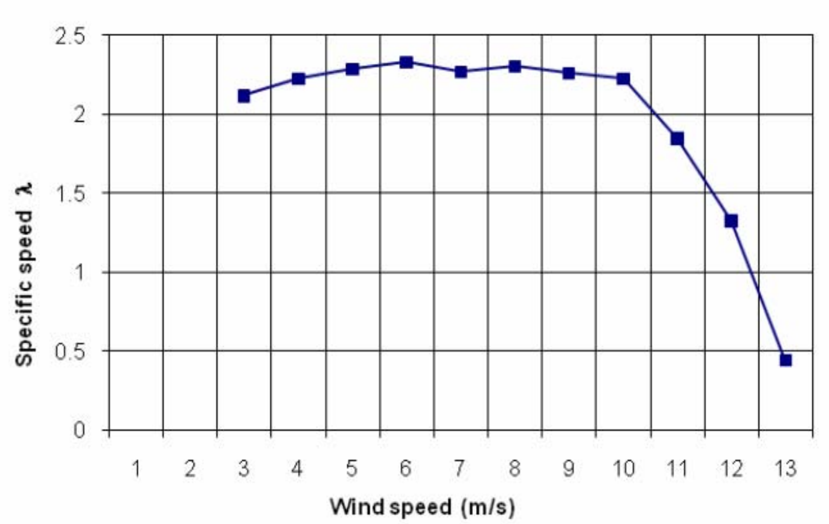

***Figure 10**. Specific speed of rotor in function of the wind speed*

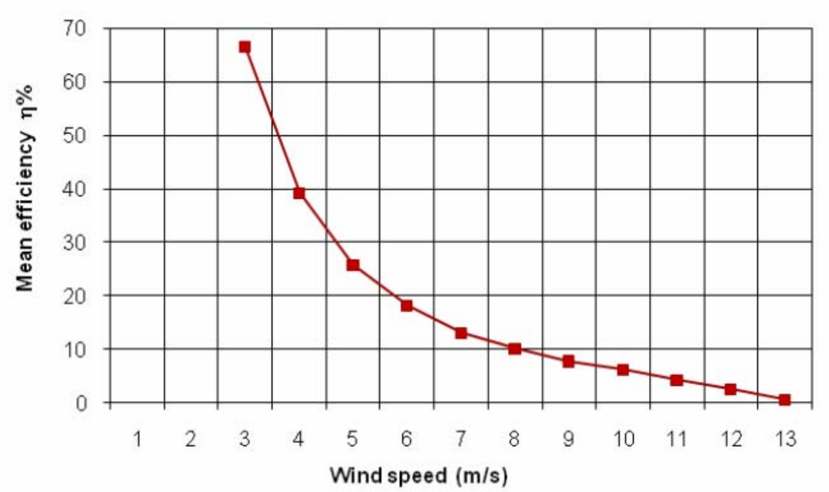

***Figure 11**. Mean efficiency of system in function of the wind speed*

Performance parameters of the pumping system

The available wind energy E_d that can be captured by the wind turbine is defined by the following expression:

$$E_d = \frac{8760}{2}.\rho S.\sum_{i=1}^{i=n}(V_i)^3 f(V_i) \quad (11)$$

The parameters which characterize a wind turbine are the nominal power P_n, the cut-in speed V_d, the nominal speed V_n and the cut-out speed V_c.

Similarly, the recoverable energy E_r at the exit of the pump (rotor, system of the movement transformation and pump) is given by the power curve of the machine and the statistical distribution of wind:

$$E_r = 8760.\left(\sum_{i=d}^{i=c} f(V_i).P_s(V_i)\right) \quad (12)$$

where: $f(V_i)$: occurrence frequency, $P_S(V_i)$: hydraulic power.

In addition, the annual energetic efficiency [17] of the machine is defined by:

$$\eta = \frac{E_r}{E_d} = \frac{2.\left(\sum_{i=d}^{i=c} f(V_i).P_s(V_i)\right)}{\rho S.\sum_{i=1}^{n}(V_i)^3 .f(V_i)} \quad (13)$$

To quantify the energy produced by the wind turbine, it is necessary to determine the use factor UF [17], which is estimated by the following equation:

$$UF = \frac{\sum_{i=d}^{c} f(V_i)P_s(V_i)}{P_n} \quad (14)$$

Similarly, to estimate the duration of operation of the machine, we define the availability rate [17], which depends on machine characteristics and wind potential in the site, such as:

$$AF = P\left(V_d \le V \le V_c\right) = F(V_c) - F(V_d) \quad (15)$$

where F(V): cumulated frequency.

The annual water quantity, which can be pumped in a site, is defined by:

$$V = 3600 \times 24 \times 365\left(\sum_{i=d}^{c} f(V_i).Q_v(V_i)\right) \quad (16)$$

Consequently, to completely describe the energy profitability of a wind pumping station, it is necessary to take into account these factors simultaneously of these: energetic efficiency, use factor, availability rate and annual volume of pumped water.

Table 4. Energetic efficiency, use factor and availability rate annuals of each site

Ranking	Sites	*η* (%)	*UF* (%)	*AF* (%)
1	Kebili	6.7	39.8	68.0
2	Tozeur	12.3	42.2	75.4
3	El Borma	12.7	43.5	80.2
4	Djerba	12.4	42.3	77.8
5	Tataouine	15.7	29.9	59.2
6	Ramada	17.2	28.6	60.8
7	Gabes	22.8	26.6	60.2
8	Mednine	23.8	21.3	50.0

The annual and seasonal energetic efficiency of the installation of each site is given by Table 4 and Figure 12. This efficiency varies from one site to another and it increases with less windy sites. Indeed, we note that the efficiency is maximum in the less windy site (Mednine) and low in very windy site (kebili) because this wind turbine type operates in the range of low wind speeds, which is between 3 and 13m/s (see Table 1).

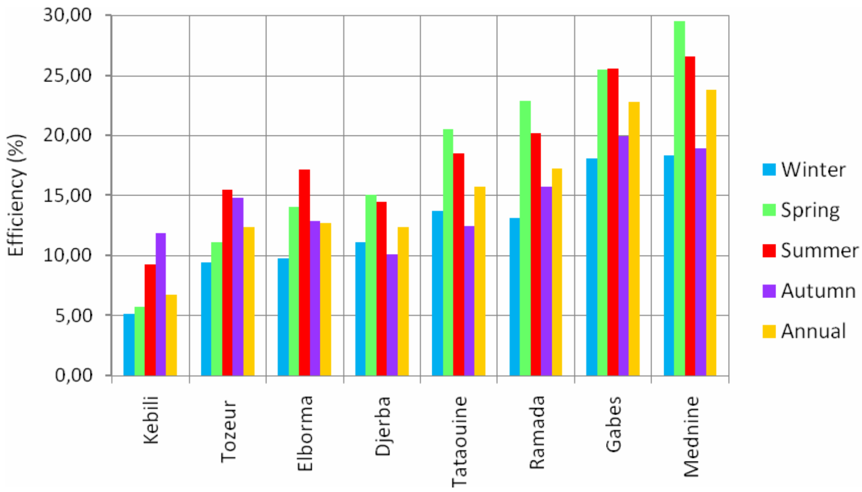

***Figure 12**. Energetic efficiency of each site*

The annual use factor decreases with the less windy sites and varies from 21 % to 43%. It is maximum in spring and summer for the majority of the sites and reaches 60% in Elborma (Figure 13).

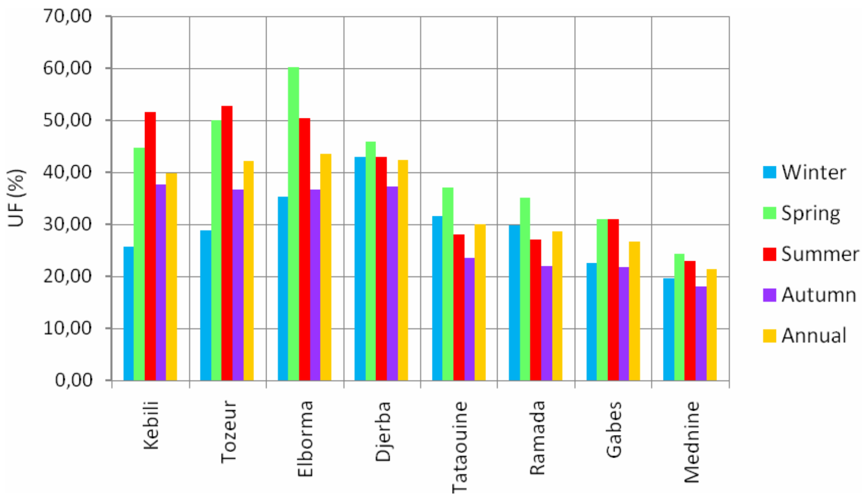

***Figure 13**. Use factor (UF) of each site*

The annual availability rate is excellent and varies from 50% to 80%. Also, it is maximum in spring and summer for the majority of sites and reaches 90% in Elborma (Figure 14).

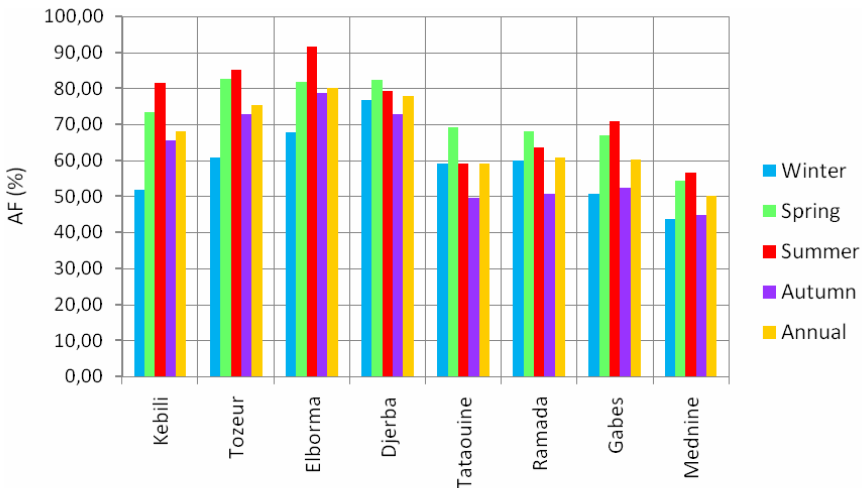

***Figure 14**. Availability rate of each site*

Table 5 and Figure 15 show that: The annually pumped water in different sites is important. Its volume varies from 23470 m^3/year (i.e. 64.5 m^3/day) in Mednine to 47800 m^3/year (i.e. 131.4 m^3/day) in Elborma. The water volume also reaches its maximum in spring and summer for all the sites. Indeed, the water needs vary during the vegetative cycle according to the date of cultivar maturity, plant density and climatic conditions and which are most important in summer.

Table 5. Annual and seasonal percentage of pumped water of each site

Sites	Winter (%)	Spring (%)	Summer (%)	Autumn (%)	Annual (m^3)
Kebili	15.9	28.2	32.5	23.5	44122.526
El Borma	20.0	28.0	29.2	22.7	47792.813
Tozeur	16.9	29.9	31.5	21.7	46583.634
Djerba	25.1	27.3	25.6	22.0	46653.046
Tataouine	25.9	31.1	23.5	19.5	33125.601
Ramada	12.5	38.4	27.2	21.9	27664.053
Gabes	20.9	29.4	29.4	20.3	29372.075
Mednine	22.7	28.7	27.1	21.4	23473.881

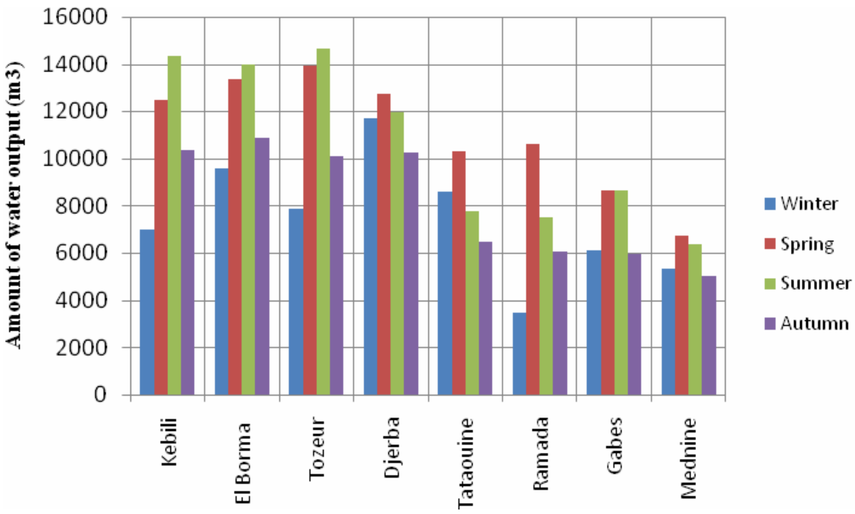

Figure 15. *Seasonal pumped water in various sites*

Conclusions

The study of mechanical wind pumping system, using multiblade wind turbine SEN 5000 P8, has determined:

1. The specific speed λ for each the wind speed: this speed λ is optimal for wind speeds between 3 and 10 m/s.
2. The annual and seasonal energy efficiency of the installation: this efficiency is maximal at the site of lower wind potential (Mednine) and minimum in the site of greatest wind potential (kebili). Indeed, the used wind turbine operates in the range of the low wind speeds, which lies between 3 and 13 m/s.
3. The annual and seasonal use factor of the installation: this factor is interesting and can reach 43% annually (and 60% seasonally) in Elborma.

4. The annual and seasonal availability rate of the installation: this rate is excellent and can reach 80% annually (and exceeds 60% seasonally) in Elborma.
5. The annual and seasonal volume of water pumped: this volume can reach 47793 m^3/year (31.4 m^3/day) in Elborma and it can exceed 14500 m^3 during the summer in windy sites.

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