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Wind Energy Assessment of the Sidi Daoud Wind Farm - Tunisia

F. Ben Amar^{1,2} and M. Elamouri¹

¹*Preparatory Institute for Engineering Studies of Sfax*

²*Network and Machines Electric Research Unit, INSAT, Tunisia*

1. Introduction

In a world increasingly conscious of the degrading state of its environment and with the surge of the oil prices, renewable energies have found a choice place in the energy supply strategies of a great number of countries.

In fact, the growing interest in clean and durable energies in general, and in the wind energy in particular, is more than one society phenomenon. It presents today a true stake to which the energy supply security and the reduction of the toxic emissions are closely related. That's why, the contribution of the backers for the mobilization of the necessary financial and technical resources is a guarantee to support the efforts deployed by our countries in order to control the advanced technologies in this domain.

The African continent disposes of an important potential in renewable energies notably the hydraulics, the solar, the wind, the biogas and the geothermal. However, this potential remains strongly under exploited because of a certain number of obstacles related to the high cost of investment for these systems, the absence of competences and skilled human resources, the limit of the regional co-operation in this domain, the lack of maintenance structures and the absence of information and reliable data on the energy consumptions.

In Tunisia, the development that the country's economy has known for these last years with its positive repercussions on the social plan as well as on the living standard has contributed to the acceleration of the energy consumption rhythm, which on average has increased by 4% per year, thus exceeding the development rate of the hydrocarbons production. Indeed, since 2001, Tunisia has become an importer of primary energy (Fig. 1) [1-4].

In the electricity production sector, the Tunisian Company of Electricity and Gas (STEG) has engaged in a diversification of its production park mainly composed of conventional units (vapor thermic, gas turbine and combined cycle), through a progressive recourse to the production projects starting from renewable energies (hydraulic and wind turbines), in spite of their investment cost still high on a worldwide scale (Figs. 2 and 3) [1-4].

The wind power in Tunisia is considered, in the electricity production sector, as a vector carrying in the medium term in contribution to the energy balance improvement and equally to the fight against the climate change. In fact, it is proved that Tunisia is endowed with good wind energy potentials, hardly exploited so far. Moreover, this wind energy currently arouses a great interest not only on behalf of the authorities but also of the private

sector. An effort has been made in order to adapt the legal and institutional framework to this orientation [1-4].

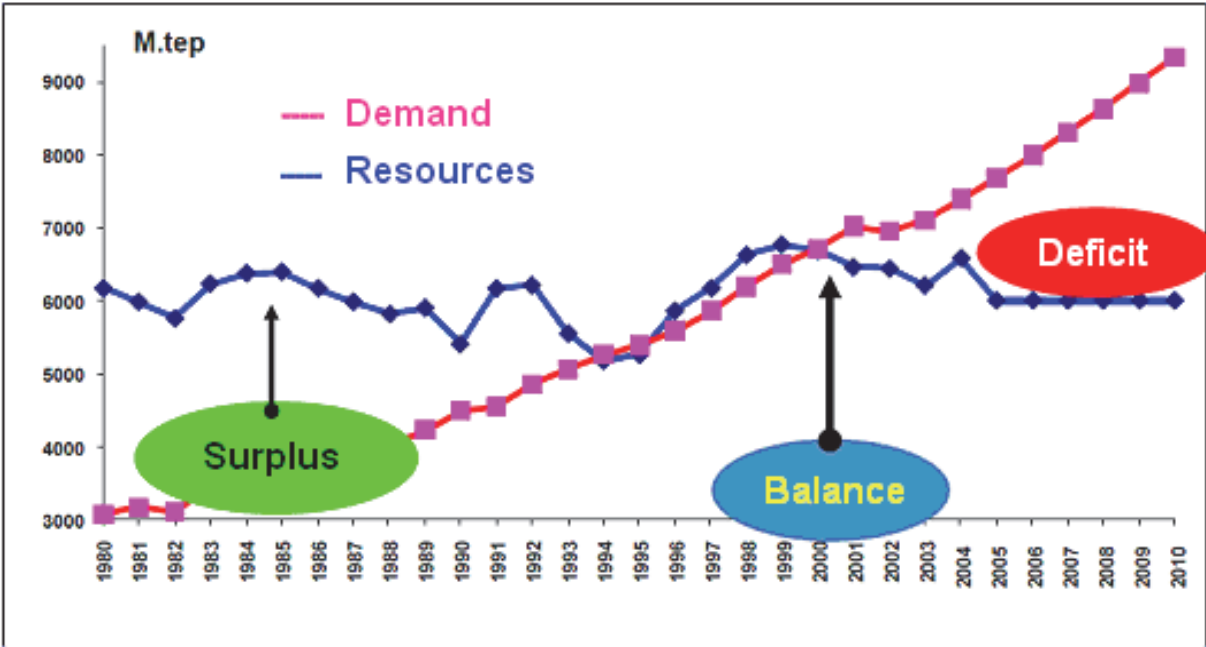


Fig. 1. Energy resources and demand in Tunisia.

Currently, the use of the wind energy in Tunisia and, consequently, the installation of wind farms have become unavoidable realities, due to the environmental problems posed by the traditional energy sources and of the aerogenerators technological progress. In fact, in order to meet the country's energy needs in the best economic conditions, of quality and respect of the environment as well as the users' safety, the STEG has already established its first wind park in Sidi Daoud in the area of the Cap Bon, in the North-East of the country (Fig. 4). This power station currently comprises 70 wind turbines of an installed power generation capacity of 53.6 MW, which corresponds to approximately 1 % of the national production park (Table 1). It has been accomplished in three stages [1-4]:

The first section of a power capacity of 10.56 MW, created in 2000, incorporates 32 aerogenerators (Made AE-32) with a asynchronous motor, having the unit nominal power of 330 kW. The second section of power capacity of 8.72 MW, created in 2003, comprises 12 aerogenerators: one wind turbine Made AE-52 with a synchronous motor of 800 kW and 11 wind turbines with asynchronous motor of which one machine Made AE-61 of 1.3MW capacity and 10 machines Made AE-46, each of them with a capacity of 660kW. The third section of power capacity of 34.32 MW, created in 2009, comprises 26 powerful wind turbines (MADE AE-61).

The wind energy station, the object of this study, with these 3 sections is located approximately 5 km of the coastal village of Sidi Daoud (800 inhabitants approximately). It is a sufficiently windy site, able to receive several wind turbines, far from the buildings and the obstacles and close to the electrical supply network (Fig. 5) [1-4].

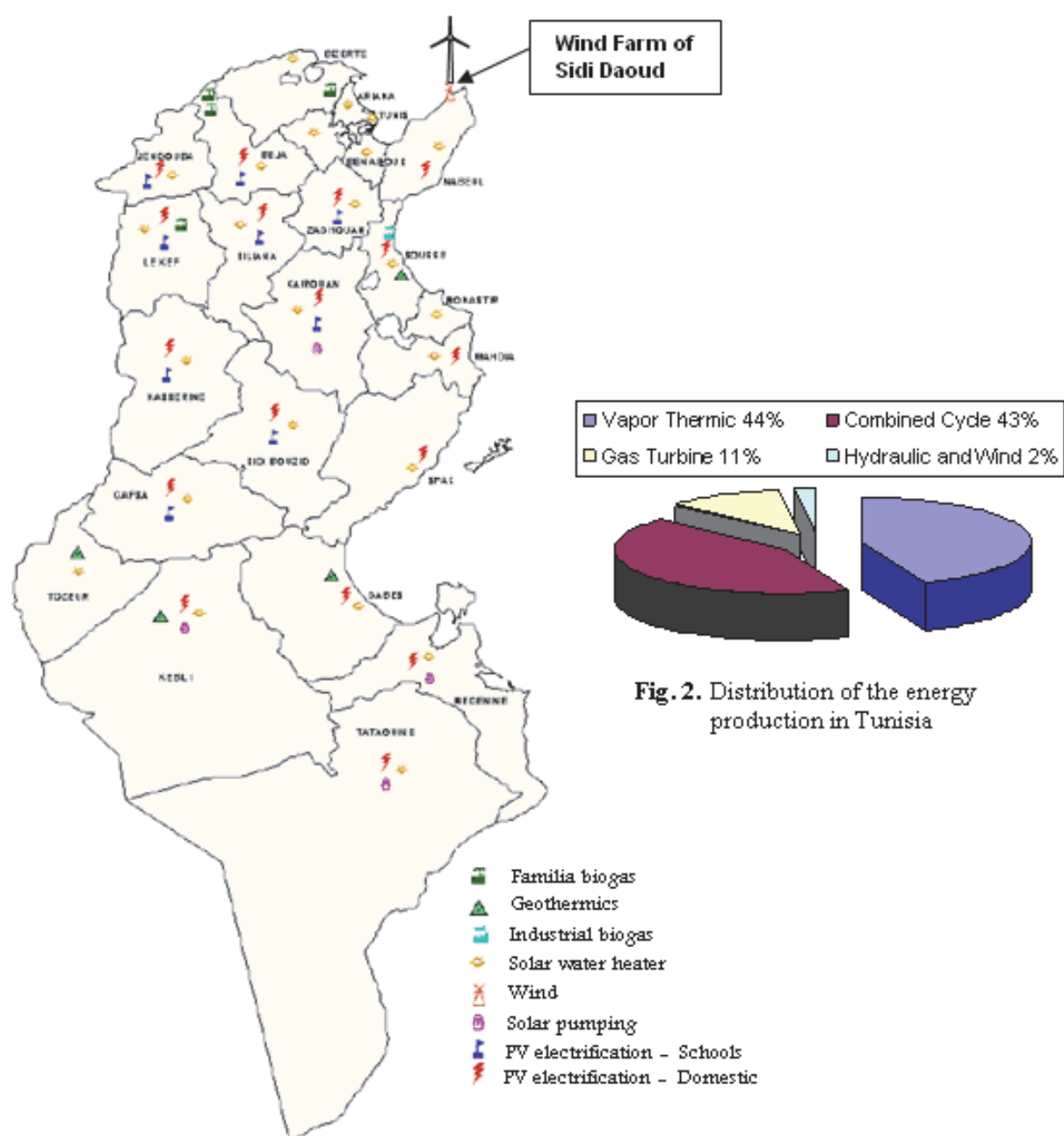


Fig. 3. Distribution of renewable energy used in Tunisia.

Aerogenerator MADE	Generator type	Nominal power kW	Height (m)	Number	Section
• AE-32	Asynchronous	330	30	32	First
• AE-46	Asynchronous	660	45	10	Second
AE-52	Synchronous	800	50	1	"
AE-61	Asynchronous	1320	60	1	"
• AE-61	Asynchronous	1320	60	26	Third

Table 1. Aerogenerators of the Sidi-Daoud wind farm.

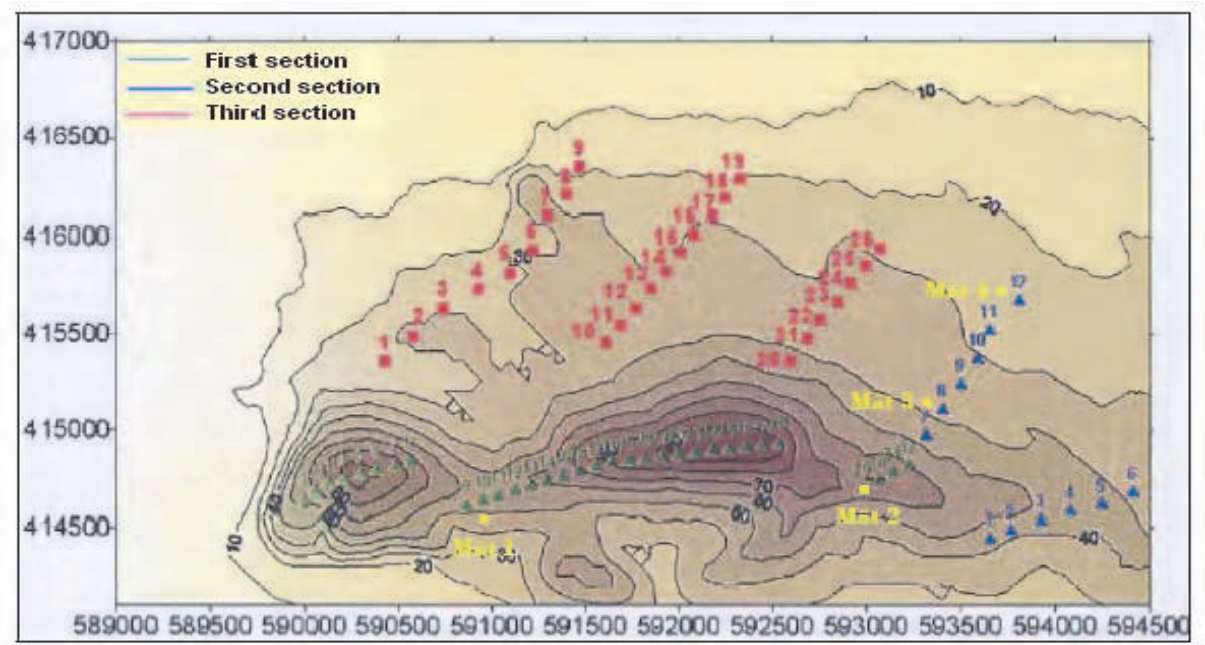


Fig. 4. Wind turbines installation of the Sidi Daoud wind farm - Tunisia.

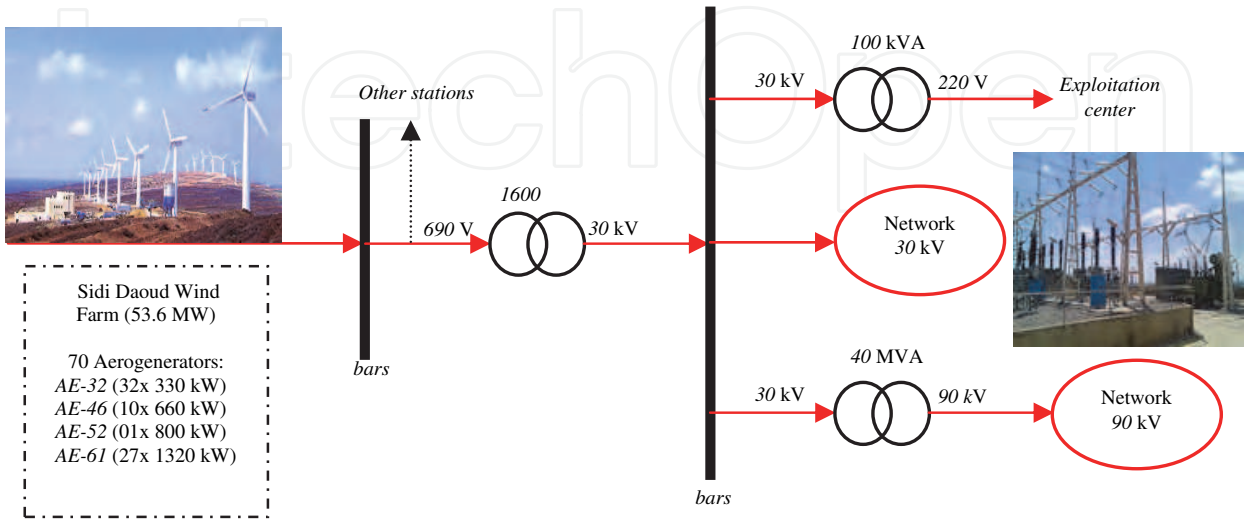


Fig. 5. Wind farm and electrical network of Sidi Daoud.

The objectives of this study are:

- The evaluation of the wind annual characteristics (distribution, direction, characteristic speeds and wind potential) of Sidi Daoud site by the meteorological method and the Weibull and Rayleigh analytical methods [5-21]. The data treated in this study, during four years period (2004-2007), are the measurements recorded in four places of the site (masts 1, 2, 3 and 4) at altitudes which correspond to the heights of the aerogenerators hubs (30, 45, 50 and 60 m above ground level). To evaluate statistically the performances of the Weibull and Rayleigh analytical distributions compared to the experimental distribution, we calculate the statistical parameters analysis for the wind speed and the power density distributions (The determination coefficient R^2 , the chi-square coefficient χ^2 and the root mean square error (RMSE)) [5-12].
- The modeling of the vertical profile of the wind speed in the measurement place mast 4 by the power and logarithmic laws, in order to know the evolution the wind speed at altitudes representing an energy interest [22-27]. A close attention is paid to the study of the influence height on the wind characteristics (mean speed and power density) by using the Rayleigh distribution.
- The determination of the energetic performances of the four aerogenerators with horizontal axis MADE AE-32, AE-46, AE-52 and AE-61 installed in site. From its characteristic curves, we study the aerodynamic and energy efficiency in terms of the wind speed, the use factor and the availability rate of each type of aerogenerator, installed with the various masts, and the whole wind farm [28-35].

2. Adjustment methods of the meteorological data

During the evaluation of the energetic performance of a wind system, it is essential to study the characteristics of the two elements: the site and the aerogenerator.

The object of the study of the site is to evaluate the following characteristics [5-21]:

- Mean speed ;
- Most energetic speed ;
- Most frequent speed ;
- Occurrence frequency ;
- Power density ;
- Available energy ;
- Duration of wind availability ;
- Shear coefficient.

The study of the aerogenerator makes it possible to define [28-35]:

- Usable energy ;
- Recoverable energy ;
- Power coefficient ;
- Mean efficiency ;
- Use factor ;
- Availability rate.

The used calculation methods [5-12]:

- Meteorological experimental method ;
- Weibull and Rayleigh distribution analytical methods.

From the tables of cumulated frequency of the classified wind speeds, the wind characteristics of the site are given by the following table 2:

The standard deviation enables to study the dispersion of wind speeds measurements around the mean speed. Indeed, if this standard deviation is weak, the values of measurements are regrouped around the average; if it is significant, they are very dispersed. The annual available energy of the wind in the site per unit area is given by the following relation:

$$E_d = 8,76 \cdot P_d \tag{1}$$

Wind characteristics	Meteorological method	Weibull method	Rayleigh method
Cumulated frequency	Tableau de l'I.N.M.	$F(V) = \int_V^{+\infty} f(V) \cdot dV = \exp \left[- \left(\frac{V}{A} \right)^k \right]$	$F(V) = \exp \left[- \frac{\pi}{4} \left(\frac{V}{V_m} \right)^2 \right]$
Occurrence frequency	$f(V) = F(V) - F(V + 1)$	$f(V) = \frac{K}{A} \left(\frac{V}{A} \right)^{K-1} \exp \left[- \left(\frac{V}{A} \right)^K \right]$	$f(V) = \frac{\pi}{2} \left(\frac{V}{V_m^2} \right) \exp \left[- \frac{\pi}{4} \left(\frac{V}{V_m} \right)^2 \right]$
Mean speed	$V_m = \sum_{i=1}^n V_i f(V_i)$	$V_m = A \cdot \Gamma \left(1 + \frac{1}{k} \right)$	$V_m = \int_0^{+\infty} V \cdot f(V) \cdot dV$
Most frequent speed	$V_f = V [f(V)_{\max}]$	$V_f = A \cdot \left(1 + \frac{1}{k} \right)^{1/k}$	$V_f = \sqrt{\frac{2}{\pi}} \cdot V_m$
Most energetic speed	$V_e = V [P_d(V)_{\max}]$	$V_e = A \cdot \left(1 + \frac{2}{k} \right)^{1/k}$	$V_e = \sqrt{\frac{8}{\pi}} \cdot V_m$
Power Density	$P_d = \frac{1}{2} \cdot \frac{16}{27} \cdot \rho \cdot \sum_{i=1}^n V_i^3 f(V_i)$	$P_d = \frac{1}{2} \cdot \frac{16}{27} \cdot \rho \cdot A^3 \cdot \Gamma \left(1 + \frac{3}{k} \right)$	$P_d = \frac{3}{\pi} \cdot \rho \cdot V_m^3$
Standard deviation	$\sigma = \left[\sum_{i=1}^n (V_i - V_m)^2 f(V_i) \right]^{1/2}$	$\sigma = A^2 \left[\Gamma \left(1 + \frac{2}{k} \right) - \Gamma^2 \left(1 + \frac{1}{k} \right) \right]$	$\sigma = V_m^2 \left(\frac{4}{\pi} - 1 \right)$

Table 2. Evaluation methodologies of the wind characteristics.

3. Characterization of the site and evaluation of the wind potential

3.1 Sidi Daoud site relief

The establishment site of this wind station is located between the Mediterranean coasts in the north, of the villages of Sidi Daoud, Ghorman and of the forest dar Chichou in the south and the mountains of El Haouaria in the west coast. It has a mountainous relief, slightly lengthened according to the East-West direction. The vegetation in the neighborhoods of the site is practically uniform and it is composed of trees and shrubs of small sizes. Its geographical coordinates are of 37°02 ' for latitude and of 10°56 ' for longitude. The total

area used for the establishment of the power station is approximately 9 ha and extends on 3.5km from the coast (Fig. 6). It is a sufficiently windy site, able to receive several wind turbines, far from the buildings and the obstacles and close to the electrical supply network [1-4].

The aerogenerators of the first and the second section are established on the summits of the two mountains "Djebel El Hammam " and " Djebel Ghormane" whose altitude is respectively 50 and 100 m above sea level. The aerogenerators of the third section are located at the bottom of these two hills and about a hundred meters from the marine coasts.

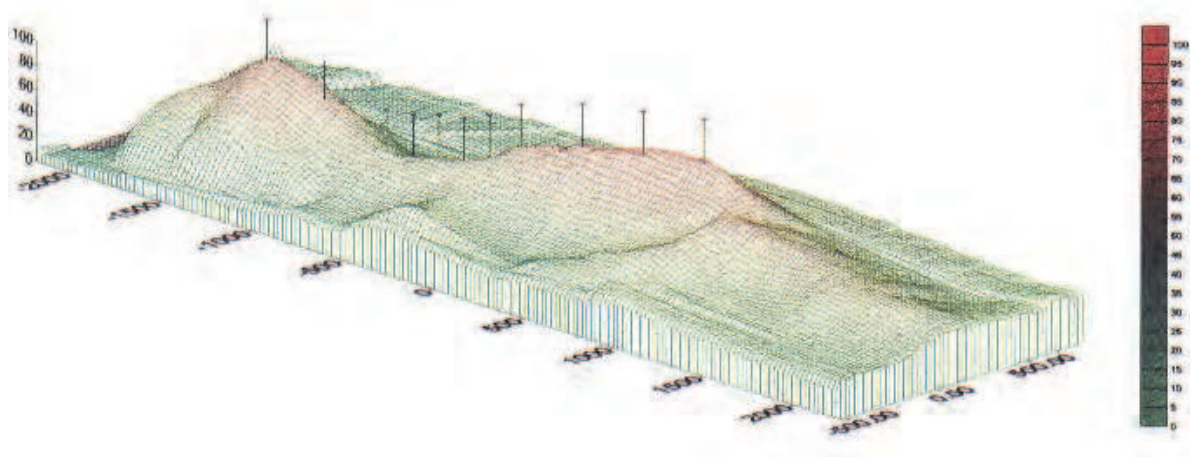


Fig. 6. Sidi Daoud site relief.

The meteorological data of the Sidi Daoud site used in this study were measured by the technical service of the wind farm during four years (2004–2007). The data relating to the direction and the wind speed were taken by four measurement masts at altitudes which correspond to the heights of the aerogenerators hubs (30, 45, 50 and 60 m above ground level) (Table 3).

Mast	1	2	3	4
Altitude (m)	68	75.3	40.42	22.78
Height sensor (m)	30	30	45 and 50	45 and 60

Table 3. Characteristics of the four measurement masts.

3.2 Wind roses

The wind rose is a spatial representation of the variation of the wind direction for such a site. It illustrates the direction of the dominant winds on a site and enables to plan the wind turbines installation in order to minimize the wake effect caused by nearby obstacles [5-12]. Fig. 7 represents the wind roses with 36 directions for the various masts. We note the importance of the wind coming from the West and South-East sectors and the wind's non-negligible existence from the North-West sector. In addition, the calm wind persists from both the north-east and south sectors.

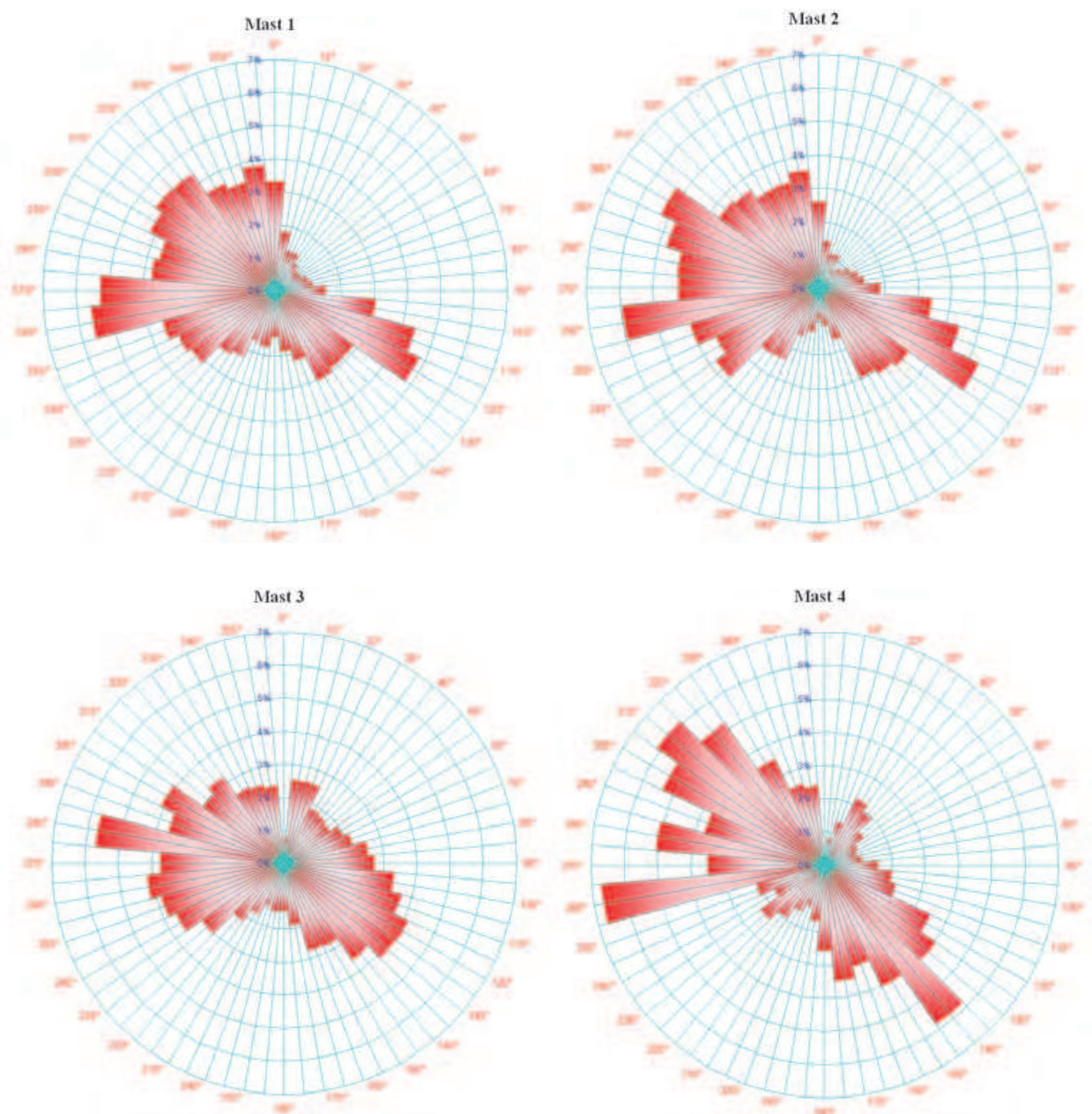


Fig. 7. Wind roses for the various measurement masts.

3.3 Wind characteristics: speeds and wind energy estimation

The statistical processing of the measured data has made it possible to determine the histograms and their adjustments by the meteorological method and the Weibull and Rayleigh methods, for various masts and heights, whose characteristic elements are:

- The analysis of table 4 shows that the wind characteristics (speeds and energy at the height 30 m) of mast 1 are better than those of mast 2. Indeed, the wind potential increased by 14% had with the increase the mean wind speed of 3.3% and the most energetic speed of 10%. The parameter k of the Weibull law, which characterizes the frequency distribution form, is about 1.9; whereas the parameter A , which determines the quality of the wind, is better with mast 1 (Figs. 8a and 8b).

- The wind characteristics at the height 45 m of mast 4 are slightly superior to those of mast 3 (Table 5). Indeed, the mean speed passes from 6.31m/s (mast 3) to 6.41 m/s (mast 4), which allows an energy profit of 5.6%. The most frequent and the most energetic speeds are respectively 5 m/s and 11 m/s for the two masts.
- For Mast 3, the passage of the height 45 m to 50 m allows a gain of 2.5% on the mean speed and 5.73% on the power density.
- For Mast 4, the passage of the height 45 m to 60 m allows a gain of 6.4% on the mean speed, 9% on most energetic speed and 20.12% on the power density.
- For masts 3 and 4, the parameter k of the Weibull law is about 2 for the various heights, whereas parameter A believes with the height. The distributions of the frequency classified speeds calculated by the two laws are equivalent; which seems normal to us because the form factor k is almost equal to 2 (Figs. 8c, 8d, 8e and 8f).
- The standard deviation σ is weak enough, which shows that the measurements are centered on the average (Tables 4 and 5).

	Mast 1 – 30 m			Mast 2 – 30 m		
Method	M	W	R	M	W	R
V_m (m/s)	6.59	6.68	6.59	6.38	6.45	6.38
V_f (m/s)	5	4.97	5.26	5	4.89	5.09
V_e (m/s)	11	11.13	10.51	10	10.62	10.18
E (kWh/m ² /an)	1921.61	1951.38	1737.17	1689.79	1719.9	1578
P (W/m ²)	219.36	222.76	198.31	192.90	196.34	180.14
A (m/s)		7.52035			7.26489	
k		1.86065			1.89609	
σ (m/s)	3.72887	3.72573	3.44427	3.53762	3.53601	3.33568

Table 4. Wind characteristics of the Sidi Daoud site calculated at the masts 1and 2.

	Mast 3 – 45 m			Mast 3 – 50m			Mast 4 – 45 m			Mast 4 – 60 m		
Method	M	W	R	M	W	R	M	W	R	M	W	R
V_m	6.31	6.40	6.31	6.47	6.59	6.47	6.42	6.54	6.42	6.83	6.91	6.83
V_f	5	5.12	5.04	5	5.36	5.16	5	5.19	5.12	5	5.47	5.45
V_e	11	10.201	10.071	11	10.38	10.32	11	10.46	10.24	12	11.08	10.89
E	1584.6	1588.9	1526.8	1675.4	1698.9	1644.7	1676.6	1704.4	1606.7	2013.8	2020.1	1932.3
P	180.89	181.38	174.29	191.25	193.94	187.75	191.39	194.57	183.41	229.89	230.61	220.58
A		7.222			7.440			7.374			7.794	
k		2.004			2.048			1.990			1.982	
σ	3.388	3.339	3.299	3.405	3.372	3.382	3.447	3.432	3.356	3.685	3.640	3.568

Table 5. Wind characteristics of the Sidi Daoud site calculated at the masts 3 and 4.

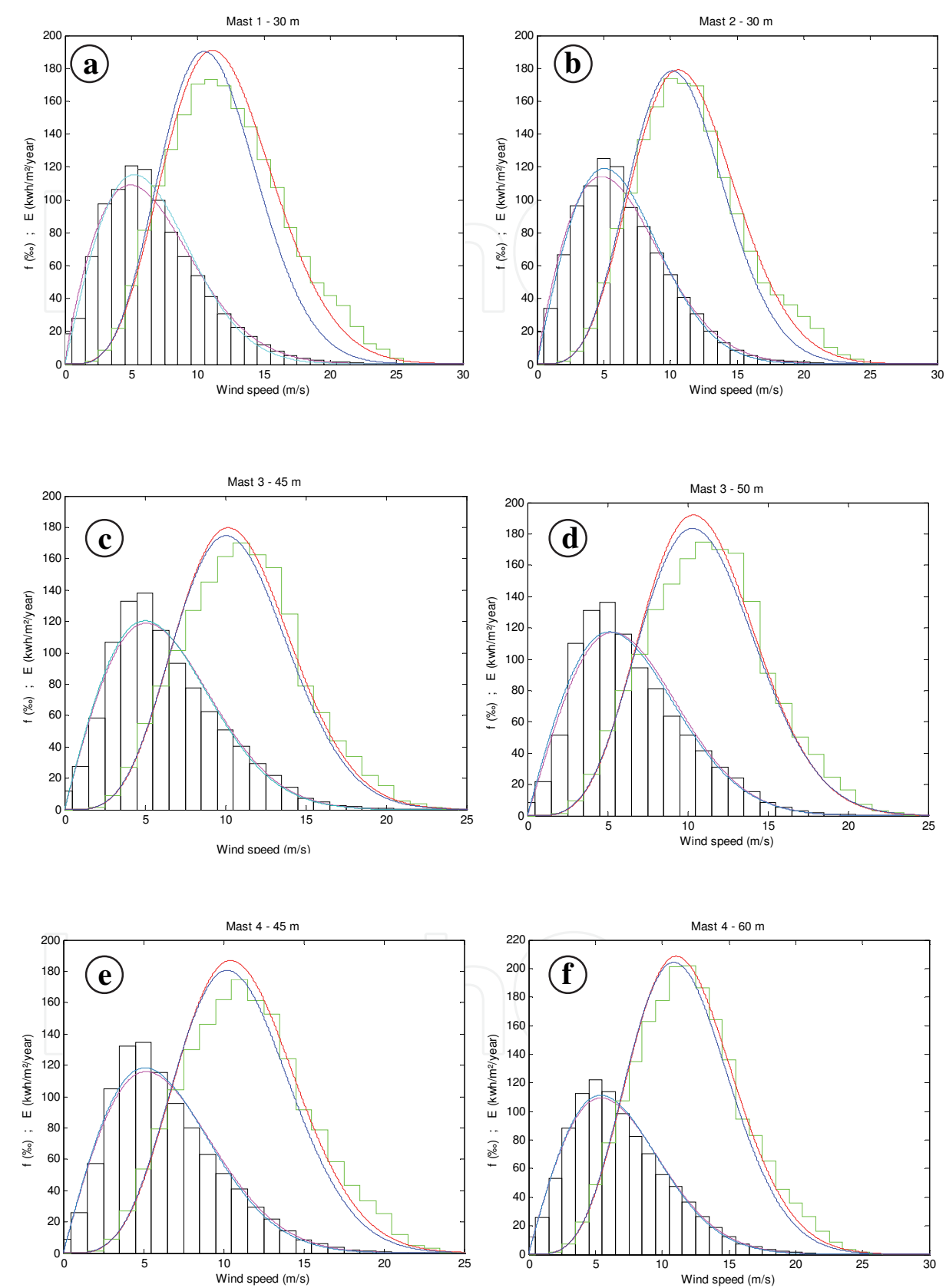


Fig. 8. Annual distributions of the wind speed and the available energy for the period 2004-2007.

These results prove that the Sidi Daoud site conceals a strong wind potential. Despite the complex relief of the site, the annual wind potential calculated at the various masts for the same height is almost constant, which shows the good stability of the wind resource of the Sidi Daoud site.

3.4 Statistical analysis parameters of Weibull and Rayleigh distributions

The determination coefficient R^2 (R is the correlation coefficient), the chi-square coefficient (χ^2) and the root mean square error (RMSE) analysis are statistically calculated to evaluate the performances of Weibull and Rayleigh models. Consequently, a better distribution has the highest value of R^2 and the lowest values of RMSE and χ^2 [5-21].

The R^2 gives the effectiveness of the adjustment model. It is much better than its value being nearer to 1. It is calculated as follows:

$$R^2 = \frac{\sum_{i=1}^n (y_i - y_m)^2 - \sum_{i=1}^n (y_{ic} - y_i)^2}{\sum_{i=1}^n (y_i - y_m)^2} \quad (2)$$

The χ^2 is employed to determine the adjustment quality. At low values of χ^2 , the better adjustment quality is obtained. It is given by the following relation:

$$\chi^2 = \sum_{i=1}^n \frac{(y_i - y_{ic})^2}{y_i} \quad (3)$$

The RMSE also gives the difference between computed and experimental values. Its minimal value tends toward zero. It is defined by the following expression:

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^n (y_i - y_{ic})^2 \right]^{1/2} \quad (4)$$

The values of these parameters are given in table 6.

The comparison of the meteorological distribution (wind speed frequency and power density) with the Weibull and Rayleigh approximations shows that the latter two models present a better adjustment. Indeed, for these two models and for the four measurement masts (Table 6):

- The determination coefficient R^2 is very near to the unit.
- The RMSE is very weak and does not exceed 0.95% for the adjustment of the wind frequency distribution and lower than 2 for the power density distribution.
- The chi-square coefficient χ^2 is also low and does not exceed 4% for the adjustment of the wind distribution and it varies from 2.7 to the 16.5 for the power density distribution.

It is noticed that the two adjustment models are equivalent for masts 3 and 4; which seems normal to us because the Rayleigh distribution is a particular case of Weibull (the form factor k of the studied site is about 2).

3.5 Availability duration of wind

Another parameter to be considered is the wind availability in the site. The curve speed-duration allows to determine the number of availability hours of the wind speed superior

or equal to a given threshold (Fig. 9); it is noticed that the wind blows at a speed higher than V_f (V_m and V_e , respectively) about 66% (48% and 11%, respectively) of annual time. Table 7 gives the durations and the minimum power densities for characteristic speeds (V_f , V_m and V_e) for various masts and at various heights.

Method		Occurrence frequency			Power density		
		R^2	χ^2	RMSE	R^2	χ^2	RMSE
Mast 1 30 m	W	0.977131	0.0321404	0.00617719	0.978849	3.63072	1.02
	R	0.982379	0.0314141	0.00542237	0.917189	16.5487	2.01828
Mast 2 30 m	W	0.981702	0.027062	0.00566918	0.988095	2.65463	0.754208
	R	0.985106	0.026041	0.00511471	0.973947	7.73753	1.11571
Mast 3 45 m	W	0.96582	0.0311569	0.00828543	0.973673	3.00107	1.12096
	R	0.968769	0.0317353	0.00791994	0.966837	4.14245	1.25812
Mast 3 50 m	W	0.956009	0.0365952	0.00942688	0.966365	3.65163	1.32168
	R	0.960885	0.0389296	0.00888907	0.972464	3.13961	1.19586
Mast 4 45 m	W	0.966577	0.0296976	0.00810549	0.973502	3.77	1.11853
	R	0.971301	0.0295496	0.00751076	0.965527	6.13694	1.2758
Mast 4 60m	W	0.980766	0.0230902	0.00563687	0.98726	2.74201	0.904176
	R	0.982598	0.0233729	0.00536173	0.979106	5.04789	1.15792

Table 6. Statistical analysis parameters for the wind speed distribution and the power density distribution relating to the various masts.

The curve power-duration also gives the hours' number when the site has a power density superior or equal to a given threshold (Fig. 10). For example, the site presents a power density higher than 0.5 kW/m² only from 12% (mast 3 at 45 m) to 16% (mast 4 at 60 m) of the annual time.

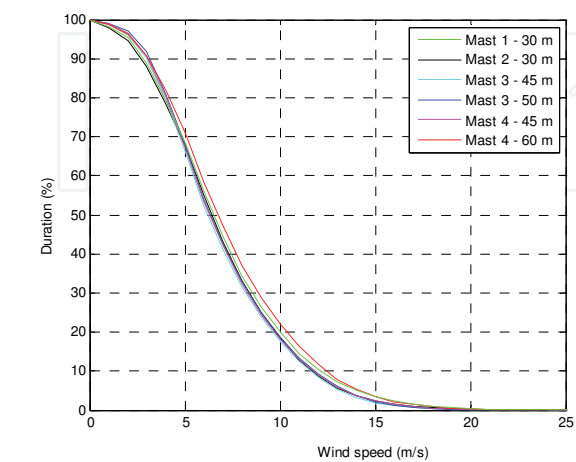


Fig. 9. Curve speed-duration of Sidi Daoud site.

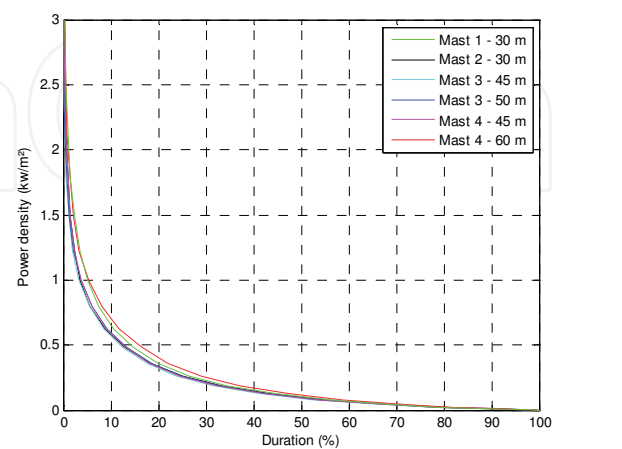


Fig. 10. Curve power-duration of Sidi Daoud site.

	Duration (%)			Minimum power density (W/m²)		
	$V \geq V_m$	$V \geq V_f$	$V \geq V_e$	$V \geq V_m$	$V \geq V_f$	$V \geq V_e$
Mast 1 – 30 m	49.3	68.37	14.58	103.87	45.37	483.1
Mast 2 – 30 m	50.4	67.5	18.3	94.3	45.4	363.0
Mast 3 – 45 m	48.8	66.2	12.5	91.2	45.4	483.1
Mast 3 – 50 m	48.6	67.7	13.4	98.3	45.4	483.1
Mast 4 – 45 m	48.7	67.0	13.1	96.0	45.4	483.1
Mast 4 – 60 m	49.1	70.8	11.6	115.6	45.4	627.2

Table 7. Duration and minimum power density for the characteristic speeds.

4. Vertical extrapolation of the wind speed

4.1 Extrapolation laws

The precise evaluation of the wind power potential at a site place requires the knowledge of the wind speed at various heights. The standard height of measurement is generally of 10 m, but during a prospection of a site, in order to draw up a wind project, it is preferable to take measures at two or three levels for one period at least six months in order to know the evolution of the wind speed at altitudes representing an energy interest. The majority of work on the determination of the wind vertical profile in the surface boundary layer is based on the similarity theory of Monin-Obukov [22-23]. This theory was supplemented by studies which proposed extrapolation laws of the wind speed of a level H_1 on a level H_1 according to the variation of roughness classes.

In order to draw up a comparative study, two extrapolation laws are retained [22-27]:

- Logarithmic law ;
- Power law.

4.1.1 Logarithmic law

For neutral atmospheric conditions (i.e. when the turbulence forces are in balance), the Monin-Obukov expression, giving the wind speed profile, is written:

$$V(H) = \frac{u^*}{K} \cdot \text{Ln}\left(\frac{H}{Z_0}\right)$$

(5)

The ground roughness Z_0 and the corresponding friction speed u^* are then given starting from the wind speed measurements in two levels H_1 and H_2 by the following relations:

$$u^* = K \cdot \frac{V(H_2) - V(H_1)}{\text{Ln}\left(\frac{H_2}{H_1}\right)}$$

(6)

$$Z_0 = \exp\left[\text{Ln}(H_1) - \frac{K \cdot V(H_1)}{u^*}\right]$$

(7)

4.1.2 Power law

The extrapolation of the speed measured V_0 on a level H_0 towards speed $V(H)$ on a level H , is written:

$$V(H) = V_0 \cdot \left(\frac{H}{H_0} \right)^\alpha$$

(8)

α is the shear coefficient whose value depends on several factors like roughness, the topography and the atmosphere stability. It is given starting from the speed measurements in two levels H_1 and H_2 by the following relation:

$$\alpha = \frac{\ln\left(\frac{V_2}{V_1}\right)}{\ln\left(\frac{H_2}{H_1}\right)}$$

(9)

4.2 Results and comments

To identify the parameters of the site u^* , Z_0 and α , we applied the two extrapolation laws to mast 4 on the base of the annual mean speed (Table 8). It is noticed that these coefficients correspond to a rough ground with many hedges. Indeed, the Sidi Daoud site has a complex relief and very influenced by the sea (North and South-West sectors) and by the El Haouaria town (South-East and South-West sectors).

u^* (m/s)	Z_0 (m)	α
0.5701	0.4977	0.2152

Table 8. Extrapolation laws parameters calculated at mast 4.

The two extrapolation laws applied to the mast 4 have made it possible to trace the variation of the annual mean wind speed with height (Fig. 11). We note that the obtained results perfectly conform for all heights superior than 30 m. The passage of level 30 m at 100 m allows a gain on the mean speed of 30% and an energetic gain of 116%.

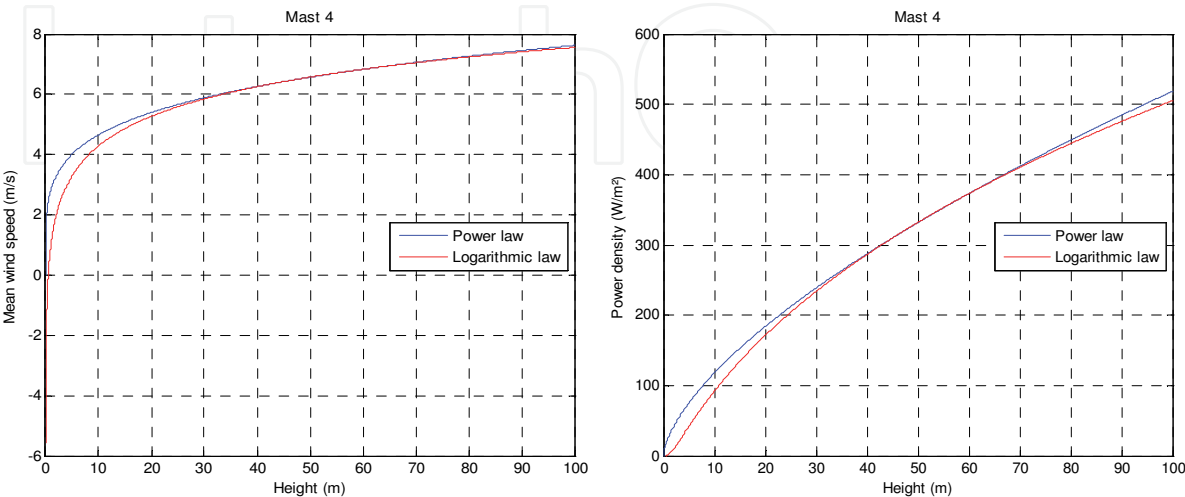


Fig. 11. Vertical profile of the wind speed and the power density.

5. Characterization of installed aerogenerators and evaluation of the energetic efficiencies

5.1 Aerodynamic efficiency of the aerogenerators

In this part, we are interested in the four types of aerogenerators MADE AE-32, AE-46, AE-52 and AE-61 with horizontal axis, installed in the Sidi Daoud wind farm. According to the technical document of the manufacturer, the characteristics of the machines studied are given by Table 9.

Aerogenerators MADE	Regulation type	Generator speed	Nominal power (kW)	Multiplication coefficient	Rotor diameter (m)	Speeds (m/s)		
						Cut in V_d	nominal V_n	Cut out V_c
AE-32	Stall	1 speed	330	44.4	32	4	13	25
AE-46	Stall	2 speeds	660	59.5	46	3	15	"
AE-52	Pitch	variable	800	58.3	52	3	12	"
AE-61	Stall	2 speeds	1320	80.8	61	3	17	"

Table 9. Technical data of the aerogenerators.

Fig. 12. illustrates the variation of the electric power of each machine in function of the wind speed. The machines start from the same speed of 3 m/s (except the AE-32 which begins to 4 m/s) and must stop at 25 m/s. Beyond nominal speed, the power provided by synchronous machine AE-52 remains constant; on the other hand, that provided by asynchronous machines AE-32, AE-46 and AE-61 decreases slightly with the wind speed.

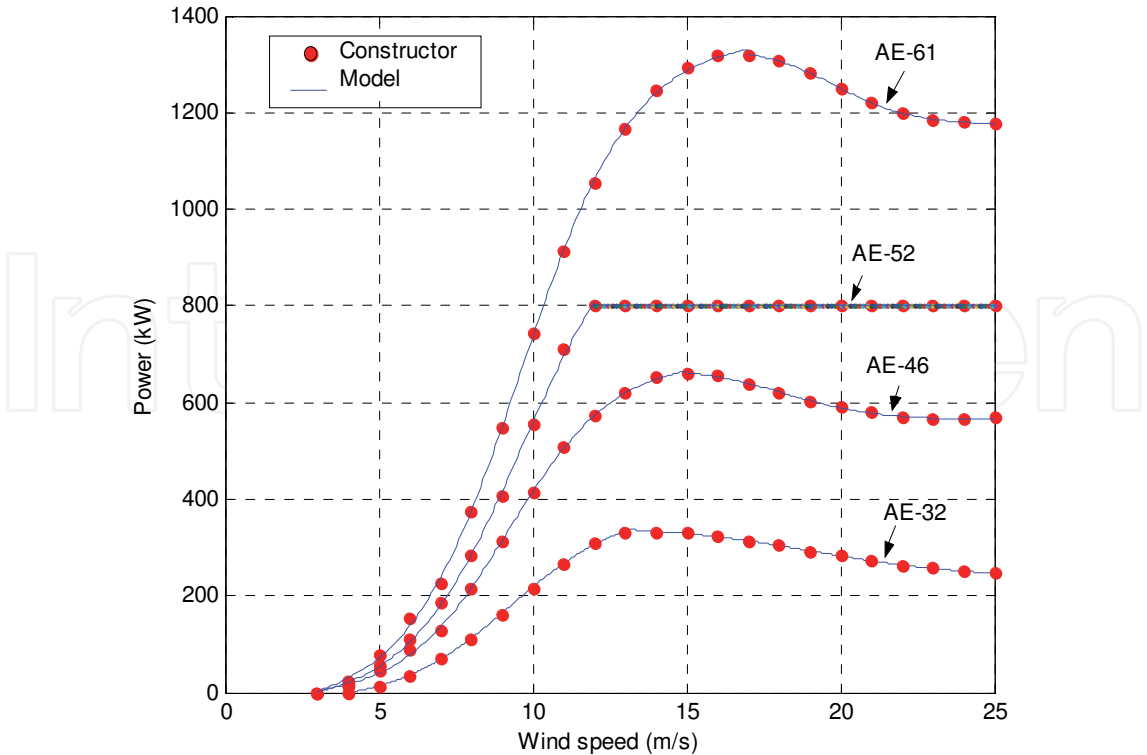


Fig. 12. Power curves of the aerogenerators.

The aerodynamic efficiency of the wind rotor defined by its power coefficient C_p is written:

$$C_p = \frac{P_s(V)}{\frac{1}{2} \cdot \rho \cdot S \cdot V^3 \cdot \mu_m \cdot \mu_g} \tag{10}$$

where μ_m and μ_g respectively represent the gearbox efficiency and the generator efficiency. This dimensionless parameter, which expresses the aerodynamic effectiveness of rotor of the various aerogenerators [20-21], is represented by Fig. 13. For such an aerogenerator, this coefficient is a function the wind speed wind, the chock angle and the rotational speed of rotor. The maximum theoretical value of C_p given by Betz limit is 59.3%. For the four machines, this coefficient reaches its maximum at the optimal wind speed $V_{opt}=9\text{ m/s}$ (Table 11). This maximum varies from 45.51% (AE-61) to 49.07% (AE-32). For low speeds, the curve of the power coefficient progresses quickly towards the optimum operating point. Beyond this point, we observe degradation slower of C_p towards a limiting value of the order 4% which corresponds at the cut out speed of the machine.

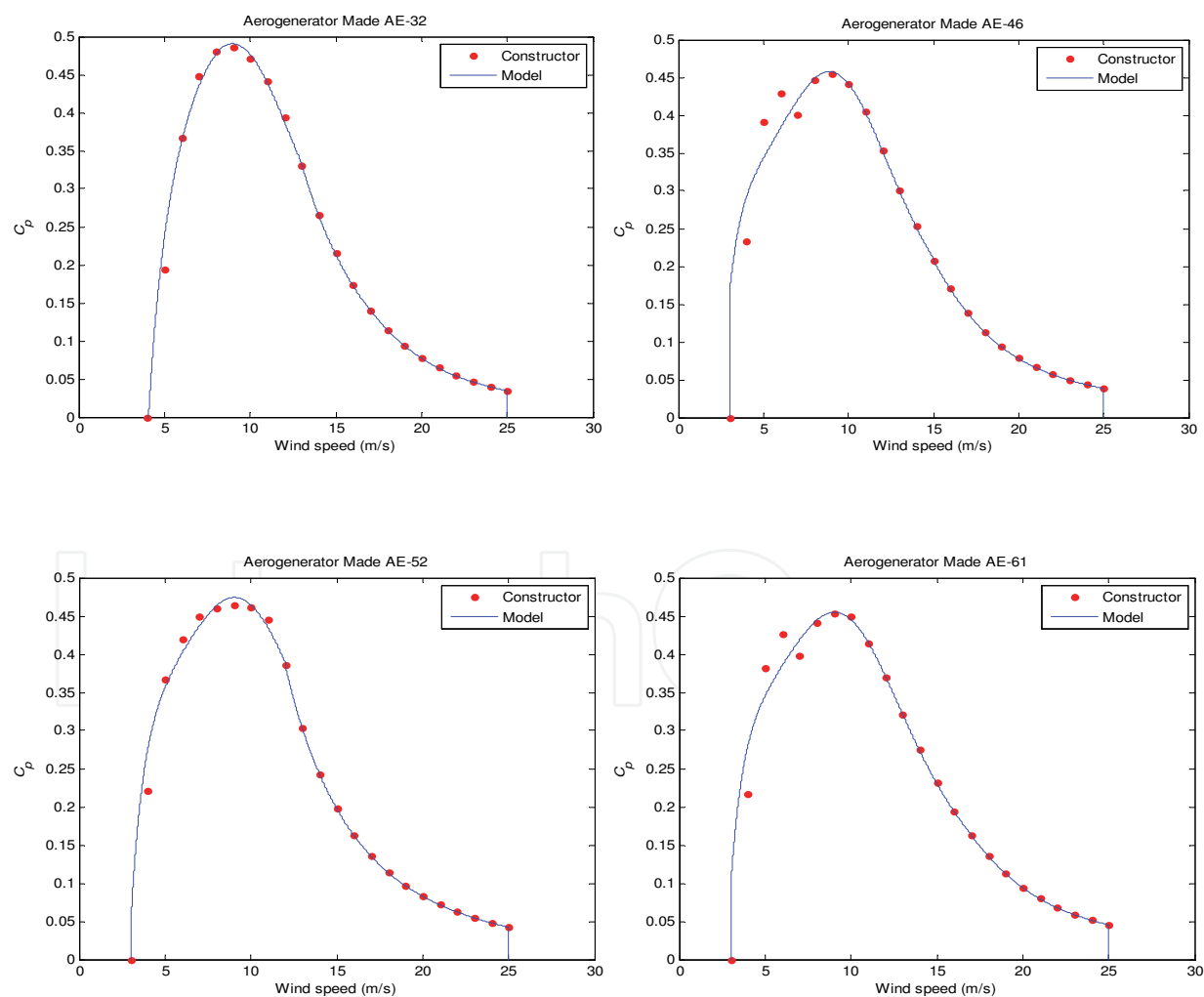


Fig. 13. Curves of aerodynamic efficiency $C_p=f(V)$ of the various aerogenerators.

In addition to the estimate of produced annual energy, it is interesting to know the annual time of the wind turbine production. Fig. 14 illustrates the site frequency-speed histograms and the machines reduced power curve. We observe that during 22 % (respectively 10%, 8% and 9.5%) of the annual time, the wind speed is insufficient to operate the wind turbine AE-32 (respectively AE-46, AE-52 and AE-61) and it blows sufficiently to obtain the full efficiency during 6 % (respectively 2%, 9% and 1.5%) of the annual time. The remaining time of value 72 % (respectively 88%, 83% and 89%), the efficiency varies with the wind speed. Also, we have plotted the power-duration curve of each aerogenerator indicating the time percentage when the wind turbine provides a power higher than a given threshold (Fig. 15). Thus, the machine AE-32 (respectively AE-46, AE-52 and AE-61) will produce its maximum power only for 526 h/year (respectively 175 h/year, 788 h/year and 131 h/year) of the annual time; which accounts for approximately 7.7% (respectively 2.2%, 9.8% and 1.7%) of its operating annual time. We notice that the four aerogenerators most of the time function below their nominal capacities.

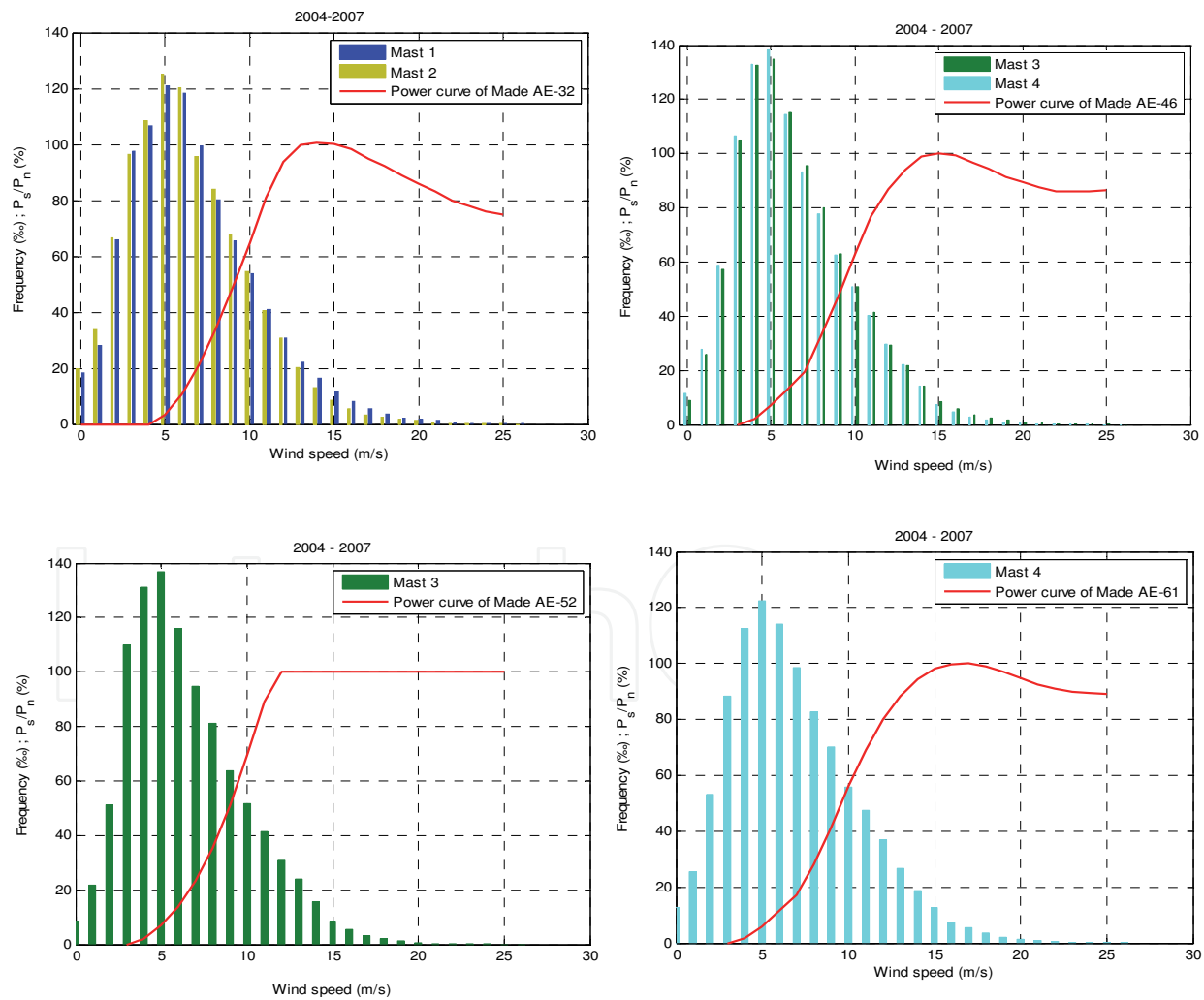


Fig. 14. Annual frequency-speed histograms of the site.

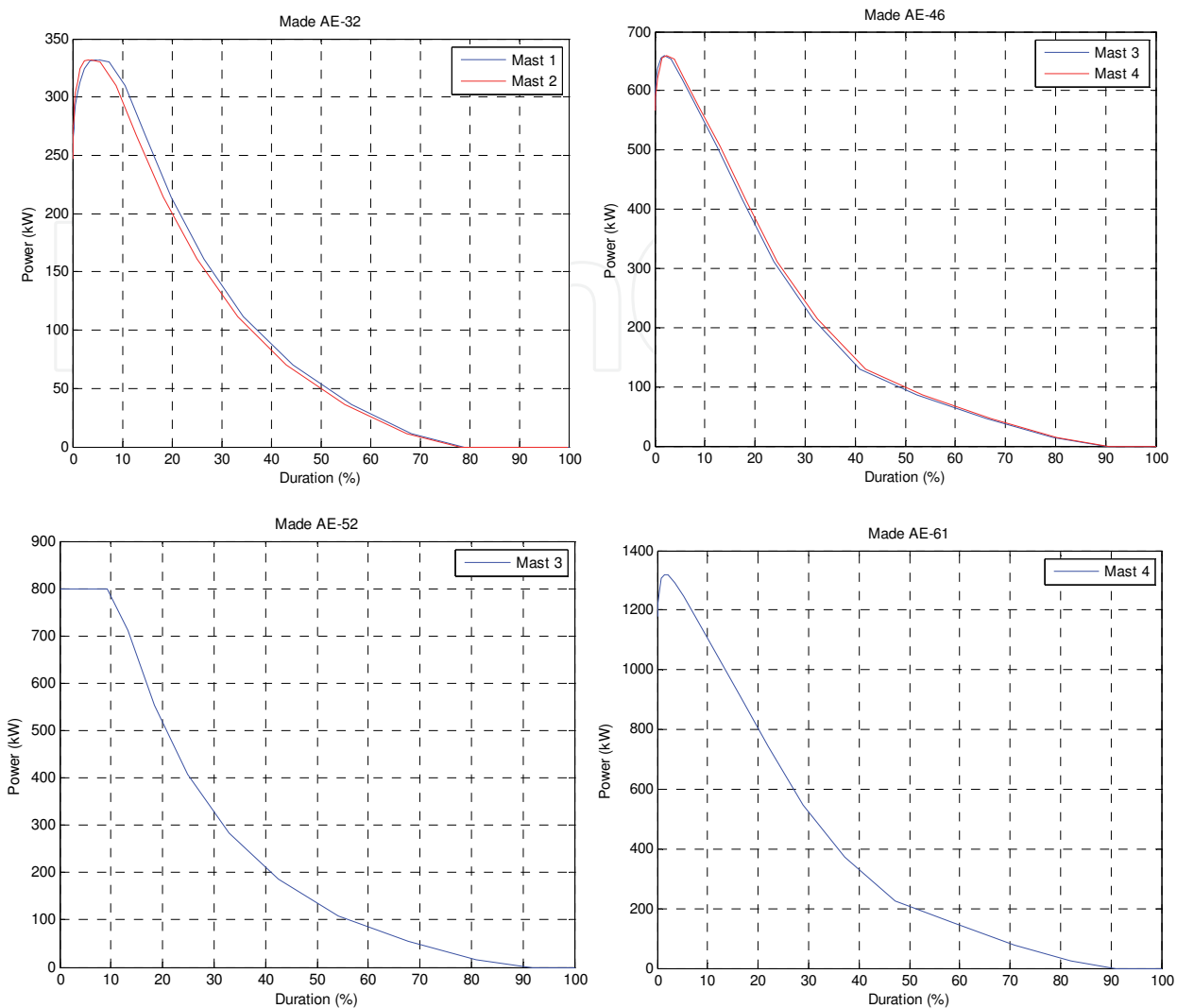


Fig. 15. Annual power–duration curves of the aerogenerators.

5.2 Annual energy produced by the various aerogenerators

The available energy really usable E_u that can be received by the aerogenerator is proportional to the cube of the wind speed and the wind distribution in the site [28-35]. Knowing the wind mode, this usable energy is given by the following expression:

$$E_u = \frac{1}{2} \cdot 8,76 \cdot \rho \cdot S \cdot \left(\sum_{i=d}^n (V_i)^3 f(V_i) + (V_n)^3 \sum_{i=n}^c f(V_i) \right) \tag{11}$$

where $S = \pi R^2$ is the rotor swept surface of radius R .
In the same way, recoverable energy E_r on the aerogenerator outlet (rotor+gearbox+generator) is given by the machine power curve and the wind statistical distribution.

$$E_r = 8,76 \cdot \left(\sum_{i=d}^c f(V_i) P_S(V_i) \right) \tag{12}$$

where $P_s(V_i)$ is the electric power on the aerogenerator outlet.
We notice that the calculation of recoverable energy by the Weibull and Rayleigh analytical methods necessitates of modeling the power curve $P_s(V)$ by an analytical expression. The Boltzman theoretical model allows reproducing this curve correctly. It is written as follows:

$$P_s(V) = \frac{A_1 - A_2}{1 + \exp\left(\frac{(V - V_0)}{\omega}\right)} + A_2$$

(13)

The parameters V_0 , A_1 , A_2 and ω of each aerogenerator are identified by the software "Origin 5.0" and their optimal numerical values are determined by minimizing the quality criterion χ^2 (Table 10).

Aerogenerators	AE-32		AE-46		AE-52		AE-61	
Parameters	$3 \leq V \leq 13$	$13 \leq V \leq 25$	$3 \leq V \leq 15$	$15 \leq V \leq 25$	$3 \leq V \leq 12$	$12 \leq V \leq 25$	$3 \leq V \leq 17$	$17 \leq V \leq 25$
A_1	381.89	241.133	-13.38	672.75	-27.93	$P_s(V) = 800$ kW	-32.405	1334.8
A_2	-22.464	338.249	688.25	563.45	1045.5		1354.9	1175.2
V_0	9.3116	19.4191	9.2317	18.227	9.6543		9.6006	19.86
ω	-1.852	-2.136	1.6999	1.484	1.861		1.8287	1.221

Table 10. Boltzman theoretical model parameters of the power curve of each aerogenerator.

Fig. 16 represents the variation of annual energies (available, usable and recoverable) in function of the wind speed for the various masts and aerogenerators. We see that the maxima of the three energies curves pass approximately by the same wind speed, which shows the good adaptation of the aerogenerators to the Sidi Daoud site.
We notice that the annual wind power produced by each wind turbine represents approximately one-third of the total available energy in the site.

5.3 Energy efficiencies of the aerogenerators

Using the computed energies, the wind turbine mean efficiency relating to the available energy is estimated by the expression [28-35]:

$$\mu_d(V_i) = \frac{E_r(V_i)}{E_d(V_i)} = \frac{P_s(V_i)}{\frac{1}{2} \cdot \rho \cdot S \cdot V_i^3}$$

(14)

The wind turbine mean efficiency relating to usable energy can also be defined by the following expression:

$$\mu_u(V_i) = \frac{E_r(V_i)}{E_u(V_i)} = \begin{cases} \frac{P_s(V_i)}{\frac{1}{2} \cdot \rho \cdot S \cdot (V_i)^3} & \text{pour } V_d \leq V_i \leq V_n \\ \frac{P_s(V_i)}{\frac{1}{2} \cdot \rho \cdot S \cdot (V_n)^3} & \text{pour } V_n \leq V_i \leq V_c \end{cases}$$

(15)

These two ratios of energy represent the product of the mechanical efficiency (gearbox and generator) and the rotor aerodynamic efficiency.

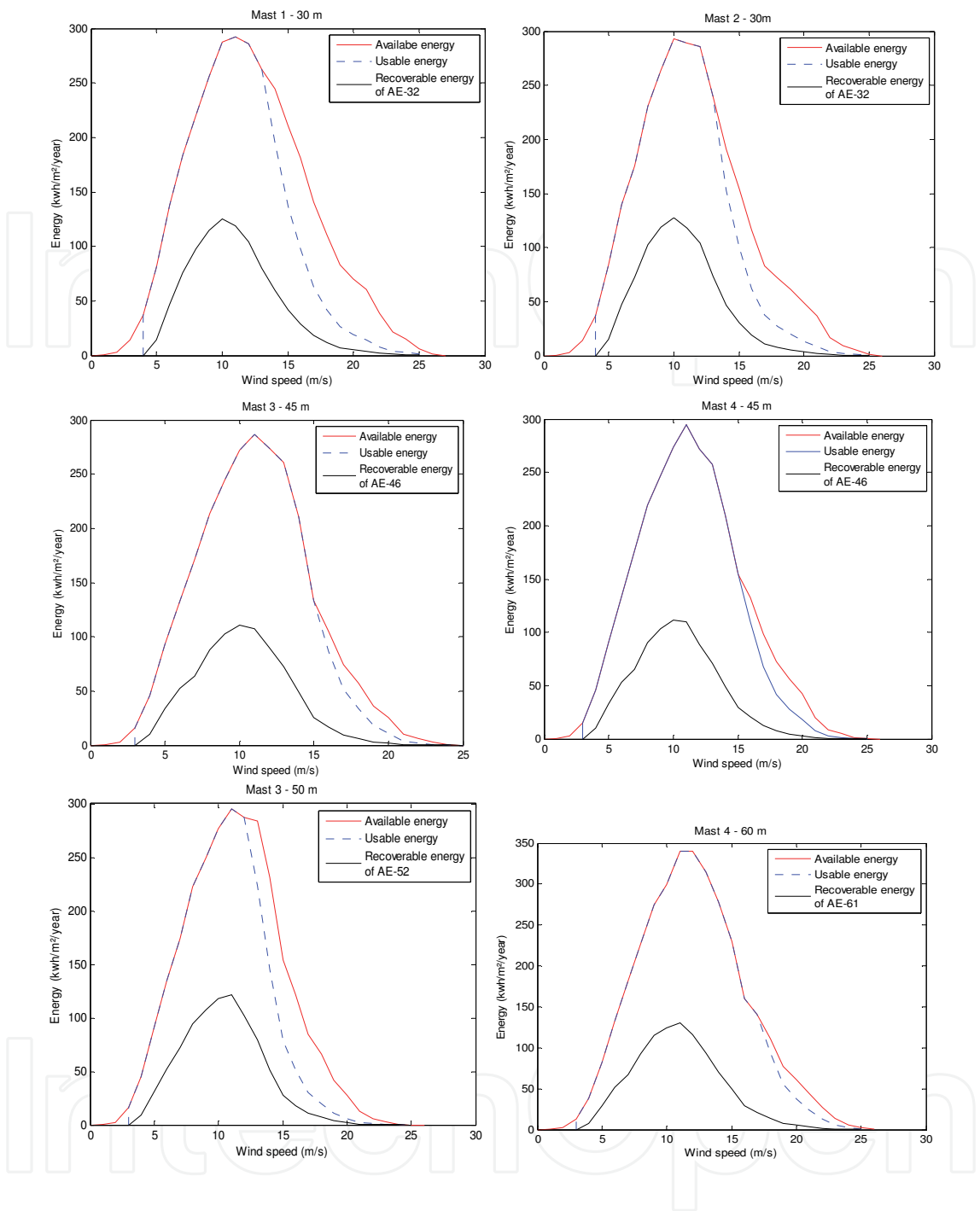


Fig. 16. Energies curves calculated by the meteorological method.

Fig. 17 represents the variation of these mean efficiencies as a function of the classified speed for the various aerogenerators. It is noted that the mean efficiencies pass by the same maximum μ_{max} for a wind speed of approximately 9 m/s. This maximum varies from 41.92 % (AE-61) to 44.8% (AE-32) (Table 11). It is significant to notice that this mean efficiency remains superior to 0.4 in the wind speed zone included between 6.8 m/s and 11.2 m/s for the AE-32, between 7.7 m/s and 10.25 m/s for the AE-46, between 6.5 m/s and 11.25 m/s for the AE-52 and between 7.8 m/s and 10.45 m/s for the AE-61.

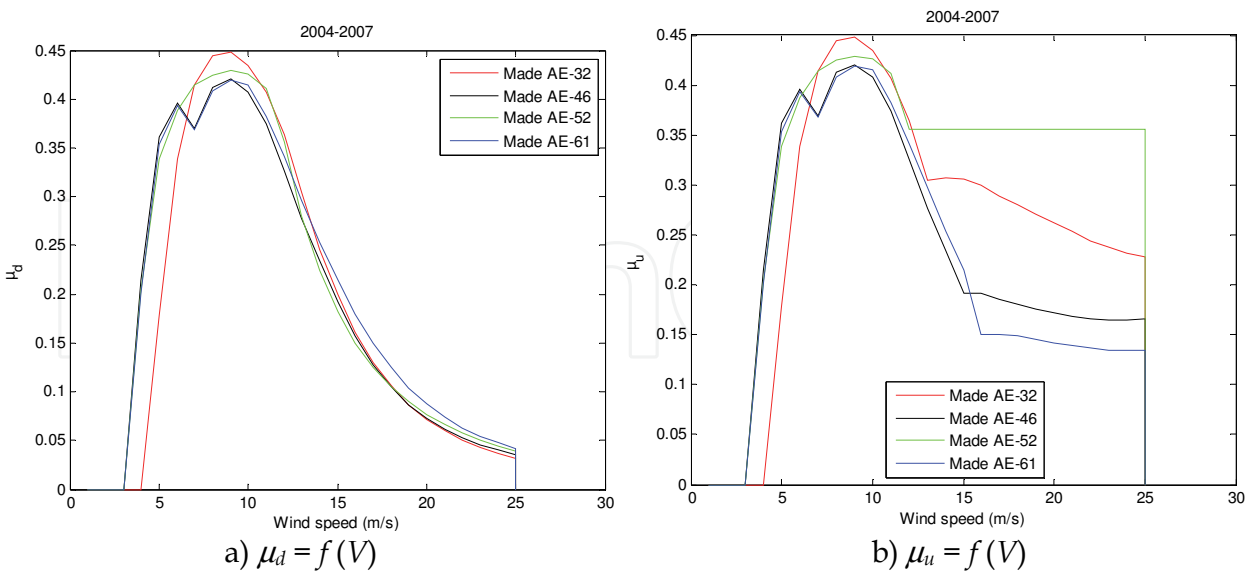


Fig. 17. Mean efficiencies curves of the aerogenerators calculated by the meteorological method.

Aerogenerators	C_{pmax} (%)	μ_{max} (%)	V_{opt} (m/s)
AE-32	49.07	44.83	9
AE-46	45.77	42.05	9
AE-52	47.44	42.92	9
AE-61	45.51	41.92	9

Table 11. Optimum operating point of wind turbines.

In addition, the annual mean efficiency of each wind turbine is defined by:

$$\mu = \frac{E_r}{E_d}$$

(16)

The numerical results obtained by the three methods are comparable and indicate that the annual mean efficiency remains higher than 30% for the various machines (Table 12). Consequently, the energy produced by each machine is important and reaches the 1/3 of the site available energy.

Aerogenerator	AE-32		AE-46		AE-52	AE-61
Mast	1	2	3	4	3	4
Meteorological	29.54	31.74	31.52	30.61	32.18	30.31
Weibull	30.53	32.10	32.45	31.73	34.63	31.09
Rayleigh	32.96	33.75	32.75	32.32	34.53	31.64

Table 12. Annual mean efficiency μ (in %) of each aerogenerator.

In practice, a maximum energy efficiency of wind turbine is ensured by an optimal aerodynamic efficiency of rotor. To optimize this efficiency, the control of the aerogenerator must be made so that the rotational rotor speed adapts to the site wind speed.

5.4 Use factor and availability rate

However, the wind turbine cannot function with full power all the time (maintenance, breakdowns, wind availability, etc.). To quantify the recovered power by each aerogenerator, it is interesting to calculate its annual use factor *UF* which is defined by the ratio of the produced electric power on the installed power [28-35]:

$$UF(\%) = 100 \cdot \frac{\sum_{i=d}^c f(V_i)P_S(V_i)}{P_n}$$

(17)

According to the relation (16), we note that this factor *UF* depends only on the wind frequency (at the nacelle height) for such an aerogenerator. Table 13 shows that the machine AE-52, which has the lowest nominal speed (*V_n*=12m/s), presents the best use factor.

Aerogenerator	AE-32		AE-46		AE-52	AE-61
Mast	1	2	3	4	3	4
Meteorological	26.65	25.18	24.23	24.90	27.58	26.04
Weibull	28.00	25.92	25.01	26.22	30.08	26.79
Rayleigh	26.90	24.99	23.70	25.19	29.04	26.11

Table 13. Annual use factor *UF* (in %) of each aerogenerator.

Based on the results of the annual energy recovered by each machine, we note that the use factor of the whole wind farm (70 aerogenerators of an installed power generation capacity of 53.6 MW) is about 25.87%; what shows that the maximum annual energy production of the wind power station is approximately 121.5 GWh/an.

To estimate the operation duration of an aerogenerator, we define the availability rate *AF* which depends on the machine characteristics and the wind potential in the site. For such a wind turbine having a cut in speed *V_d* and a cut out speed *V_c*, the availability rate *AF* is the probability *P* calculated by the following equation [28-35]:

$$AF(\%) = 100 \cdot P(V_d \leq V \leq V_c) = 100 \cdot [F(V_d) - F(V_c)]$$

(18)

In general, this factor rises when the difference (*V_c*-*V_d*) and the mean wind speed increase. The obtained values for the various aerogenerators are excellent (Table 14) and show that the production time exceeds 90% of annual time for machines AE-46, AE-52 and AE-61 and about 80% for the AE-32.

Aerogenerator	AE-32		AE-46		AE-52	AE-61
Mast	1	2	3	4	3	4
Meteorological	79.01	78.24	90.18	90.76	91.86	90.86
Weibull	73.41	82.94	92.66	92.81	93.44	93.47
Rayleigh	74.87	84.06	92.42	92.66	92.77	93.48

Table 14. Annual availability rate *AF* (in %) of each aerogenerator.

Consequently, to completely describe the energetic profitability of an aerogenerator, it is necessary to take account simultaneously of these four factors: the aerodynamic efficiency, the mean efficiency, the use factor and the availability rate.

6. Conclusion

This study has presented the development of the wind power use in Tunisia for the electricity production. The main contribution of this chapter is the energy performance evaluation of the first wind farm installed in Sidi Daoud - Tunisia, particularly the effectiveness of various aerogenerators (MADE AE-32, AE-45, AE-52 and AE-61) implanted on the site, by the meteorological experimental method and the Weibull and Rayleigh analytical methods.

The data treated in this study are the measurements recorded in four places (masts 1, 2, 3 and 4) of the site at altitudes which correspond to the heights of the aerogenerators hubs (30, 45, 50 and 60 m above ground level) (Tab. 2). These measurements are spread out over a four-year period (2004-2007).

The principal results of this study are:

Concerning the wind resource of the site,

- The Sidi Daoud site has an important and stable wind potential. Indeed, the power density calculated at the various heights (30, 45, 50 and 60 m) varies from 180 to 230 W/m² according to the measurement mast place. The mean speed also varies from 6.3 to 6.8 m/s. The dominant directions of the wind are the west and south-east sectors.
- The identified parameters of the two distribution functions (*A*, *k* and *V_m*) show that the two models are quasi-equivalent. Indeed, the values of the statistical analysis parameters (*R*², *RMSE* and χ^2) indicate a better adjustment of the meteorological data by the two models.
- The modeling of the wind vertical profile by the logarithmic and power laws is applied to the mast 4 place. The extrapolation of the height 30 to 100 m enables us to obtain a gain on the mean speed of 30% and a gain on the power density of 116%.

Concerning the aerogenerators performance,

- The maximum power coefficient *C_{pmax}* varies from 45.51% (AE-61) to 49.07% (AE-32) for the same optimal wind speed *V_{opt}* = 9 m/s.
- The annual mean efficiency remains superior to 30% for the various machines. Indeed, recoverable energy is important and it is about the 1/3 of the available energy in the site.
- The use factor *UF* varies from 23 to 28% according to the type and place of the aerogenerator. It is about 25.87% on average for the whole wind farm.
- The availability rate *AF* is excellent and exceeds 90% of annual time for aerogenerators AE-46, AE-52 and AE-61 and about 80% for the AE-32.
- The aerogenerator AE-52 presents the energetic performances higher than those of the other machines.

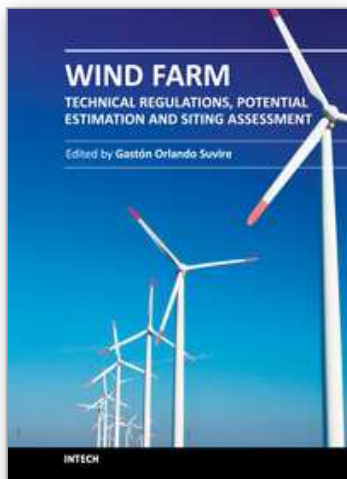
7. Nomenclature

V	Wind speed (m/s)
$F(V)$	Cumulated frequency
$f(V)$	Occurrence frequency
n	Number of wind-speed classes
V_m	Mean speed (m/s)
V_f	Most frequent speed (m/s)
V_e	Most energetic speed (m/s)
P_d	Power density at Betz limit (W/m ²)
E_d	Available energy at Betz limit (kWh/m ² /year)
E_u	Usable energy (kWh/m ² /year)
E_r	Recoverable energy (kWh/m ² /year)
P_s	Electric power on the aerogenerator outlet (W)
P_n	Nominal power of the aerogenerator (W)
$P_{d(M)}$	Mean power density calculated from the meteorological method (W/m ²)
$P_{d(W,R)}$	Mean power density calculated from the Weibull and Rayleigh functions (W/m ²)
μ_d	Mean efficiency relating to the available energy
μ_u	Mean efficiency relating to the usable energy
μ	Mean efficiency
μ_m	Gearbox efficiency (96%)
μ_g	Generator efficiency (96.2%)
u^*	Friction speed (m/s)
Z_0	Ground roughness (m)
a	Shear coefficient
H	Measurement height (m)
C_p	Power coefficient
UF	Use factor
AF	Availability rate
A	Paramètre d'échelle de Weibull (m/s)
k	Weibull scale factor
K	Von-Karman constant ($K=0.4$)
S	Rotor area (m ²)
ρ	Air density (1.225 kg/m ³)
$\sigma_{(M,W,R)}$	Standard deviation calculated from the meteorological, Weibull and Rayleigh methods (m/s)
R^2	Determination coefficient
χ^2	Chi-square coefficient
$RMSE$	Root mean square error
y_i	ith measured value
y_{ic}	ith calculated value
y_m	Mean value
Γ	Gamma function
M	Meteorological method
W	Weibull method
R	Rayleigh method

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Wind Farm - Technical Regulations, Potential Estimation and Siting Assessment

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The evolution of wind power generation is being produced with a very high growth rate at world level (around 30%). This growth, together with the foreseeable installation of many wind farms in a near future, forces the utilities to evaluate diverse aspects of the integration of wind power generation in the power systems. This book addresses a wide variety of issues regarding the integration of wind farms in power systems. It contains 10 chapters divided into three parts. The first part outlines aspects related to technical regulations and costs of wind farms. In the second part, the potential estimation and the impact on the environment of wind energy project are presented. Finally, the third part covers issues of the siting assessment of wind farms.

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