

WIND ENERGY RESOURCE ASSESSMENT FOR ALGERIA

R. Maouedj^{a,*}, S. Bousalem^b, Y. Hadji^a & B. Benyoucef^b
^a Unity of Research in Renewable Energies in Saharan Medium.
B.P 478, Road of Reggane - Adrar. Algeria.
E-mail address: ra_maouedj@yahoo.fr
University of Tlemcen, Algeria

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Abstract

The paper presents a study of the wind layer in six Algerian sites (Algiers, Oran, Tlemcen, Djelfa, Adrar and Ghardaia). It is based on the atlas of the wind of Algeria established by the National office of the Meteorology runs 37 stations of measures. The wind speed extrapolated to the standard height 10m for 30m and 50m using vertical extrapolation laws.

The annual average wind speed for the considered sites ranges from 3,63 m/s to 6,38 m/s and mean wind power from 79,78 W/m² to 283,12 W/m² at standard height of 10 m. The wind speed characteristics and wind power potential of each station is determined using Rayleigh distribution.

Keywords: wind conversion system, wind speed, wind energy, Rayleigh distribution.

Résumé

Ce travail présente une étude du gisement éolien dans six sites Algériens (Alger, Oran, Tlemcen, Djelfa, Adrar et Ghardaïa). Cette étude est basée sur l'atlas du vent de l'Algérie établi par l'Office National de la Météorologie qui dispose de 37 stations de mesures. La vitesse du vent a été extrapolée de la hauteur standard 10m à 30m et 50m en utilisant les lois d'extrapolation verticale.

La vitesse moyenne annuelle du vent pour les sites considérés s'étend de 3,63 m/s à 6,38 m/s et le potentiel moyen de vent varie entre 79,78 W/m² et 283,12 W/m² à la hauteur standard de 10 m. Les caractéristiques de la vitesse du vent et le potentiel éolien pour chaque station ont été déterminées en appliquant la distribution de Rayleigh.

Mots clés : système de conversion éolienne, vitesse du vent, distribution de Rayleigh.

1. Introduction

The wind energy knew a very important growth during the last decade thanks to the advantages that it has for the environment, with the related technological breakthroughs and with the governmental programmes of encouragement in the world.

The estimate of the wind power resources presents a major difficulty. Unlike fossil fuel reserves, the quantity of energy available varies with the season and the hour of the day. Contrary of the solar energy, the wind power is influenced by topography. Moreover, the total quantity of convertible wind power on the territory of a nation depends to a significant degree on the characteristics, the hoped output, the dimensioning and the horizontal distribution of the wind generators.

2. Geographical situation of Algeria

Algeria is located in North Africa bordered north by the Mediterranean Sea (1200 km), east by Tunisia (965 km) and Libya (982 km), south-east by Niger (956 km), south-west by Mali (1,376 km) and Mauritania (463 km), west by Morocco (1,559 km) and the Western Sahara (42 km). Its geographical coordinates are represented by a latitude of 28°00' North of the equator and longitude of 3°00' East of Greenwich. On the African continent, Algeria is after Sudan, the second-largest country with an area of 2 381 740 km², whose four fifths are occupied by the Sahara desert.

3. Wind data

The geographical locations (latitude, longitude and altitude) for the sites considered in this study are presented in Table 1 and figure 1. Wind data for 20

meteorological stations were obtained from the Algerian Meteorological National Office. The data were collected over a period spanned between 1976 and 1988 [2, 3].

At all stations the measurements are obtained at a height of 10 m above sea level.

Therefore, the wind parameters are extrapolated from the standard height 10m to 30m and 50m using the power law expression. The Weibull parameters k and c are determined and used to estimate the annual mean wind speed and the wind power density for each site.

Table 1

Geographical locations for the different sites [4]

Sites	Longitude (°)	Latitude (°)	Altitude (m)
Algiers	03° 15' E	36° 43' N	25
Oran	00° 37' W	35° 38' N	99
Tlemcen	01° 19' W	34° 56' N	810
Djelfa	03° 15' E	34° 41' N	1144
Adrar	00° 17' W	27° 53' N	264
Ghardaia	03° 49' E	32° 23' N	450

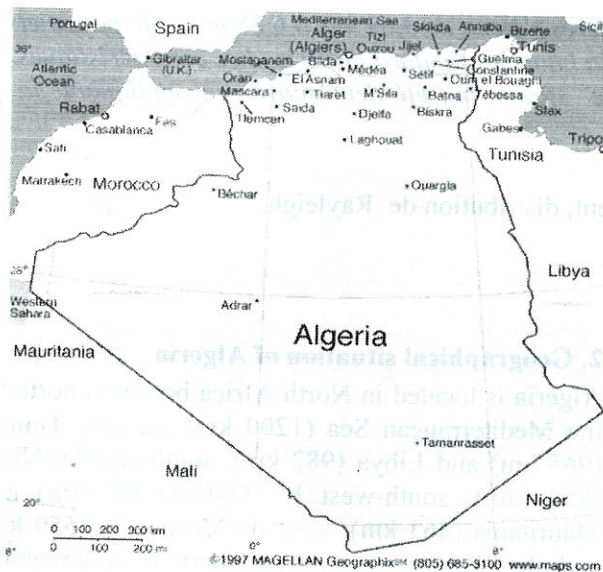


Figure 1. Map of Algeria [5, 6].

4. Mathematical formulation

4.1. Rayleigh distribution

Rayleigh distribution is a simplified case of the Weibull distribution which is derived by assuming the shape factor as equal to 2. Owing to its simplicity, this distribution is widely used for wind

energy modelling. Under the Rayleigh based approach, the cumulative distribution function and the probability density function of wind velocity are given by [7-9]:

$$f_R(V) = \frac{2}{c^2} V e^{-\left[\left(\frac{V}{c}\right)^2\right]} \quad (1)$$

Where v is the wind speed and C Weibull scale parameter in the unit of wind speed (m/s).

Similarly, the cumulative distribution is given by:

$$F_R(V) = 1 - e^{-\left[\left(\frac{V}{c}\right)^2\right]} \quad (2)$$

The average wind velocity is given by the distribution of Rayleigh:

$$\bar{V} = 0,8862c \quad (3)$$

The average cubic speed of the wind is given by the following relation:

$$\langle V^3 \rangle = 1,3293c^3 \quad (4)$$

The variance may expressed as:

$$\sigma^2 = 0,2146c^2 \quad (5)$$

The standard deviation of the wind velocity following the Rayleigh distribution is:

$$\sigma = 0,4632c \quad (6)$$

4.2. Vertical extrapolation of wind speed

The wind data measurements used in this study are used from stations set at a standard height of 10 m. The vertical extrapolation of wind speed is based on the Power law [14, 15]:

$$v(z) = v(z_{ref}) \left(\frac{z}{z_{ref}} \right)^\alpha \quad (7)$$

Where $v(z_{ref})$ is the actual wind speed recorded at height z_{ref} , $v(z)$ is the wind speed at the required or extrapolated height z and α is the surface roughness exponent and is a terrain-dependent parameter.

4.3. Vertical extrapolation of Weibull parameters



The Weibull parameters are also function of height [16, 17],

$$c(z) = c(z_{ref}) \left(\frac{z}{z_{ref}} \right)^n \quad (8)$$

$$k(z) = k(z_{ref}) \frac{1 - 0.088 \ln \left(\frac{z_{ref}}{10} \right)}{1 - 0.088 \ln \left(\frac{z}{10} \right)} \quad (9)$$

n is a scalar obtained using the relation

$$n = \frac{0.37 - 0.088 \ln (c(z_{ref}))}{1 - 0.088 \ln \left(\frac{z_{ref}}{10} \right)} \quad (10)$$

4.4. Estimating wind power

The kinetic energy of air stream with mass (m) and moving with a velocity (v) is given by [18]

$$E = \frac{1}{2} m v^2 \quad [\text{J}] \quad (11)$$

The power in moving air is the flow rate of kinetic energy per second. Therefore [18]:

$$P = \frac{E}{t} = \frac{1/2 m v^2}{t} \quad [\text{W}] \quad (12)$$

The wind power density (P_d) representing the power per unit area can be written [19]:

$$P_d = \frac{P}{A} = \frac{1}{2} \rho_0 v^3 \quad [\text{W}/\text{m}^2] \quad (13)$$

ρ_0 is the standard air density (1.225 kg/m³),

A is the area swept by the rotor blades ($A = \pi R^2$) [m²],

The theoretical maximum power that can be extracted from a wind turbine is limited by Betz's law [20, 21]:

$$P_{ext} = \frac{1}{2} C_p(\lambda, \beta) \rho_0 A V^3 \quad (14)$$

$C_p(\lambda, \beta)$ the power coefficient represents the wind turbine aerodynamic efficiency. It depends on the tip speed ratio (λ) and the blade pitch angle (β). The theoretical maximum value for the power coefficient $C_{p \max}$ is 0.59 (the Betz limit).

The air density ρ_0 varies with temperature and elevation. The monthly mean air density (kg/m³) is calculated using the equation [22]:

$$\rho(T, Z) = \frac{353.049}{T} \exp \left(-0.034 \frac{Z}{T} \right) \quad (15)$$

Finally, the corrected wind power density (KWh/m²) can be computed using:

$$E_{wdp} = 2.586 \rho v^3 \quad (16)$$

According to [23-27], the wind turbine power curve can be well approximated with the parabolic law:

$$P(v) = \begin{cases} 0 & \text{if } v < v_c \\ P_R \left(\frac{v^k - v_c^k}{v_R^k - v_c^k} \right) & \text{if } v_c \leq v \leq v_R \\ P_R & \text{if } v_R \leq v \leq v_F \\ 0 & \text{if } v > v_F \end{cases} \quad (17)$$

In integrating equation (17):

$$P_{avg} = \int_{v_c}^{\infty} P(v) f(v) dv = \int_{v_c}^{v_R} P(v) f(v) dv \quad (18)$$

Substituting Equation 17 into Equation 13 yields:

$$P_{avg} = \int_{v_c}^{v_R} P_R \left(\frac{v^k - v_c^k}{v_R^k - v_c^k} \right) f(v) dv + \int_{v_R}^{v_F} P_R f(v) dv \quad (19)$$

P_{avg} can finally be expressed as [28-30]:

$$P_{avg} = P_R C_F \quad (20)$$



5. Results and discussion

Table 2

Rayleigh distribution parameter and characteristics speeds for different sites at 10m height

Sites	c (m/s)	V _m (m/s)	$\langle V^3 \rangle$ (m/s) ³	σ^2 (-)	σ (-)
Algiers	5.00	4.43	166.17	13.60	3.69
Oran	4.10	3.63	91.62	9.14	3.02
Tlemcen	4.70	4.17	138.02	12.02	3.47
Djelfa	4.40	3.90	113.24	10.53	3.24
Adrar	7.20	6.38	496.17	28.20	5.31
Ghardaia	5.60	4.96	233.45	17.06	4.13

Table 3

Rayleigh distribution parameter and characteristics speeds for different sites at 50m height.

Sites	c (m/s)	V _m (m/s)	$\langle V^3 \rangle$ (m/s) ³	σ^2 (-)	σ (-)
Algiers	7.21	6.39	0498.24	28.28	5.32
Oran	6.08	5.39	0298.78	20.11	4.48
Tlemcen	6.83	6.05	0423.54	25.37	5.04
Djelfa	6.46	5.73	0358.37	22.70	4.76
Adrar	9.86	8.74	1274.29	52.88	7.27
Ghardaia	7.94	7.04	0665.42	34.29	5.86

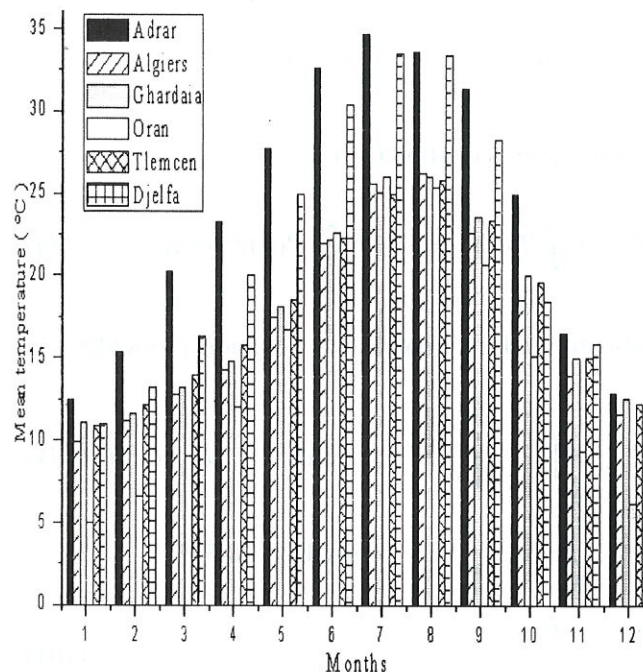


Figure 2. Mean monthly temperatures for the selected sites.

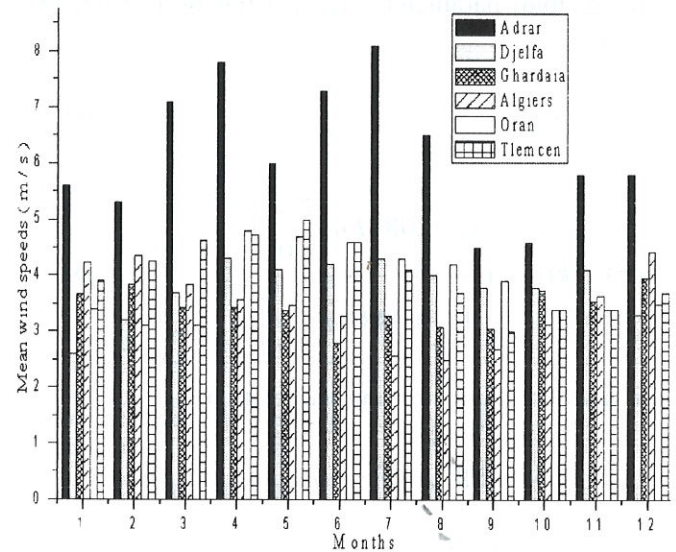


Figure 3. Mean monthly wind speeds for selected sites

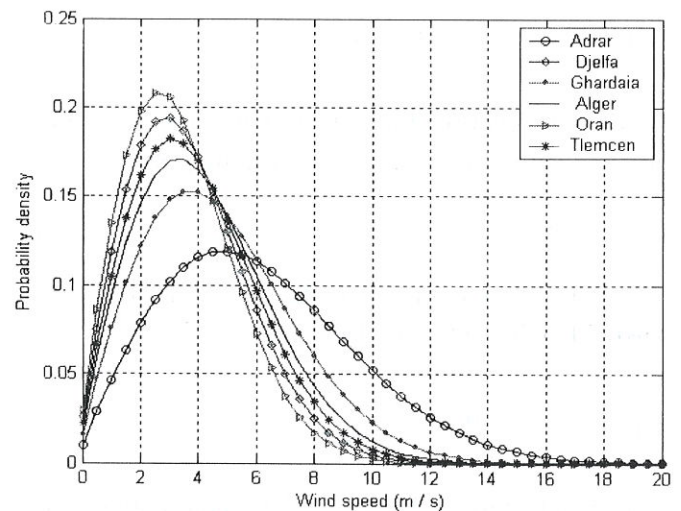


Figure 4. Rayleigh probability density function at 10m height

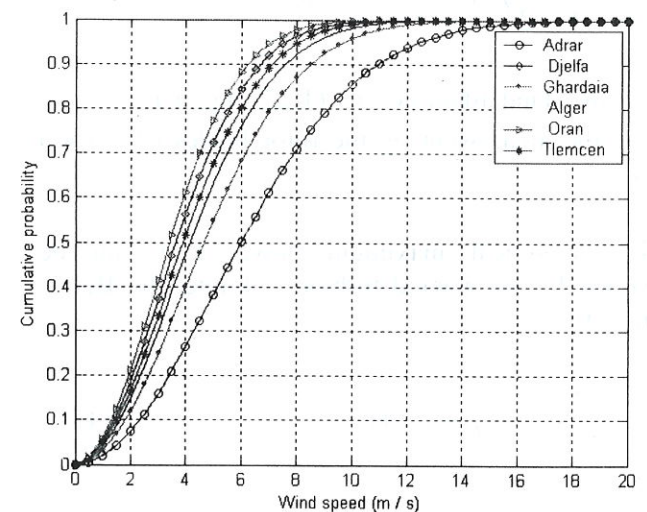


Figure 5. Rayleigh cumulative distribution function at 10 m height.

- It is noticed that the great decreases of the air density is recorded in the sites of Djelfa and Tlemcen. these sites are respectively characterized by the very elevated heights above sea level (1144m and 810m), while the weak variation is noticed in the very low heights sites, Algiers (25m) and Oran sites (99m).
- Annual values of corrected wind power are smallest that the uncorrected wind power (see Figure 6 and 7).
- The density of air decreases with the increase in site elevation and temperature as illustrated.
- The highest decreases of the air density are found during the summer season in all stations and the lowest values are found during the winter season.

Table 4

Annual mean wind power for different stations at height of 10 m calculated by the Rayleigh distribution ($k = 2$)

Sites	ρ_{10} kg/m ³	P^{10} w/m ²	Pc^{10} w/m ²	P^{10}_{ext} w/m ²	Pc^{10}_{ext} w/m ²	$\rho_0 - \rho_{10}$ kg/m ³
Algiers	1,19	101,78	098,78	060,05	058,28	- 0.04
Oran	1,18	056,12	053,98	033,11	031,85	- 0.05
Tlemcen	1,09	084,56	075,10	049,88	044,31	- 0.14
Djelfa	1,06	069,36	059,75	040,92	035,25	- 0.17
Adrar	1,17	303,91	290,01	179,30	171,10	- 0.06
Ghardaia	1,12	142,99	130,62	084,36	077,07	- 0.11

Table 5

Annual mean wind power for different stations at height of 50m calculated by the Rayleigh distribution ($k = 2$).

Sites	ρ_{50} kg/m ³	P^{50} w/m ²	Pc^{50} w/m ²	P^{50}_{ext} w/m ²	Pc^{50}_{ext} w/m ²	$\rho_0 - \rho_{50}$ kg/m ³
Algiers	1,18	305,17	294,81	180,05	173,94	- 0.04
Oran	1,17	183,00	175,23	107,97	103,39	- 0.05
Tlemcen	1,08	259,42	229,42	153,06	135,36	- 0.14
Djelfa	1,05	219,50	188,22	129,51	111,05	- 0.18
Adrar	1,16	780,50	741,35	460,50	437,40	- 0.06
Ghardaia	1,11	407,57	370,64	240,47	218,68	- 0.11

The wind speed, power and energy are evaluated, respectively by Rayleigh method. The numerical results for six Algerians sites are presented in Tables 2 to 5.

The extrapolation of wind speed form 10m to 30m and 50m heights is used to calculate the monthly wind power density at all stations.

Analysis of the results continued in these table leads to the classification of these sites in three groups:

- Group A**, that includes Adrar and Ghardaia, This group is ideal (excellent for production of electricity and wind farms setting up).
- Group B**, that includes Oran and Algiers. This group has a good wind potential.
- Group C**, that includes, Tlemcen and Djelfa (favourable for applications of low power, as water pumping systems)

It is noticed that the shape and scale parameters increase with height. At 10m height, the shape parameter k varies between 1,26 (Oran) and 2,15 (Adrar) while the scale parameter c varies between 4,10 m/s (Algiers) and 7,20 m/s (Adrar).

For 50m height, the shape parameter varies between 1,47 (Oran) and 2,50 (Adrar) while the scale parameter c varies between 6,08 m/s (Algiers) and 9,86 m/s (Adrar).

The highest values of the annual mean wind power density are found in Adrar ($P_{10} = 283,12 \text{ W/m}^2$). While the lowest values of annual mean wind power density are found in Tlemcen ($P_{10} = 79,78 \text{ W/m}^2$).

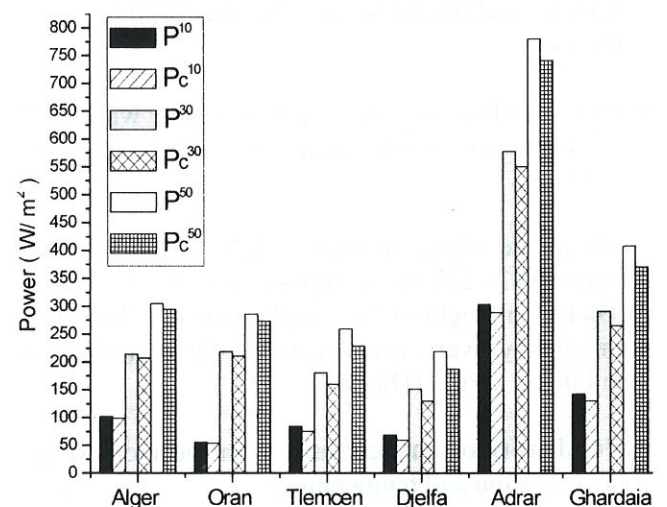


Figure 6. Computations of the annual corrected and uncorrected wind power using the Rayleigh distribution for different heights.

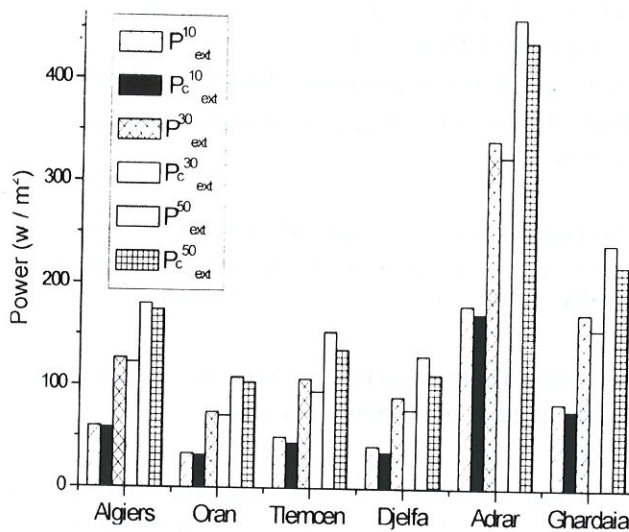


Figure 7. Calculated of the annual corrected and uncorrected recoverable wind power by the Rayleigh distribution for different heights.

6. Conclusions

From this study, the following conclusion may be drawn:

- The annual average wind speed for the considered sites ranks from 3,81 m/s to 6,38 m/s and the mean wind power density vary between 70,88 w/m² and 283,12 w/m² at standard height of 10m.
- The variation of the value of the annual average temperature has an important influence on the air density and therefore on the recoverable wind power.
- The wind power densities increase with hub height as the wind speed and scale parameter increase.
- The air density correction widely varies, ranging from 0,036 kg/m³ (Algiers) to 0,170 kg/m³ (Djelfa) at height of 10m, and at a height 50m the air density vary between 0,041 kg/m³ (Algiers) and 0,175 kg/m³ (Djelfa).
- The density of air decreases with the increase in site elevation and temperature.
- Annual values of corrected wind power are smaller that the uncorrected wind power.

Nomenclature

$f_R(V)$	Probability density function of wind speed
v	Mean wind speed [m/s]
C	Weibull scale parameter [m/s]
K	Weibull shape parameter.
$F_R(V)$	Cumulative density function of wind speed
$\bar{V}$	Average wind velocity [m/s]
σ	Standard deviation of the wind velocity [m/s]
E	Kinetic energy [J]
P_d	Wind power density [w/ m ²]
ρ_0	Standard air density [kg/m ³]
A	area swept by the rotor blades [m ²]
$C_p(\lambda, \beta)$	Power coefficient
λ	Tip speed ratio
β	Blade pitch angle [°]
$C_{p_{max}}$	Theoretical maximum value for the power coefficient
Z	Elevation of the site [m]
T	Monthly average air temperature [K]
P_R	Rated power output of wind speed
V_C	Cut-in speed of wind generator [m/s]
V_R	Rated speed of wind generator [m/s]
V_F	Furling wind speed [m/s]
C_F	Capacity factor



References

- [1] B. MULTON, « L'énergie électrique : analyse des ressources et de la production », Journées électrotech. du club EEA, 28-29 janvier 1999, Paris, 8 p.
- [2] Hammouche R. Atlas du vent de l'Algérie/ONM. Alger: *Office des publications Universitaires (OPU)*, 1990.
- [3] Kasbadji Merzouk N. Wind energy potential of Algeria. *Renewable energy* **21**. 2000. 553-562.
- [4] Capderou M, Atlas solaire de l'Algérie, **Tome 2**, *Aspect énergétique*. 1987.
- [5] MAGELLAN Geographis SM 1997. (805) 685-3100. www.maps.com.
- [6] www.infoplease.com/atlas/africa.html
- [7] Darwish ASK, Sayigh AAM. Wind energy potential in Iraq. *Solar and Wind Technology* **1988**; **5** (3):215-22.
- [8] Chang TJ, Wu YT, Hsu HY, Chu CR, Liao CM. Assessment of wind characteristics and wind turbine characteristics in Taiwan. *Renew energy* **2003**; **28**:851-71.
- [9] Justis C.G. / Traduit et adapté par J. L. Plazy, "Vent et performances des éoliennes", édition S.C.M, Paris.1982.
- [10] Jamil M, Parsa S, Majidi M. Wind power statistics and evaluation of wind energy density. *Renew Energy* **1995**; **6**: 623-8.
- [11] Elamouri M. and Ben Amar F. Wind energy potential in Tunisia. *Renewable energy* **33**. 2008. 758-768.
- [12] Gary L. Johnson .Wind Energy Systems, October 10, 2006
- [13] Keoppl GW. Putnam's power from the wind. New York: Van Nostrand Reinhold; 1982.
- [14] Troen I, Lundtang E. European wind atlas. Roskilde, Denmark: Riso National Laboratory; 1988.
- [15] Amr M, Petersen H, Habali SM. Assessment of wind farm economics in relation to site wind resources applied to sites in Jordan. *Solar Energy* **1990**; **45**: 167-75.
- [16] De Moor G. Les théories de la turbulence dans la couche-limite atmosphérique. Ministère des transports. Direction de la meteorology, 1983.
- [17] Hladik J. Energétique éolienne. Chauffage éolien. Production d'électricité. Pompage, Masson, 1984.
- [18] www.state.mn.us/mn/externalDocs/Commerce/WRAP_Report_110702040352_WRAP2002.pdf.
- [19] H. S. Bagiorgas, M. N. Assimakopoulos, D. Theoharopoulos, D. Matthopoulos and G. K. Mihalakakou. Electricity generation using wind energy conversion system in the area of Western Greece. *Energy conversion and management* **48**. 2007. 1640-1655.
- [20] Petru T, Thiringer T. Modelling of wind turbines for power system studies. *IEEE Trans. Energy Convers.* **17** (November (4)) (2002) 1132-1139.
- [21] E. Muljadi, K. Pierce, P. Migliore, Control strategy for variable speed stalls regulated wind turbines, in: Proceedings of the American Control Conference, Philadelphia, June 1998, pp. 1710-1714.
- [22] Sathyajith M., Wind Energy Fundamentals, Resource Analysis and Economics, Springer. 2006.
- [23] Powell WR. An analytical expression for the average output power of a wind machine. *Solar Energy* **1981**; **26**: 77-80.
- [24] Chedid R, Akiki H, Rahman S. A decision support technique for the design of hybrid solar-wind power systems. *IEEE Trans Energy Convers* **1998**; **13**(1):76-83.
- [25] Stevens MJM, Smulders PT. The estimation of the parameters of the Weibull wind speed distribution for wind energy utilization purposes. *Wind Eng* **1979**; **3**:132-45.
- [26] Pallabazzer R. Previsional estimation of the energy output of wind generators. *Renew Energy* **2004**; **29**: 413-20
- [27] Ssu-yuan Hu and Jung-ho Cheng. Performance evaluation of paring between sites and wind turbine. *Renewable energy* **32**. 2007. 1934-1947.
- [28] Nfaoui H, Bahraui J. Wind energy potential in Morocco. *Renewable Energy* **1991**; **1**:1-8.
- [29] El-Mallah A, Soltan AM. A nomogram for estimating capacity factors of wind turbines using site and machine characteristics. *Sol Wind Technol* **1989**; **6**: 633 -5.
- [30] Torres JL, Prieto E, Garcia A, De Blas M, Ramirez F, De Francisco A. Effects of the model selected for the power curve on the site effectiveness and the capacity factor of a pitch regulated wind turbine. *Solar Energy* **2003**; **74**: 93-102.