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Wind power statistics and an evaluation of wind energy density in Algeria

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Abstract— **In this study, wind characteristics were analyzed using the wind speed collected of six meteorological stations in Algeria during 1976-1988. Wind data collected at 10m of height above ground, were extrapolated to 30 m and 50m using power law. The annual average of wind speed for the considered sites rand from 2.96 to 6.38 m/s and mean wind power density from 40.61 W/m2 to 283.12 W/m^2 at standard height of 10m. The wind speed characteristics and wind power potential of each station have been determined using Weibull distribution.**

Keywords— **Wind speed; wind energy; Weibull parameters; wind generators.**

I. INTRODUCTION

The geographical locations (latitude, longitude and altitude) for the sites considered in this study are presented in Table 1 and fig.1 [1, 2]. Wind data for six meteorological stations were obtained from the Algerian Meteorological National Office. The data were collected over a period spanned between 1976-1988 [3, 4].

At all stations the measurements were obtained at a height of 10 m above sea level. Therefore, the wind parameters were extrapolated from the standard height 10m to 30 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 LOCATION FOR DIFFERENT SITES

	Sites	Longitude (°)	Latitude (°)	Altitude (m)	Topographic Situation
01	Skikda	06° 57' E	36°52'N	9	Coastal zone
02	Algiers	03° 15' E	36° 43'N	25	
03	B.B Arriredj	04° 46' E	36° 04'N	904	
04	Tiaret	01° 20' E	35° 23'N	1023	Highlands
05	InSalah	02° 28' E	27° 12'N	243	Sahara
06	Tindouf	08°08' W	27° 40'N	402	

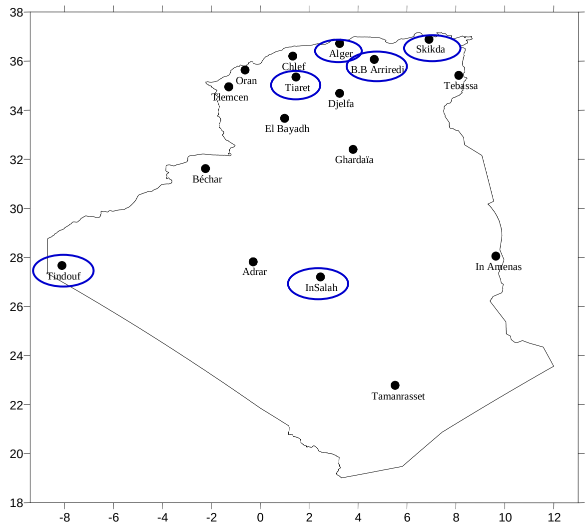


Fig. 1. Distribution of meteorological stations over Algeria territory.

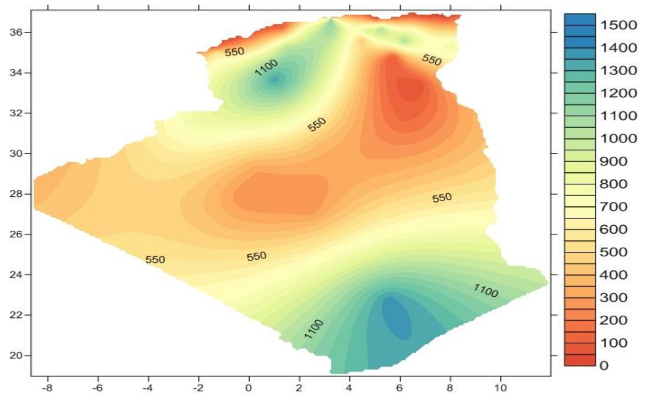


Fig. 2. Relief map of Algeria.

II. MATHEMATICAL FORMULATION

1. Weibull method

The Weibull distribution function [5, 6] is the most frequently used model to describe wind speed distribution. This function gives a good match with the experimental data.

It is characterized by two parameters k and c. this distribution takes the form:

$$f\,(V)=\left(\frac{k}{c}\right)\cdot\left(\frac{v}{c}\right)^{k-1}\cdot\exp\left[-\left(\frac{v}{c}\right)\right]^{k}\quad \text{for (k>0, v>0, c>1)} \qquad (1)$$

Where v is the wind speed, k is the dimensionless shape parameter, describing the dispersion of the data, and c Weibull scale parameter in the unit of wind speed (m/s).

Moreover, the cumulative density function of the Weibull distribution is defined as:

$$F\,(v)=\int_0^{\alpha} f\,(v).dV=1-e^{-\left(\frac{v}{c}\right)^{k}} \qquad (2)$$

The cumulative distribution function can be used for estimating the time for which wind is within a certain velocity interval. Probability of wind velocity is between v_1 and v_2 is given by the difference of cumulative probabilities corresponding to v_2 and v_1. Thus [7]

$$P(v_1 \prec v \prec v_2)=F(v_2)-F(v_1) \qquad (3)$$

That is

$$P(v_1 \prec v \prec v_2)=\exp\left(-\left(\frac{v_1}{c}\right)^{k}\right)-\exp\left(-\left(\frac{v_2}{c}\right)^{k}\right) \qquad (4)$$

We may be interested to know the possibilities of extreme wind at a potential location, so that the system can be designed to sustain the maximum probable loads. The probability for wind exceeding V_x in its velocity is given by

$$P(v\geq v_x)=1-\left[1-\exp\left(-\left(\frac{v_x}{c}\right)^{k}\right)\right]=\exp\left(-\left(\frac{v_x}{c}\right)^{k}\right) \qquad (5)$$

The mean of the distribution [7, 8], i. e., the mean wind speed, V_m is given by the relation (6)

$$v_m=\int_0^{\infty} f\,(v)\cdot dv=c\cdot\Gamma\left(1+\frac{1}{k}\right) \qquad (6)$$

The most probable wind speed (V_E), which represents the most frequent wind speed, is expressed by Elamouri M. and Ben Amar F. [9]

$$v_E=c.\left(1+\frac{2}{k}\right)^{\frac{1}{k}} \qquad (7)$$

Wind speed carrying maximum energy represents wind speed which carries maximum wind energy can be expressed as follow [9]

$$v_F=c\cdot\left(1-\frac{1}{k}\right)^{\frac{1}{k}} \qquad (8)$$

The variance σ^2 of the data is then defined as cited Refs [8, 10]

$$\sigma^2=\int_0^{\infty}(v-\prec v\succ)\cdot f\,(V)\cdot dv=c^2\cdot\left[\Gamma\left(1+\frac{2}{k}\right)-\Gamma^2\left(1+\frac{1}{k}\right)\right] \qquad (9)$$

The standard deviation σ is then defined as the square root of the variance [10]

$$Stadard\ \ deviation=\sqrt{Variance} \qquad (10)$$

The average cubic speed of the wind is given by the following relation [11]

$$\left\langle v^3\right\rangle=\int_0^{\infty} v^3\cdot P(v)\cdot dv=c^3\cdot\Gamma\left(1+\frac{3}{k}\right) \qquad (11)$$

Where Γ is the defined gamma function, for any reality x positive not null, by

$$\Gamma(x)=\int_0^{\infty}\exp(-t)\cdot t^{x-1}\cdot dt\quad \text{with}\quad x>0 \qquad (12)$$

2. Vertical extrapolation of wind speed

The wind data measurements used in this study are used from stations set at a standard height of 10m. Vertical extrapolation of wind speed where based on the Power law,[7,12, 13]

$$v(z)=v(z_{ref}).\left(\frac{z}{z_{ref}}\right)^{n} \qquad (13)$$

$v\,(z_{ref})$ 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 is also a terrain-dependent parameter, given by equ.16.

3. Vertical extrapolation of Weibull parameters:

Weibull parameters are also functions of height [7, 14, 15],

$$c(z)=c(z_{ref}).\left(\frac{z}{z_{ref}}\right)^{n} \qquad (14)$$

$$k(z)=k(z_{ref}).\frac{1-0.088.Ln\left(\frac{z_{ref}}{10}\right)}{1-0.088.Ln\left(\frac{z}{10}\right)} \qquad (15)$$

Where
n is a scalar obtained using the relation

$$n=\frac{0.37-0.088.Ln\ \ (c(z_{ref}))}{1-0.088.Ln\left(\frac{z_{ref}}{10}\right)} \qquad (16)$$

4. Estimating wind power

The kinetic energy of a stream of air with mass (m) and moving with a velocity (v) is given by [16]

$$E=\frac{1}{2}mv^2\quad [\text{J}] \qquad (17)$$

The power in moving air is the flow rate of kinetic energy per second. Therefore [16]:

$$P = \frac{E}{t} = \frac{1/2.m.v^2}{t} \quad \text{(w)} \tag{18}$$

The wind power density (P_d) is the power per unit area, can be written as follow [17]:

$$P_d = \frac{P}{A} = \frac{1}{2}.\rho.v^3 \quad \text{(w/ m}^2\text{)} \tag{19}$$

ρ_0 is the standard air density, (1.225 kg/m^3)
A is the area swept by the rotor blades (A= π.R^2), [m^2]
v is the mean wind speed,[m/s]

The theoretical maximum power that can be extracted from a wind turbine is limited by Betz' Law [18, 19]

$$P_{ext} = \frac{1}{2}.\ C_p(\lambda,\beta)\ \rho\ AV^3 \tag{20}$$

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

Finally, the available annual energy Ewdp (kwh/m^2/year) can be computed using Eq. (21) [20]:

$$E_{wdp} = 3.1678.v^3 \tag{21}$$

According to Refs.[21-25], the power curve of a wind turbine can be well approximated with the parabolic law as

$$P(v) = \begin{cases} 0 & if \quad v \prec v_C \\ P_R\left(\frac{v^k - v_C^k}{v_R^k - v_C^k}\right) & if \quad v_C \le v \le v_R \\ P_R & if \quad v_R \le v \le v_F \\ 0 & if \quad v \succ v_F \end{cases} \tag{22}$$

P_R is the rated electrical power, v_C is the cut-in wind speed,
v_R is the rated wind speed, v_F is the furling wind speed,
k is the Weibull shape parameter.

The average power output from a wind turbine is the power produced at each wind speed times the fraction of time that wind speed is experienced, integrated over all possible wind speeds.

Integrating equation (22):

$$P_{avrg} = \int_0^{\infty} P(v).f(v).dv = \int_{v_c}^{v_F} P(v).f(v).dv \tag{23}$$

Substituting Eqs. 22 into Eq. 23 yields

$$P_{avrg} = \int_{v_C}^{v_R} P_R.\left(\frac{v^k - v_C^k}{v_R^k - v_C^k}\right).f(v).dv + \int_{v_R}^{v_F} P_R.f(v).dv \tag{24}$$

There are two distinct integration in Eq. 24 which need to be integrated. One has the integrand $v^k.f(v)$ and the other has the integrand $f(v)$. The integration can be accomplished in a better way by making the change in variable.

Therefore [10, 21, 26-28]

$$P_{avrg} = P_R\left(\frac{\exp\left[-\left(\frac{v_C}{c}\right)^k\right] - \exp\left[-\left(\frac{v_R}{c}\right)^k\right]}{\left(\frac{v_C}{c}\right)^k - \left(\frac{v_R}{c}\right)^k} - \exp\left[-\left(\frac{v_F}{c}\right)^k\right]\right) \tag{25}$$

P_{avrg} can be expressed as:

$$P_{avrg} = P_R.C_F \tag{26}$$

Where C_F is the capacity factor.

III. Results and Discussion

The wind speed, power and energy are evaluated, respectively by Weibull method. The results for six Algerian sites are presented in Figs. 5-7 and 11-12.

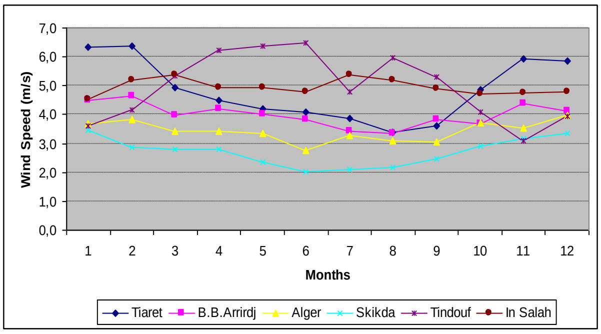


Fig.3. Monthly mean wind speed for the different sites

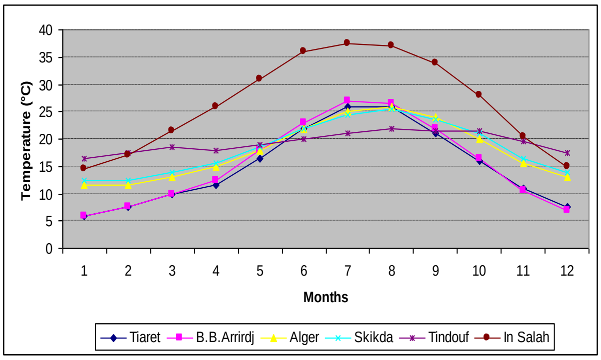


Fig.4. Monthly mean temperature for the different sites

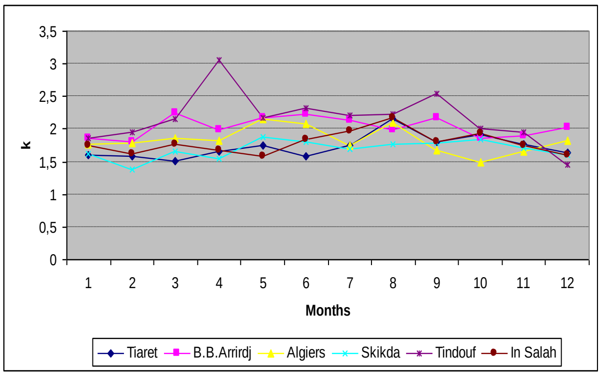


Fig.5. Monthly Weibull shape parameter k for the different sites.

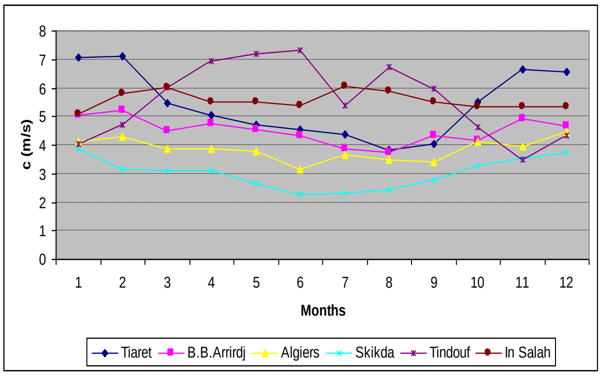
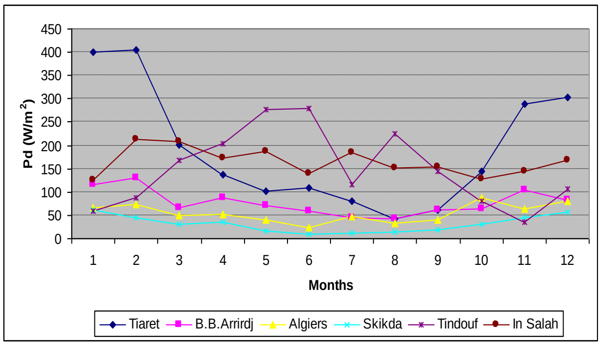


Fig.6. Monthly Weibull scale parameter C for the different sites



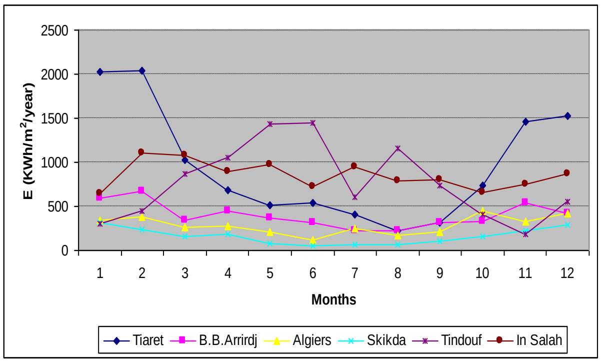
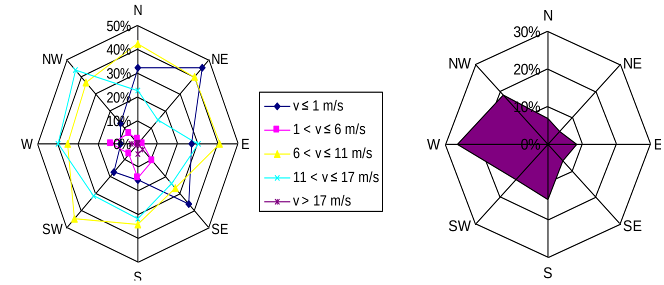
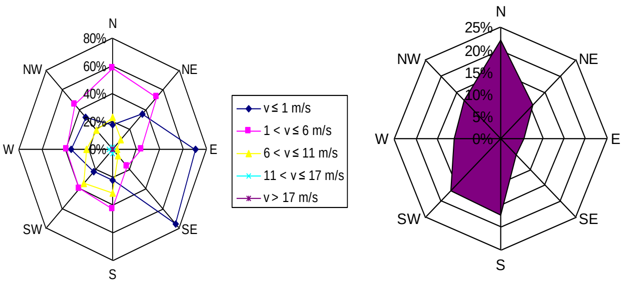


Fig.7. Average monthly wind power density for different stations at 10 m height (W/m^2)

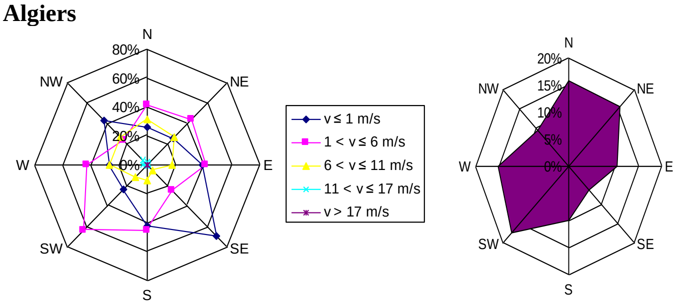
Tiaret



B.B. Arriredj



Algiers



Skikda

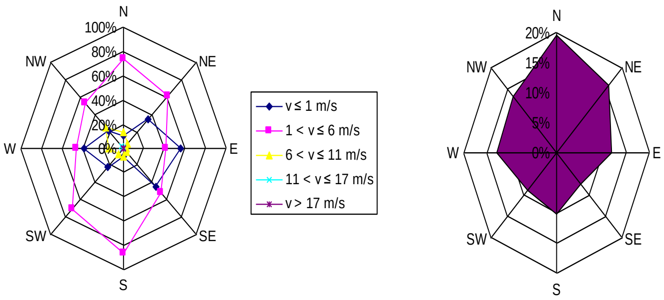


Fig.8. Wind roses charts for different sites

The wind data used in this study consist of wind speed values recorded at six stations which are located in different parts of Algeria. The extrapolated wins speed from 10m to 30m and 50m height are used to calculate the monthly and the annual men wind power at all stations.

We notice that Tiaret has significantly the highest annual value of V_F, while Skikda has the lowest one. Moreover, Tindouf has the highest annual value of V_E and Skikda has the lowest one.

Finally, higher monthly values of V_E and V_F are observed during winter, while lower ones are observed during summer.

Using the monthly mean values of temperature T and wind speed V for the six selected sites and the Weibull parameters at 10 m height to calculate the monthly mean power densities. These values for six stations are presented in Fig.5. As shown, Tiaret has the highest power density, but presents significant fluctuation between months and seasons. Tindouf has also high power densities, with limited fluctuation over the year.

Besides, Skikda presents rather lower power densities. In Tiaret, B.B. Arriredj, Algiers and Skikda, wind speeds generally are the fastest in winter and spring (October- Mars) and it is the slowest during summer, on the contrary at Tindouf and In Salah (Saharan sites) wind speeds generally are fastest in summer (April- August) and it's the slowest during winter.

The maximum value of monthly mean wind speed is determined as 6,48 m/s at Tindouf in June and a minimum value of 2,02 m/s occurs at Skikda in June. A maximum value of annual mean wind speed is obtained at Tiaret as 6,19 m/s.

Monthly Weibull shape parameter k varies between 1,39 and 3,05 , while scale parameter c varies between 2,27 and 7,31 m/s. The mean annual value of Weibull shape parameter k is between 1,39 and 3,05 while the mean annual value of Weibull scale parameter c is between 2,27 and 7,31 m/s. The shape parameter k has a minimum value of 1,39 at Skikda in February and it has a maximum value of 3,05 at Tindouf in April. The highest value of c is found at Tindouf in June as 7,31 m/s and the lowest value of c is 2,27 m/s at Skikda in June.

In order to prove the most frequent direction of the wind, we have traced a wind roses chart with 08 directions for each site (see Fig.8). The examination of these wind roses show that the dominant direction of the wind are : the West in Tiaret and In Amenas, the North in B.B Arriredj and Skikda, the North West in Tindouf and South West in Algiers.

The relative frequency of the dominant wind direction is low, ranging between 17.5 % (Algiers) and 26.7 % (Tindouf). Relative frequencies of 1-6 m/s winds are the highest (see Fig.8); the minimum is 6.92 % in Tiaret, while the maximum is 60.67 % in In Skikda. However , the relative frequencies 11-17 m/s winds are low, the minimum is 0.70 % in Skikda, while the maximum is 29.72 % in Tiaret. Fréquency distribution of the wind speeds greater than 17 m/s is very low, lies betwen 0.00 % and 1.63 %.

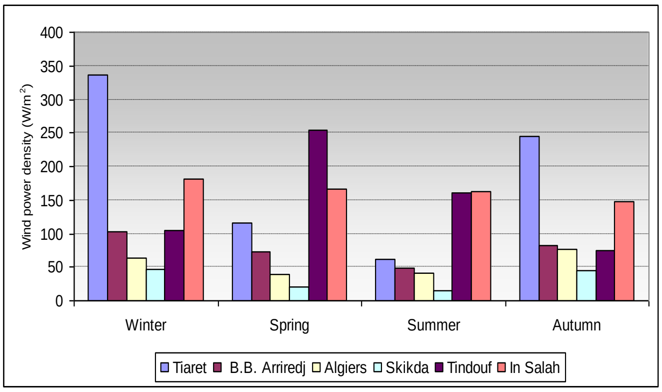


Fig.9. Seasonal assessment of the wind power density for the six locations

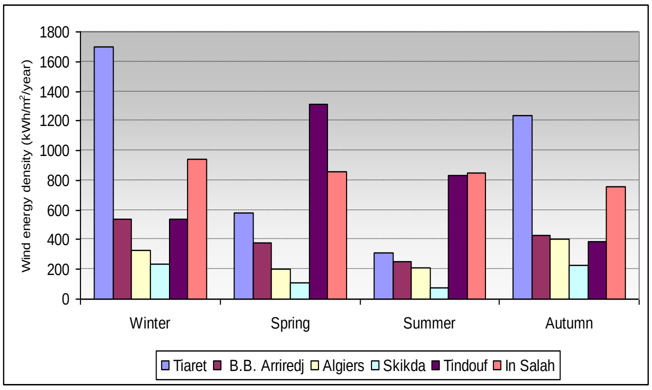


Fig.10. Seasonal assessment of the wind energy density for the six locations

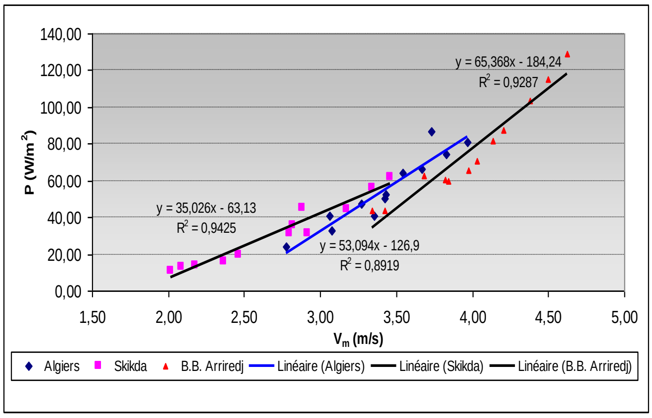


Fig.11. Monthly mean power density (P) as a function of monthly mean wind speed (Vm) in Algiers, Skikda and B.B. Arriredj.

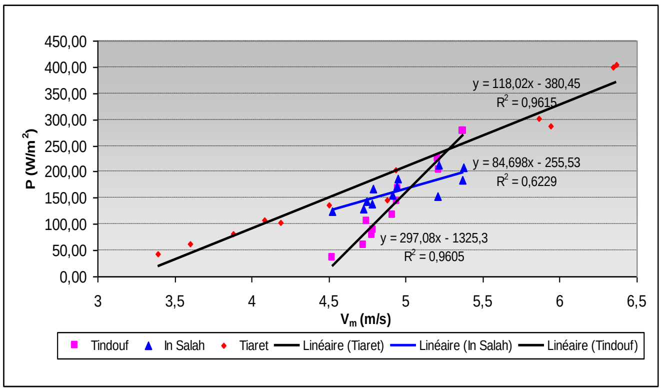


Fig.12. Monthly mean power density (P) as a function of monthly mean wind speed (Vm) in Tindouf, In Salah and Tiaret.

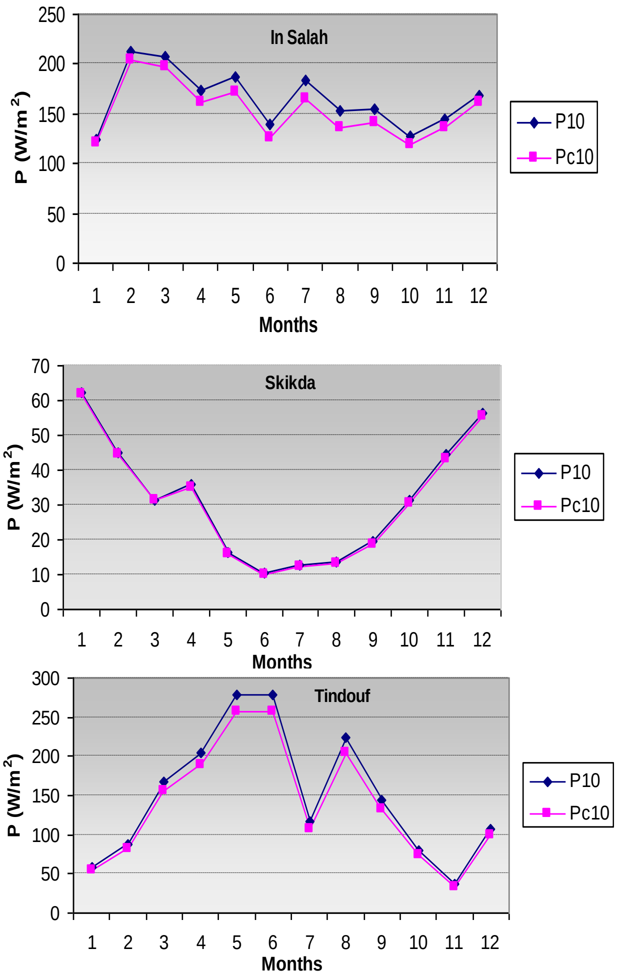


Fig.13. Comparison between corrected and uncorrected wind power

- It is noticed that the great decreases of the air density is recorded in the sites of B.B Arriredj and In Salah, these sites are respectively characterized by the very elevated heights above sea level (904m and 243m), while the weak variation is noticed in the very low heights sites, Algiers (25m) and Skikda (9m).
- Annual values of corrected wind power are the smallest that the uncorrected wind power (see fig.13).
- The density of air decreases with the increase in site elevation and temperature as illustrated in Fig.13.
- The highest decreases of the air density are found during summer and the lowest values are found during winter season for the sites of Skikda, Algiers, InSalah and Tindouf, contrary to the sites of B.B Arriredj and Tiaret.

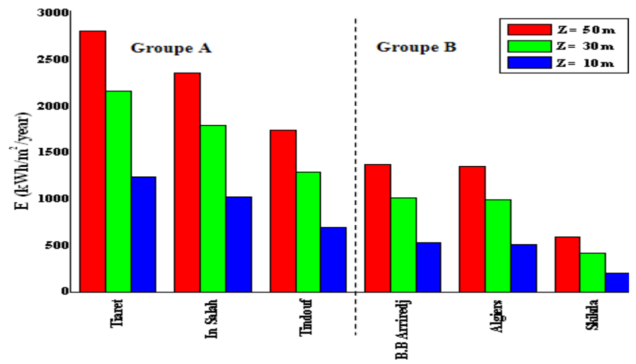


Fig.14. Annual wind energy for the various groups at height of 10m, 30m and 50 m.

IV. CONCLUSIONS

In this study, we have evaluated the wind resource of six Algerian sites, the annual average wind velocity and power density at the standard height (10m above the ground) are calculated using the Weibull distribution function. The analysis of the results leads to the classification of these sites into two groups:

Group A, that includes Tiaret, In Salah and Tindouf, This group is ideal (excellent for production of electricity and wind farms setting up).

- **Group B,** that includes B.B Arriredj, Algiers and Skikda. This group is favourable for applications of low power, as water pumping systems.

Wind energy exploitation in Algeria is favourable in group B for applications of low power, as water pumping systems and production of electricity using small wind turbines, and for group B even for the installations of great power and wind farms.

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