Estimation of wind power density in Ouargla region using Weibull Distribution

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***Abstract* -In this paper, the wind potential of Ouargla region was assessed using by Weibull distribution function. Ten years (2006-2015) daily wind database was utilized. The Weibull parameters were determined using conventional methods as well as optimization based methods. These methods are used to calculate the wind power density. In addition, the assessed wind power density of each method been compared with the actual data. The results show that, PSO has the best performance compared to other methods. A set of simulation results obtained during this study is presented. These results show the atmosphere is not stable throughout the year. This indicates the existence of seasonal winds and power increases considerably after extrapolation to 50 m, giving estimated energy of 953.77 KWh/m².**

***Keywords*— Weibull parameters; Statistical analysis; Ouargla; wind potential; power density**

I. INTRODUCTION

These last years, the world has experienced a rapid increase in energy demand, in addition to economic and demographic growth and improved living standards, this growing demand for energy has led to the inability to meet energy needs. In the other hand, utilization of fossil fuels as a main source of energy deteriorate environment. Number of researchers considering renewable energy sources (solar, wind, biomass .... etc.) are the optimal alternative to fossil energy, renewable energy has remarkably developed and become more economically competitive [1]. Wind energy is considered a more sustainable and more environmentally friendly source of energy [2], [3]. Moreover, wind energy does not consume water, which makes it more attractive than thermal plants that require intensive use of fresh water for cooling, especially in hot or arid areas .At the level of our country, Algeria has a diversity of renewable energy sources (solar, wind) and this in an area of 2 381 741 km². Algerian has completed several projects related to wind energy, for example in the wilaya of Adrar, it has created a large station of a wind farm [4].In this work we want to look for ways to invest in this energy in our country Algeria, and use it in the best way, we wanted by virtue of our presence in Ouargla region to take advantage of these energy circumstances. But before starting any project, we must study whether the site you want to establish the project is suitable or not?

II. WEIBULL DISTRIBUTION FUNCTION

The Weibull distribution used for the statistical analysis of the data, it is better known and preferable to represent the distribution of the wind speed [6]. The Weibull distribution function is based on two parameters of modelling (k) shape parameter and scale parameter (c) [5]. The Weibull probability density is given by.

$$f(v) = \frac{k}{c}(\frac{v}{c})^{k-1}exp(-\frac{v}{v})^k \quad (1)$$

III. DETERMINATION OF WEIBULL PARAMETERS

In fact, every location has different parameters (k) and (c) to describing the distribution of wind speed for a candidate site, thus, (k) and (c) need to be determined. Several methods were used in literature to determine (k) and (c). In this section, conventional methods as particle swarm optimization method have been compared to determine the Weibull parameters (k) and (c) for our region of study (Ouargla).

A. Moment method

In 1977, Justus and Mikhail [8] introduced this method. This method is based on the standard deviation and the means of wind speeds for determining the two parameters k and c the shape parameter (c) can be calculated iteratively using Eq (2).[9],[10],[11].

$$v_m = c\Gamma(1+\frac{1}{k}) \quad (2)$$

$$\sigma = c[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)]^{1/2} \quad (3)$$

The scale parameter is calculated using Eq. (4).

$$c = (\frac{1}{n}\sum_{i=1}^{n} v_i^k)^{1/k} \quad (4)$$

B. Empirical method of Lysen

Based on the empirical method introduced by Lysen, shape parameter (k) is calculated by Eq. (5) and the scale parameter(c) is computed as Eq. (6) [8].

$$k = (\frac{v_m}{\sigma})^{-1.086} \quad (5)$$

$$c = v_m(0.568 + \frac{0.433}{k})^{-1/k} \quad (6)$$

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C. ENERGY PATTERN FACTOR METHOD

Mathematically, EPFM is given by Eq. (7). This is a dynamic method based on the fact that energy can be efficiently extracted from the wind [7], [12], [13].

$$\text{EPFM} = \frac{\text{the average power of the wind}}{\text{the power of the average wind}} \quad (7)$$

The primary step in this method is to compute energy patterns factor Epf, which is given by the following relationship.

$$E_{pf} = \left(\frac{1}{n}\sum_{i=1}^{n} v_i^3\right) / \left(\frac{1}{n}\sum_{i=1}^{n} v_i\right)^3 \quad (8)$$

Can be determined the shape parameter by Eq. (9) and the scale parameter by Eq. (4)

$$k = 1 + \frac{3.69}{(E_{pf})^2} \quad (9)$$

D. POWER DENSITY METHOD

This new and more accurate method to determine the scale and shape parameters, the parameter (k) is calculated by iterating of numerical method Eq.(10) [7],[16].

$$E_{pf} = \frac{\overline{v^3}}{\overline{v}^3} = \frac{\Gamma(1+\frac{3}{k})}{\Gamma^3(1+\frac{1}{k})} \quad (10)$$

The scale parameter(c) is calculated by the next Eq. (11)

$$c = \frac{v_m}{\Gamma(1+\frac{1}{K})} \quad (11)$$

E. PARTICLE SWARM OPTIMIZATION METHOD

PSO is a stochastic and population-based search method. It was introduced by Russell Eberhart and James Kennedy in 1995[18]. PSO is an artificial life inspired method, it is basically developed from the behavior of bird flocks to solve complex optimization problems. A PSO algorithm uses a population in the search process called a swarm, each individual particle in the swarm represents a candidate solution.

The position of a particle is influenced by the personal best particle which is the best position of the particle itself relative to its previous position.

Unlike other population based techniques, PSO uses only two equations [18]:

$$\overrightarrow{v_i} = w\overrightarrow{v_i} + c_1\overrightarrow{\varphi_{1i}}(\overrightarrow{p_i} - \overrightarrow{z_i}) + c_2\overrightarrow{\varphi_{2i}}(\overrightarrow{p_g} - \overrightarrow{z_i}) \quad (12)$$

Here w is the inertia weight, pi is the best position, pg is the global best found by the swarm to date, c1 and c2 are positive constant parameters , $\varphi 1$, $\varphi 2$ is weights randomly generated at each step for each particle component.

At each iteration of each particle, its position is updated by adding the speed vector to the position vector by the following Eq[19].

$$\overrightarrow{Z_i} = \overrightarrow{Z_i} + \overrightarrow{v_i} \quad (13)$$

PSO is used to maximize/minimize a given function. The Weibull parameters are determined by minimizing the objective function given in the following relation:

$$o(v_i) = \frac{1}{n}\sum_{i=0}^{n}(f_{real}(v_i) - f_{weibull}(v_i))^2 \quad (14)$$

Where f_{real} and $f_{weibull}$ are the real and estimated wind frequency distributions respectively.

IV. STATISTICAL ANALYSIS

There are several statistical test tools, such as the RMSE, the Chi square test (X^2) and the Mean Absolute Percent Error (MAPE) test. This test tools can be summarized as.

A. ROOT MEAN SQUARE ERROR (RMSE)

RMSE is always a non-negative value. It is used to calculate the differences between experimental (real) values and predicted values, which is given by the following Eq [7],[20].

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{1/2} \quad (15)$$

B. MEAN ABSOLUTE PERCENTAGE ERROR (MAPE)

The MPE is the average absolute percentage between the predicted values reached by the frequency distribution and the observed values. The MEP is given by the following Eq [21].

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}|y_i - x_i| \quad (16)$$

C. CHI-SQUARE (X^2)

Chi-square is a statistical tool, it is used to compare the differences between the expected data results the observed data results , the X^2 is given by Eq[20].

$$x^2 = \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{N-n} \quad (17)$$

With: xi: the value frequency obtained by the Weibull distribution, N: the total number of intervals, yi: the observed value frequency and n: the number of constants.

V. EXTRAPOLATION OF WIND SPEED AND WEIBULL PARAMETERS

In general, wind speed measurements are made at 10 m altitude above the surface of the earth. However, it is necessary to estimate the wind speed at different altitudes, the extrapolation formula (Eq.19) of the wind speed for different altitudes have to be used [22],[17].

$$V = V_0\left(\frac{H}{H_0}\right)^{\alpha} \quad (18)$$

$$\alpha = \frac{1}{\ln(\frac{H_g}{r_0})} \quad (19)$$

With, V_0 is the wind speed measured at 10 m altitude. α,is the exponent of power law that is depending on the surface roughness.H_g,the geometric mean of the height.r_0 the roughness of the soil.

The extrapolation of the Weibull parameters from a standard level (10 m) to a level of interest, such as the height of the wind turbine hub that determines the available wind power density at that height. The expressions used are the following [22],[23].

$$K_h = \frac{k(10)}{1 - 0.088 \times \ln(h/10)} \quad (20)$$

$$C_h = C(10) \times (h/10)^n \quad (21)$$

Where (h) is the desired height and n is the coefficient of the power law.

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VI. Evaluation of the Average Wind Power Density

The power density of the wind gives the strength of the wind available at a particular site. Wind Power Density (WPD) is a principal factor in determining wind potential and makes it possible to quantify the energy produced during a time T by the wind turbines. WPD is calculated by two approaches

The first approach, the power density for the real time series wind speed data for a site can be calculated using the following Eq. [14], [15].

$$P = 0.5\rho\overline{v^3}(\text{W/m}^2) \quad (22)$$

With, V: is wind speed (m/s),ρ is density of surrounding air (kg/m^3).

The second approach, the WPD is calculated by using Weibull probability density function and can be estimated by the next Eq.

$$\frac{p}{A} = 1/2\rho c^3\Gamma\left(1+\frac{3}{k}\right)(\text{W/m}^2) \quad (23)$$

It is possible to calculate the available wind energy at a given location using the Weibull distribution, the annual wind energy, expressed in kWh/m². This calculation can yield by the following relation [17].

$$E = 3.56\, c^3\Gamma(1+{}^{3}/_{k})(\text{Kwh/m}^2\text{/an}) \quad (24)$$

VII. Results and Discussion

For this study, we chose the Ouargla region. Ouargla is a city in the south-east of Algeria. It is characterized by a Saharan climate. The site is geographically located at 31.93° is latitude and 5.4° longitude. We obtained the data used in this study from the meteorological service in Ouargla region. The measurements of wind speed were taken every day for ten years (2006-2015) at 10m height (figure1). Figure (1) represents the average monthly wind speed distribution of Ouargla, this figure shows the monthly wind speed varies from (1, 19-5, 51 ms^{-1}). We noted that the lowest value was observed in December, while the maximum value was observed in May and June. This is evident in Figure 1 where the wind speed exceeds (v> 3.45 ms^{-1}) In April, May and June. However, January, October, November and December are the least windy months where the wind speed is less than (v< 3.33).This characteristics reflects a variance in wind speed through the year.

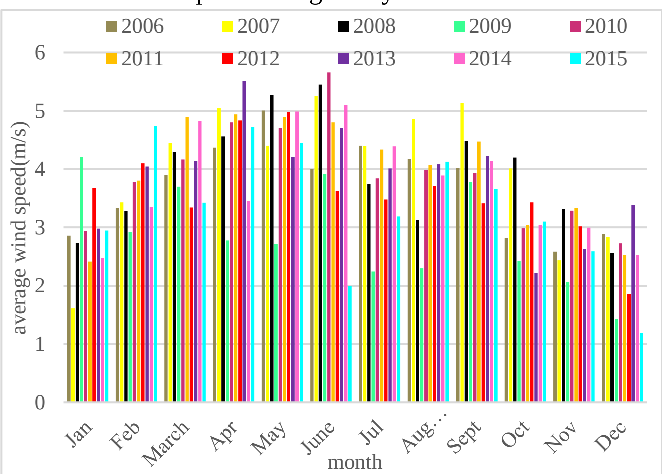

Fig.1. Monthly average wind speed for ten years

In this study the wind power density was estimated using five methods, theses lasts have been compared with measured data values, to determine the most accurate method. In order to achieve this goal we have used statistical analyses (RMSE, Chi-Square and MAPE).The results obtained in this study can be summarized as follows.

A. Estimation the Weibull Parameters in Ouargla Region

Determination of Weibull parameters (k and c) is an essential step before estimation of the power of wind. In this part we have determined these parameters by using five methods: Moments method (MOM), the Empirical method of Lysen (EML), power density method (PDM), Energy Pattern Factor method (EPFM) and Particle Swarm (Optimization) method (PSO). The results are listed in Table I.

The moment's method and empirical method of Lysen estimated monthly shape parameter varies from 1.2766 to 2.5749. The monthly scale parameter varies from 2.5810 to 5.1501 ms^{-1} by the moment's method but by the empirical method of Lysen, it varies from 2.5825 to 5.1528 ms^{-1}. Power density method and Energy Pattern Factor Method estimated monthly shape parameter varies from 1.3388 to 2.5339. Monthly scale parameter varies from 2.6469 to 5.1883 ms^{-1} by the Power density method and it varies from 2.6054 to 5.1583 ms^{-1} by Energy Pattern Factor Method in the year. Particle Swarm method estimated monthly shape parameter varies from 1.2868 to 2.4833 and monthly scale parameter varies from 2.6107 to 5.5624 ms^{-1}in the year.

Table 1 shows that the highest monthly wind speeds occur in the spring and summer months of March, April, May, June and July. In contrast, October, November, December and January have low wind, this is evident by the small monthly values of wind speeds, it is ranging from (2.39-3.12 ms^{-1}).

Figures 2,3,4,5 represent the seasonal variation of the Weibull distribution and the histograms of the wind frequencies.

The figures show that the wind speed covers a wide range that extends up to 4.30 ms $^{-1}$ in spring and summer, while the average wind speed can reach 3.60 ms^{-1} in winter, 3.30ms^{-1} in autumn.

As for the two parameters of Weibull, the shape parameter (k) is quite important during the four seasons when it exceeds the value 2.96 in spring and summer. The scale parameter (C) is a very important factor for knowing the wind potential and depends mainly on measured values of average monthly wind speed. It is varies from (3-5.56 ms^{-1}), this parameter reaches its maximum in spring (see figure 3), this confirms that the atmosphere is not stable throughout the year on Ouargla region, and the existence of seasonal winds and as indicated in the figures below.

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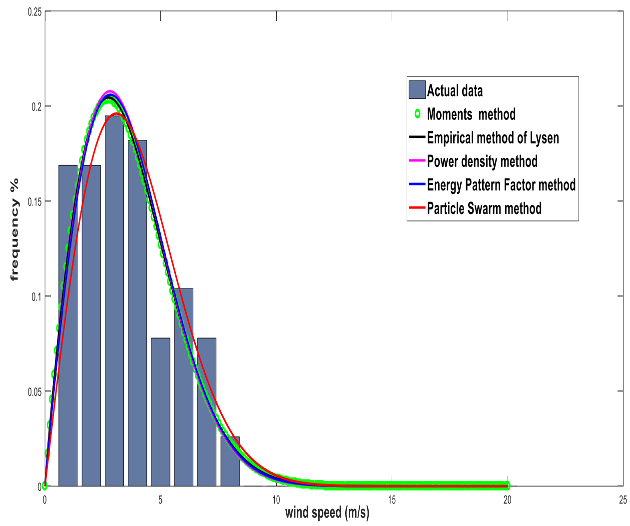

Fig.2 Observed and predicted wind speed frequencies in winter(c=3.6910m/s).

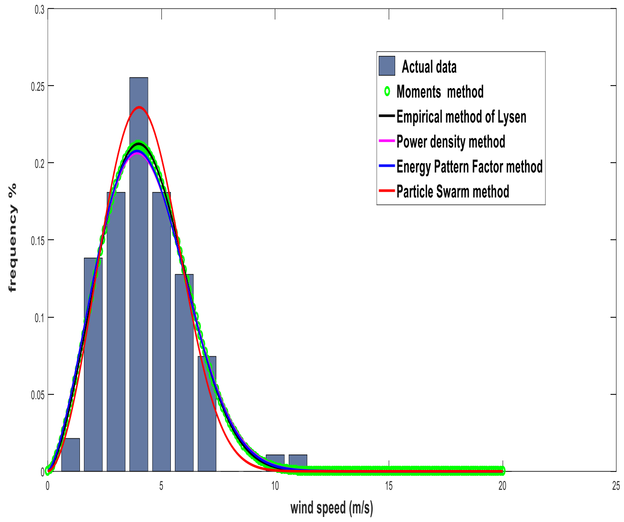

Fig.3 Observed and predicted wind speed frequencies in spring (c=4.6870m/s)

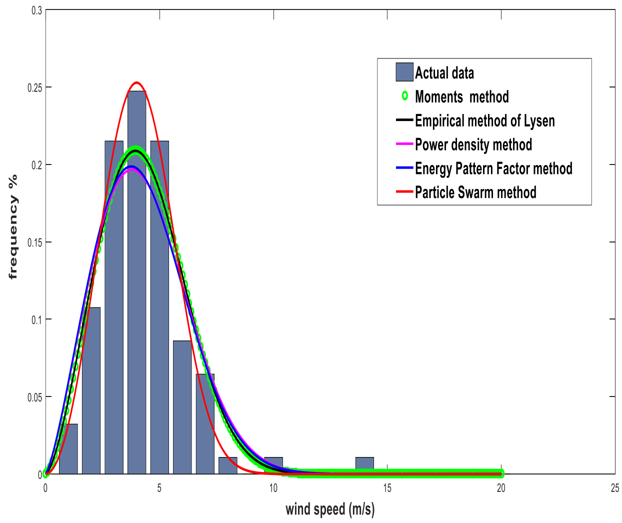

Fig.4 Observed and predicted wind speed frequencies in summer(c=4.6104m/s)

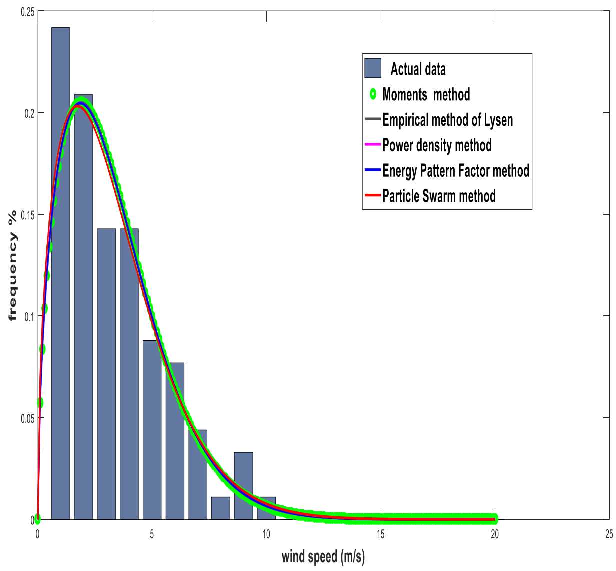

Fig. 5 Observed & predicted wind speed frequencies in autumn(c=3.2869m/s).

B. Estimation the Wind Power Density from Weibull Distribution Parameters

1) Monthly power density: The monthly wind power density is estimated by using air density and Weibull parameters in (22,23). Measured monthly WPD and estimated monthly WPD using Weibull parameters from MOM, EML, PDM, EPFM and PSO methods at different heights are shown in the figure (1-2).The results obtained show the monthly power density values varied between (29.82-245.64)W/ m² at 10m height, and for the 50m height the monthly power density values varied between(48.25- 398.27) W/m², this is according to moment's method and empirical method. For the Power density method and Energy Pattern Factor method, the monthly power density values varied between (27.35-259.54) and (44.34-420.64)W/m² at 10m-50m height respectively.

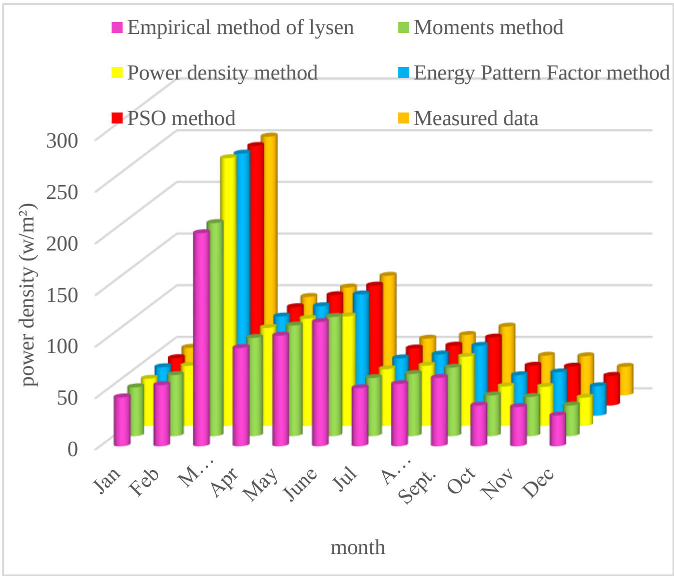

Fig.6 Estimate the Monthly Power Density (W/m²) by the five methods at 10m.

TABLE I
Estimate Weibull parameters by five methods at Ouargla region

Month	V(m/s)	Moments method		Empirical method of Lysen		Power density method		Energy Pattern Factor method		Particle Swarm method	
		K (-)	C (m/s)	K (-)	C (m/s)	K (-)	C (m/s)	K (-)	C (m/s)	K (-)	C (m/s)
Jan	2.88	1.3470	3.1446	1.3470	3.1468	1.3740	3.1841	1.3740	3.1554	1.2868	3.0909
Feb	3.67	1.9629	4.1494	1.9629	4.1519	1.9947	4.2330	1.9947	4.1508	1.7823	4.1179
March	4.56	2.5749	5.1501	2.0686	5.1528	2.1399	5.1883	2.5339	5.1512	1.9933	4.6811
Apr	4.50	2.2563	5.0823	2.2563	5.0842	2.2631	5.1041	2.2631	5.0822	2.3855	5.1550
May	4.27	1.1553	4.4998	1.1553	4.5004	1.0428	4.3180	1.0428	4.3492	2.2287	5.2620
June	4.59	1.0025	4.5974	1.0025	4.5930	1.0183	4.6166	1.0183	4.6272	2.4893	5.5614
Jul	3.80	2.3106	4.2924	2.3106	4.2937	2.3810	4.3064	2.3810	4.2905	2.2931	4.2586
August	3.83	2.1922	4.3274	2.1922	4.3292	2.2744	4.3522	2.2744	4.3265	2.2827	4.3227
Sept	4.12	2.0686	4.6479	2.5749	4.6485	2.5339	4.6424	2.1399	4.6499	2.7187	4.6857
Oct	3.12	1.8223	3.5183	1.8223	3.5208	1.8709	3.5525	1.8709	3.5220	1.7561	3.4372
Nov	2.82	1.4880	3.1277	1.4880	3.1303	1.4891	3.2371	1.4891	3.1280	1.4297	3.0386
Dec	2.39	1.2766	2.5810	1.2766	2.5825	1.3388	2.6469	1.3388	2.6054	1.3132	2.6107

And for PSO optimization method the monthly power density values varied between (28.77-251.5), (46.64-407.61)W/m² at the 10m-50m height respectively.

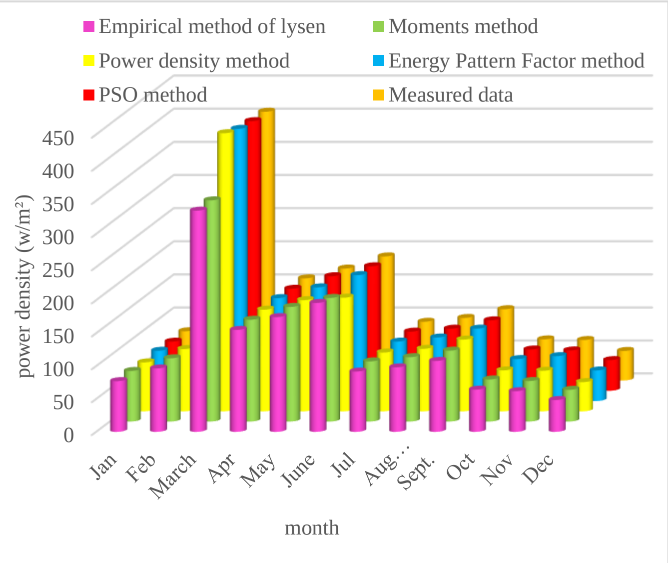

Fig.7 Estimate the Monthly Power Density (W/m²) by the five methods at 50m

The results obtained show the power density shows a large month-to-month variation. The minimum power densities occur in December (28.77- 46.64) W/m² at 10m-50m heights and we recorded the highest value in March (250.63- 450) W/m² at 10m-50m heights respectively (figure 1-2). It is interesting that highest power density values occur in the spring months of March, April and May.The results indicate that Ouargla site has a seasonal wind potential, as the wind blows at a relatively high speed in spring and summer.

Considering the tow figures (1) (2) we note, the values of the power density estimated from the PSO method close to the values measured in comparison with the estimates of other methods.

2) Seasonal Power Density: The maximum seasonal average power density of (64.05- 103.80) W/ m² is recorded in the spring for heights (10m , 50m) successively, while the minimum values of (45.06-73.03) W/m² are recorded in the winter for heights (10m,50m) successively (Table II). Thus, the higher power density at the Ouargla site in two seasons (spring - summer) and low in winter and autumn.

TABLE II
Estimate Seasonal power density at (10 m, 50 m) altitude

	Weibull parameters		**P(Wm^{-2})**	
Season	K	C(ms^{-1})	10m	50m
Winter	1.8398	3.6910	45.0668	73.0397
Spring	2.8964	4.6870	64.0504	103.8064
Summer	2.9617	4.6104	60.3540	97.8157
Autumn	1.3517	3.2869	53.7538	87.1187

The analysis of the results also shows that:

♦ the change from the 10 m height to the 50 m height makes it possible to increase the WPD available on site by a factor of approximately 1.6 to 2.

♦ the atmosphere is not stable throughout the year on the Ouargla site and the existence of seasonal winds, this confirms that there is a potential for significant winds in this site.

♦ it is noted that the power increases considerably after the extrapolation to 50 m, which gives an estimated energy of 953.77 KWh for each m².

♦we find that the months in the centre of the year, which are part of spring and summer, are the windiest months, and this assures us the greatest power and energy is in coastal months of the year.

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C .STATISTICAL ANALYSIS

In this work, we have used the previous tools to test the accuracy of the used methods to find the most efficient method for determining the wind power density, (Table III) shows more about obtained results. It is observed that the conventional methods have the highest percentage of error. In contrary, the particle swarm optimization method (PSO) shows a more efficient and lower error percentage. It is the better method to estimate the WPD.

TABLE III
Statistical analysis for five methods at 10m, 50 m altitude

Method	Statistical Analysis					
	10m			50m		
	RSME	MAPE	X^2	RSME	MAPE	X^2
MOM	1.94	0.46	0.12	3.14	0.27	0.33
EML	2.41	0.96	0.19	3.91	1.56	0.52
PDM	3.77	0.17	0.48	6.14	0.28	1.27
EPFM	2.06	1.72	0.14	3.35	2.80	0.38
PSO	0.93	0.42	0.02	1.51	0.68	0.07

D.THE ANNUAL ENERGY DENSITY

Figure 8 shows the wind energy density in the Ouargla region for 10 years at different heights. It is remarkable that (figure 8) an aero-generator on this site can produce 588.62 KWh annually at 10 m for each m². Given the nature of the saharan soil in this region, and the effect of the roughness of the surface, we note that the power increases considerably after the extrapolation to 50 m, so that the average energy estimated (417.59 - 660.08) kWh for each m² this at the heights10m 50 m successively. After gathering knowledge about the densities of the average powers in this site, we propose the setting of small wind turbines can be chosen to produce electricity in a hybrid way with a photovoltaic system, for example.

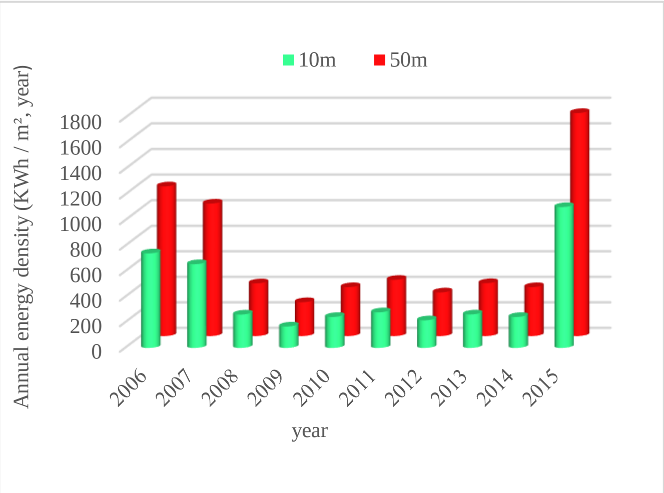

Fig.8Annual energy density at 10 m and 50 m altitude.

VIII. CONCLUSION

This study allowed us to evaluate the potential energy of the wind in the region of Ouargla. The average monthly wind speed at the Ouargla site was relatively varied between (1.19-5.51 ms^{-1}), The Weibull parameters were calculated by five methods: Moments method, the Empirical method of Lysen, power density, Energy Pattern Factor method and particle swarm optimization method, where it was found in a period the shape parameter (k) varied between (1.28 to 2.56) with respect to the parameter (c) it varies between 2.61 to 5.56.the wind power has been estimated at different heights according to the Weibull distribution. We find that the months in the centre of the year, which are part of spring and summer, are the months more windy, and this assures us the greatest power and energy that the coastal months of the year(seasonal winds). Therefore we consider that small wind power plants can be a hybrid power generation choice eg (PV-E) as a solution to avoid energy shortage throughout the year or this level of power density may be adequate for non-connected electrical and mechanical applications, such as battery charging and water pumping.

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