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Efficiency of Three Wind Turbines Installed on High Plains Region of Algeria

Nachida Kasbadji Merzouka* and Mustapha Merzoukb

aSolar Equipment development unit/Renewable Energy Development Center, Bou Ismail, Tipaza, Algeria
bEngineering Faculty, Saad Dahleb University Blida, Algeria

Abstract

A Monthly Weibull parameter k and c and a variance for three stations located in the west of high plains of Algeria (Tiarret, Djelfa and El Bayadh) have been estimated using ten years of weather data. The Weibull parameters have been extrapolated to 45 meters taken as height of wind machine rotor. The corresponding mean cubic speeds of the selected sites and the mean monthly power density have been calculated. The most interesting wind potential is obtained for Tiaret region.

Using a cut-in speed and a rated speed of a given generators, with 100 kW, 600 kW and 850 kW of nominal power, the monthly mean usable cubic wind speed for the selected sites has been computed.

The results show that a 600 kW and 850 kW wind machine are quite equivalent, in useful power density sense. The choice of an appropriate wind machine will depend of local energy needs. A big decrease noticed during hot season can be completed by a supply source or solar system.

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Keywords Weibull distribution; Wind speed; Wind power density; useful wind power.

Nomenclature

| Symbol | Description | Unit |
|--------|-------------|------|
| D_r    | Rotor diameter | M    |
| P      | Total available wind power density | W/m² |
| P_u    | Total usable wind power density | W/m² |
| V      | Wind speed | m/s |
| V_c    | Cut-in Wind speed | m/s |
| V_n    | Nominal wind speed | m/s |
| V_o    | Cut-out wind speed | m/s |
| V'     | Mean wind speed | m/s |
| V''    | Mean cubic wind speed | m³/s³ |
| Z_1    | Height of measured data | M    |
| Z_2    | Height of a generator rotor | M    |
| Z_o    | Roughness parameter | M    |
| Z_G    | Geometric length | M    |
| c, c_1, c_2 | Scale parameter of Weibull distribution | m/s |
| f      | The probability density of Weibull distribution frequency | % |
| k, k_1, k_2 | Shape parameter of Weibull distribution | |
| α      | Exponent of power law | |
| Γ      | Gamma function | |
| Γ_n   | Normalized incomplete Gamma | |
| σ²    | Variance | m²/s² |

*Corresponding author. Tel.: +213 24 41 01 33 ; fax: +213 24 41 01 33
E-mail address: nkmerzouk@cder.dz
1. Introduction

In Algeria some people live in the rural areas and often it is more expensive to transport conventional energy to these regions. So, it’s more convenient to use another type of energy which can be available locally such as the renewable energy. Because of the initial cost and with a less expensive maintenance cost, wind energy is most attractive than solar energy. It can be used for water pumping for irrigation, desalination, electricity supply and small scale industries, [1, 2, 3].

A statistical survey based on the Weibull distribution has been already established, [4,5,6], and yearly Weibull parameters have been determined, for Algeria. The results obtained permits the establishment of the map of the mean yearly wind speed and power density available in Algeria, [7]. The maximum is recorded in the south region and in the high plains where a wind power density reaches 1850 kWh/m² in a year.

However, this result is not sufficient to determine the optimal nominal power of the turbine which must be installed on a site. It’s often necessary to produce the monthly or seasonal to know if the turbine production is in line with the energy needs. In this study, the monthly Weibull parameter $k$ and $c$ and the variance, for three stations (Tiarét, Djelfa and El Bayadh located in the west high plains have been determined. The results have been extrapolated to 45 m above ground level, (i.e. the height of rotor) using the empirical formulas developed by Mikhail et al. [8]. It permitted the determination of the monthly mean cubic speeds of the selected sites and means monthly power density.

For the design studies, the determination of the usable power density is more important because it indicates the real quantity recovered by the turbine wheel. It’s function of the characteristics of wind machine as the cut-in, the rated and the cut-out wind speeds, which are given by the manufacturer, [9, 10]. Using the cubic value of these speeds and the mean Weibull distribution, the monthly mean useful cubic wind speed for selected sites has been computed. In the same way, the effect on the usable wind power of the cut-in and rated speed of the machine has been shown.

2. Mathematical Model

2.1. Weibull distribution

To describe the variation of wind speed, the law of Weibull distribution is usually used. The probability density function has the form:

$$f(V) = \frac{k}{c} \left( \frac{V}{c} \right)^{k-1} \exp \left( -\left( \frac{V}{c} \right)^k \right)$$  \hspace{1cm} (1)

With $f(V)$ being the occurrence frequency of the wind speed; $V$, $k$ and $c$ are parameters commonly known as the Weibull parameters called respectively shape and scale factors.

The mean wind speed and variance of Weibull distribution are given by :

$$\langle V \rangle = \int_0^\infty V f(V) dV$$  \hspace{1cm} (2)

After integration of Weibull distribution in equation (2), we obtain:

$$\langle V \rangle = c \Gamma\left(1 + \frac{1}{k}\right)$$  \hspace{1cm} (3)

With $\Gamma$ being known as the gamma function.

$$\bar{V} = c \Gamma(1 + 1/k)$$  \hspace{1cm} (2)

and

$$\sigma^2 = c^2 \left[ \Gamma(1 + 2/k) - \Gamma^2(1 + 1/k) \right]$$  \hspace{1cm} (3)
The reference wind speed is generally measured to a ten meters above a ground level. The vertical extrapolation in the first hundred meters above a ground level (a.g.l.) depends essentially on the roughness and the stability of the atmosphere. According to the usual height for wind machines, the Weibull parameters have been extrapolated from 10 to 45 m a.g.l., using a power law empirical formulas developed by Mikhail et al., [5:14] and giving by:

\[
k_2 = k_1 \left[ \frac{1 - 0.0881 \ln \frac{Z_1}{10}}{1 - 0.0881 \ln \frac{Z_2}{10}} \right]
\]

and

\[c_2 = c_1 \left( \frac{Z_2}{Z_1} \right) ^\alpha \]

The exponent $\alpha$ is given by:

\[
\alpha = \frac{1}{\ln \left( \frac{Z}{Z_0} \right)} + \frac{0.088 - 0.088 \ln c_1}{1 - 0.088 \ln \left( \frac{Z_1}{10} \right)}
\]

where $Z$ is a geometric length given by:

\[
\bar{Z} = (Z_1 Z_2)^{1/2}
\]

2.2. Total wind Power Density Available

Considering that the density of air is independent and is not a function of the temperature and equal to 1.225 Kg/m³, the total mean wind power density available is given by:

\[
\overline{P} = \frac{1}{2} \rho \overline{V^3}
\]

The mean cubic speed is estimated from the third moment of the Weibull distribution as, [6]:

\[
\overline{V^3} = \int_0^\infty V^3 f(V) dV
\]

So, the cubic mean wind speed is equal to:

\[
\overline{V^3} = C^3 \Gamma(1 + 3/k)
\]

2.3. Usable Wind Energy Potential

The characteristics of the turbine are usually given by the manufacturer. Using this limits usable wind power density is computed from:

\[
P_u = \frac{1}{2} \rho \begin{cases} 
0 & V < V_i \\
\overline{V^3} & V_i \leq V \leq V_s \\
\overline{V^3} & V_s \leq V \leq V_e \\
0 & V \geq V_e
\end{cases}
\]
Where:

- $V_i$: starting wind speed of turbine, m/s
- $V_n$: nominal wind speed of turbine, m/s
- $V_s$: stopped wind speed of turbine, m/s

As shown on the figure 1, the usable wind power depends on the shape of the Weibull distribution curve.

The usable wind power is estimated by calculating the area between the wind speed distribution and the characteristics of the turbine usually given by the manufacturer [5/12]. This area is equal to the sum of two parts. The first one is located between the curve of frequencies of a wind speed up to $V_i$ (cut-in speed) and under nominal wind speed $V_n$ of the turbine. The second part is the area located between this last and the cut out wind speed $V_s$.

So the usable wind power is given by:

$$P_u = \frac{1}{2} \rho \int_{V_i}^{V_s} f(V) V^3 dV + \frac{1}{2} \rho \int_{V_n}^{V_s} f(V) dV$$

After integration, we obtain:

$$P_u = \frac{1}{2} \rho \left[ \Gamma_n \left( \left[ \frac{V_n}{C} \right]^k, 1+\frac{3}{k} \right) \Gamma_n \left( \left[ \frac{V_i}{C} \right]^k, 1+\frac{3}{k} \right) \right] V_i^3 + \frac{1}{2} \rho \Gamma_n \left[ \exp \left( -\left( \frac{V_n}{C} \right)^k \right) - \exp \left( -\left( \frac{V_s}{C} \right)^k \right) \right]$$

with

$$\Gamma_n(x, a) = \Gamma(x, a) / \Gamma(x)$$

Figure 1: Shape of the Weibull distribution curve
3. Results and Discussion

3.1. Studied sites and Annual results

For hypothetical installation of a wind machines, three sites have been chosen for this analysis, namely Tiaret Djelfa and El Bayadh located in the west high plains of the country.

Its has been chosen because ten years of a hourly measured data are available at a weather stations and approximately 25% of the houses are located in isolated sites and are not connected to the national network of power supply. The statistical treatment of wind data measured over a period of ten years gives the annual results given on table 1.

It’s show that the shape factor obtained for a three considered sites is very close, whereas the scale factors are different. With 5.56 m/s of mean wind speed and a mean available power density representing a double and 1.5 times of those calculated for Djelfa and El Bayadh, respectively, Tiaret is certainly a windest site.

Table 1. Annual Statistical Parameters at 10 m above ground level

| Station   | k   | \(c,(\text{m/s})\) | \(\overline{V},(\text{m/s})\) | \(\sigma^2\) | \(\overline{V^2}, (\text{m}^2/\text{s}^3)\) | \(P, (\text{W/m}^2)\) |
|-----------|-----|---------------------|-------------------------------|--------------|---------------------------------|-------------------|
| Tiaret    | 1.72| 6.20                | 5.52                          | 11.00        | 381.91                          | 233.92            |
| Djelfa    | 1.71| 4.36                | 3.88                          | 5.46         | 133.19                          | 81.57             |
| El Bayadh | 1.62| 5.28                | 4.73                          | 8.92         | 257.13                          | 157.49            |

3.2. Monthly Wind Speed Distribution

For the calculation of a wind energy systems and a choice of a suitable site for wind park installation, it is important to have a monthly wind speed distribution. Secondly, Weibull parameters must be converted from the measurement height to the rotor height. In our case, the rotors of the three selected machines are placed at 45 m of the ground. The monthly Weibull parameters of the three stations have been calculated and are given in table 2. These results are obtained using ten years of recent wind data, [2, 3].

Table 2. Monthly Weibull Parameters at 45 m above ground level.

|         | Tiaret | Djelfa | El Bayadh |
|---------|--------|--------|-----------|
| January | 1.81   | 1.82   | 1.84      |
| February| 1.81   | 1.85   | 1.77      |
| March   | 1.72   | 1.73   | 1.76      |
| April   | 1.87   | 1.90   | 1.83      |
| May     | 1.98   | 1.86   | 1.85      |
| June    | 1.79   | 2.26   | 1.62      |
| July    | 1.99   | 2.25   | 1.60      |
| August  | 2.45   | 1.95   | 1.52      |
| September | 2.05 | 2.05   | 1.66      |
| October | 2.17   | 1.81   | 1.74      |
| November | 2.00 | 1.89   | 1.89      |
| December| 1.86   | 1.95   | 1.71      |
| Annual  | 1.98   | 1.97   | 1.87      |

A monthly variation of the Weibull parameters show a big decrease of mean wind speed (given by \(c\) parameter) during the summer for Tiaret and Djelfa and a quasi uniformity for El Bayadh.
The monthly wind speed frequency distribution curves, for the three stations, are represented in figure 2 (considering a seasonal representative months January, April, July and October). The evolution of the monthly distribution differs from one month to another. The site of Tiaret presents a wind regime being able to reach 13 m/s in July and 21 m/s in January. A family of curves related to Djelfa show that the maximum wind speed varies from 8 m/s in July to the 16 m/s in January. Lastly, El Bayadh is characterised by a similar wind regime, during the year, with 16 m/s of maximum speed. It is noticed that, in all the cases, wind speed never reaches the cut out speed of the generators (25 m/s according to the respective technical notes of the constructors).

3.3. Usable Wind Power Density

The application is made considering three different generators which are the characteristics given on table 3. The monthly available and the usable cubic mean wind speed for the three sites, are represented in figure 2. The histograms of figure 2 show that a 600 and 850 kW wind turbines have practically identical power densities and which clearly higher than that obtained by 100 kW turbine.

According to the local needs, one will choose a 600 kW or 850 kW wind machine, since the two generators differ only by their respective rotor diameters.

For El Bayadh, one notices that the useful output uniform during a year. For Djelfa and Tiaret, the figures 3 show a clear decrease of the usable wind power densities during the summer. So, the choice of a wind machine will be done according to the winter mean usable power density.
Table 3. Characteristics of wind machine

| Nominal output, kW | $V_i$(m/s) | $V_r$(m/s) | $V_s$(m/s) | $D_r$(m) |
|-------------------|------------|------------|------------|----------|
| 100               | 3.5        | 8          | 25         | 36       |
| 600               | 3          | 15         | 25         | 44       |
| 850               | 4          | 16         | 25         | 52       |

3.4. Wind machine parameters effect

The effect of the wind speed cut in (due to the inertia of the wind machine) is shown in figure 4. In the same way, the effect of the rated wind speed of the machine (i.e. the limit after which the increase of wind speed has no effect on the wind machine power delivery) is shown in figure 5. We notice from the two figures that a rated wind speed effect is more significant and strongly depending on the considered site.

This result shows the importance of the choice of the wind machine according to the considered site.

4. Conclusion

The theoretical results obtained, for a real wind machines, show that there are great differences between the usable and useful power densities. In addition, this analysis has confirmed that, for a given site, a good choice of a wind machine require a monthly simulation of a useful power density.
In the same way, to maximise the usable energy ratio we have to choose a wind machine with a cut speed as reduced as possible. This is very important since the wind potential of the country is relatively modest. As illustrated in figures 4 and 5, a bad choice of a wind machine involves automatically an oversizing machine.

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