# Wind Energy Potential of Jordan

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***Abstract*** *- The daily mean wind speed data for 5 locations in Jordan over a period of 9 years are collected and analyzed. Data are fitted to the Weibull distribution function. Weibull parameters are derived from the cumulative function of the observed data records (1989-1997), and used to calculate the mean wind speed and variance of the theoretical distribution. The goodness of representing the observed distribution with the Weibull distribution is determined using the Kolmogorov-Smirnov (K-S) test. At the 1% and 5% levels of confidence the observed data are well represented by the Weibull distribution. The annual mean values of the wind speed of the observed and theoretical distributions are 6.10ms$^{-1}$ and 6.26ms$^{-1}$ for Ras.Monief, 4.79ms$^{-1}$ and 4.77ms$^{-1}$ for Aqaba, 3.07ms$^{-1}$ and 3.15ms$^{-1}$ for Amman and 3.09ms$^{-1}$ and 3.13ms$^{-1}$ for Irbid and 2.34ms$^{-1}$ and 2.40ms$^{-1}$ for Der Alla respectively. Based on the annual wind speed, wind resource for Ras.Monief, Aqaba, Amman, Irbid and Der Alla are varied from very good to poor. The annual mean power density of Ras.Monief, Aqaba, Amman, Irbid and Der Alla are 261.76 Wm$^{-2}$, 118.95 Wm$^{-2}$, 57.45 Wm$^{-2}$, 40.95 Wm$^{-2}$, and 24.97 Wm$^{-2}$ respectively. Values of the power density obtained from the manufacturer's power distribution curve of a 300MW wind turbine at a hub height of 10 meters are also given for comparison. The result of the analysis showed that only Ras.Monief and Aqaba have good wind energy potential.*

***Keywords*** **- Wind speed, Weibull distribution, Kolmogorov-Smirnov test, Power density, Wind energy potential.**

## 1. INTRODUCTION

Wind is an air motion caused by the rotation of the earth and the heating of the atmosphere by the sun. The total kinetic energy of air movement in the atmosphere is estimated to be about 3x10 $^5$ W h or about 0.2% of the solar energy reaching the earth [1].

The maximum technically usable potential is estimated to be theoretically 30 trillion KWh per year or about 35% of the current world total energy consumption, [2]. Since the surface of the earth is neither flat nor homogeneous, the amount of heat energy that is absorbed varies spatially as well as temporally. Consequently, this creates temperature, pressure and density (specific mass) differences, which, in turn, create forces that enable air to move from one place to another. It is evident that, depending on the surface feature (morphology) of the earth, some areas would be preferable to others for extracting kinetic energy from the wind in the boundary layer of the atmosphere. Thus, wind energy can be used for many processes, such as powering, windmill, pumping water, and sailing boat. Also, wind energy is very clean but is not persistent for a long duration. Since wind energy is renewable and environmentally benign, it has the advantage of being harnessed on local basis for applications in rural areas and remote areas. Water pumping for agriculture and plantations is probably the most important application that contributes to the rural development through multiple cropping. Wind driven electric generators could be utilized as an independent power source and for purposes of augmenting the electricity supply from grids, decentralized production of electricity would help local industries.

Wind cannot be transported and therefore, wind turbines must be located where wind resources are present. The energy content of the wind being related to the cube of the wind speed varies significantly with only small changes in wind speed. The annual wind speed at a location is useful as an initial indicator of the value of the wind resources. The relation between the annual mean wind speed and the potential value of the wind energy resources is given in Table 1 [1].

**Table 1. Significant of wind energy according to speed**

| Annual mean wind speed at 10m Ht | Index value of wind resource |
|---|---|
| Below 4.5 (ms$^{-1}$) | Poor |
| 4.5 - 5.4 (ms$^{-1}$) | Marginal |
| 5.4 - 6.7 (ms$^{-1}$) | Good to very good |
| Above 6.7 (ms$^{-1}$) | Exceptional |

Theoretically, the relation between wind power density (Wm$^{-2}$) and the wind speed is

$$P = \frac{1}{2}\rho v^3 \tag{1}$$

where ρ is the air density which is a function of the air pressure B and the air temperature T [3]. This is given as,

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$$\rho = \rho_o \left( \frac{288\ B}{760T} \right) \quad (2)$$

where $\rho_o$ is the density of dry air at standard temperature and pressure (1.226kgm$^{-3}$ at 288K, 760mm Hg). In this work $\rho$ is taken to be 1.22 kgm$^{-3}$ [4].

In locations where data are not available, a qualitative indication of a high annual mean wind speed can be inferred from geographical locations, topographical features, wind induced soil erosion, and deformation of vegetation. The standard height according to the World Meteorological Organization (1964) is 10 m above the ground. This height is adopted in our analysis. In this paper an evaluation of wind energy in Jordan from climatic daily data is made. The stations and duration of records are described in Table 2.

**Table 2. Geographical locations of Jordan and duration of records of data**

| Station | Latitude (N) | | Longitude (E) | | Elevation | Duration of Records |
|---|---|---|---|---|---|---|
| | Deg | Min | Deg | Min | Meters | |
| Amman | 31 | 59 | 35 | 59 | 772.0 | 1989-1997 |
| Aqaba | 29 | 33 | 35 | 00 | 51.0 | 1989-1997 |
| Der Alla | 31 | 13 | 35 | 37 | -224 | 1989-1997 |
| Irbid | 32 | 33 | 35 | 51 | 616 | 1989-1997 |
| RasMonief | 32 | 22 | 35 | 45 | 1150 | 1989-1997 |

Different distribution functions have been suggested to represent wind speed data including the Pearson function by [5], Chi-Square function by [6], Weibull function by [7], and [8], Rayleigh function ( which is a special case of Weibull distribution) by [9], and Johnson function by [10]. Among these, Weibull distribution is the most commonly used in application because it can represent well the wind data. However, we note that the Rayleigh distribution is a special case of the Weibull distribution.

During the year 1983, an inventory and processing of available wind data was made and it was the first assessment of the wind energy potential in the country. Data collected over a ten year period from the meteorological stations were corrected first and then the estimated frequency distribution and the theoretical power outputs were calculated accordingly [11]. The study concluded that most of Jordan regions, excluding the Jordan Valley have moderate wind theoretical power of 150 to 250 W/m$^2$, which is suitable for water pumping, while there is one region in the northern part of the country having a wind theoretical power of 980 W/m$^2$ which is excellent for power production. All the values are calculated at a height of 10m. However the study also concluded that for an accurate assessment of the performance of wind systems, automatic weather stations recording data on temporal and spatial basis would be needed. In 1984, wind speed data loggers were installed for continuous recording at Ras.Monief, Shomery, Rwaished, and Dieseh.

Reference [4] analyzed wind speed data from eleven stations. Monthly average and seasonal wind speed, and average power density distributions were determined for each station. The monthly average wind speed for the two most potential sites Ras.Monief and Mafraq ranged from 3.0ms$^{-1}$ to 7.4 ms$^{-1}$ and the average power density for these two sites ranged from 110 to 370 Wm$^{-2}$ at Ras.Monief and from 105 to 470 Wm$^{-2}$ at Mafraq.

## 2. WEIBULL DISTRIBUTION

The calculation of the output of a wind machine at a particular site requires knowledge of the distribution of the wind speed. Most attention has been focused on the Weibull function, since this fitted well the experimental data. Analysis showed that the result of the wind speed (v) could be represented by cumulative distribution function T(v) using the Weibull form as follows, [12,13],

$$T(v) = 1 - \exp\left[ -\left( \frac{v}{c} \right)^k \right] \quad (3)$$

where c (scale factor), k (shape factor), are the parameters chosen to fit the data.

The probability density function f(v) is

$$f(v) = \left( \frac{k}{c} \right)\left( \frac{v}{c} \right)^{k-1} \exp\left[ -\left( \frac{v}{c} \right)^k \right] \quad k\rangle 0, c\rangle 0 \quad (4)$$

Equation (3) is equivalent to,

$$\ln\{-\ln[1 - T(v)]\} = k \ln v - k \ln c \quad (5)$$

which is of the form Y = a X + b. By plotting different values of ln [- ln (1 - T(v))] vs ln v, a straight line is fitted to the points. The slope of the line is k and the intercept on the ln [-ln (1 - T(v))] axis is [- k ln c]. Higher value of c indicates that the wind speed for the particular month is higher than the other month. In addition, the value of k indicates wind stability. One useful check of the validity of the representation of wind speed distribution is obtained by comparing the mean speed calculated from the distribution with those calculated directly from the data. The first and second moments of probability density function f (v) in terms of c, k [14] are:

$$v_w = c\,\Gamma\left( 1 + \frac{1}{k} \right) \quad (6)$$

$$\sigma^2 = c^2 \left\{ \Gamma\left( 1 + \frac{2}{k} \right) - \left[ \Gamma\left( 1 + \frac{1}{k} \right) \right]^2 \right\} \quad (7)$$

where $v_w$ is the mean Weibull wind speed, $\sigma_w^2$ are the Weibull variance of the wind speed, and $\Gamma$ is the gamma function.

Equation 1 shows the power as a function of the cube of the wind speed. At this point an important aspect must be examined. Using the annual or monthly mean wind speed value v, whether actual or derived from a Weibull fit, will not yield the right picture as far as the power density is concerned. The wind varies over time; hence wind speeds are distributed over the low and high wind speed ranges.

This illustrates that the average of the cube of many different wind speeds will be much greater than the cube of the average speed as shown in table 3 [15]. Hence one must introduce another parameter known as the Energy Pattern Factor [E.P.F] or Cube Factor [16], which adjusts the mean power density in eq. (1) by introducing a correcting factor. This factor is known as the E.P.F and can be deduced from the following:

$$\text{EPF} = \frac{\text{Total amount of power available in the wind}}{\text{Power calculated by cubing the mean wind speed}}$$

or

$$\text{EPF} = \frac{\text{Mean power density for the month}}{\text{Mean power density at the monthly mean}}$$

A more realistic monthly mean power density is then given as,

$$P = \frac{1}{2}\rho(\text{EPF})v^3 \tag{8}$$

In this work, the Weibull monthly mean wind speed $v_w$ is used to calculate the monthly mean power density of eq. (8).

## 3. TEST OF GOODNESS OF FIT

To determine the goodness of fit, it is necessary to introduce a formal statistical test that enable observed frequency distribution to be compared with the theoretical frequency distribution. Kolmogorov Simrnov (K-S) test is based on the maximum difference between an empirical and a theoretical frequency cumulative distribution. Thus

$$D = \max\ |O(v) - T(v)| \tag{9}$$

where O(v) is the value of the empirical cumulative frequency distribution evaluated at v and T(v) is the corresponding theoretical cumulative frequency distribution function. If the value of v does not exceed the critical value at a particular significance level, one can accept the null hypothesis (that there is no difference between the observed and theoretical values). The critical value of D at 5% and 1% significance level can be estimated as follows [17],

$$Q_{0.05} = \frac{1.36}{N^{\frac{1}{2}}} \tag{10}$$

$$Q_{0.01} = \frac{1.63}{N^{\frac{1}{2}}} \tag{11}$$

where N is the sample size, (N > 30). The K-S test was applied according to stations and months as shown in Tables 3-7.

## 4. RESULTS AND DISCUSSIONS

Wind data from five stations in Jordan over a period of 9 years are collected and analyzed. Information about these locations is given in Table 2. Weibull parameters are derived from graphical plot of eq. (5). The Weibull mean speed and variance are calculated using eqs. (6) and (7). The monthly mean power density of the wind is evaluated using eq. (8).

Wind speed distribution can be fitted to a mathematical model whereby certain characteristics of the wind regime can be determined. Such a model is the Weibull distribution. In Tables 3-7, the observed monthly average wind speed, Weibull wind speed, the observed and simulated (Weibull) variance of wind speed, cube of the mean wind speed, mean of the cube of wind speed, EPF, the Weibull parameters (c, and k) and K-S test are given for all stations. Also given are the annual mean values of all these quantities.

The Weibull distribution model gives a good fit to the observed monthly wind speed data. The goodness of fit is tested using the K-S test. In Aqaba, Irbid, and Dier Alla, Weibull distribution passes the K-S test at 5% significant level as shown in tables 3-5. In Ras Monief, it passed the test in all months at 5% significant level except in March, May, and September at 1% significant level as shown in Table 6. In Amman it passed the test in all months at 5% significant except in August at 1% significant level as shown in Table 7.

**Table 3. The main characteristics parameters of Aqaba wind speed**

| Aqaba | $v_{obs}$ $ms^{-1}$ | $v_w$ $ms^{-1}$ | $\sigma_{obs}^2$ | $\sigma_w^2$ | $v^3_{avg}$ obs | $(v_{avg})^3$ obs | EPF | c $ms^{-1}$ | k | K-S Test |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 3.51 | 3.39 | 3.99 | 3.77 | 87.72 | 43.14 | 2.03 | 3.81 | 1.81 | 0.06 |
| Feb | 3.66 | 3.60 | 5.04 | 4.98 | 110.03 | 49.01 | 2.24 | 4.03 | 1.66 | 0.04 |
| Mar | 4.73 | 4.66 | 7.72 | 7.02 | 257.55 | 105.70 | 2.44 | 5.24 | 1.82 | 0.03 |
| Apr | 5.38 | 5.49 | 6.09 | 5.30 | 259.44 | 155.78 | 1.67 | 6.18 | 2.56 | 0.06 |
| May | 5.75 | 5.68 | 5.29 | 5.29 | 281.69 | 189.83 | 1.48 | 6.39 | 2.66 | 0.04 |
| Jun | 6.26 | 6.26 | 5.85 | 7.07 | 355.18 | 245.81 | 1.44 | 7.05 | 2.52 | 0.03 |
| Jul | 5.00 | 4.98 | 4.31 | 4.62 | 193.05 | 125.18 | 1.54 | 5.62 | 2.48 | 0.03 |
| Aug | 5.48 | 5.49 | 3.93 | 3.92 | 230.07 | 164.18 | 1.40 | 6.15 | 3.03 | 0.03 |
| Sept | 6.02 | 6.11 | 4.61 | 5.05 | 303.85 | 217.97 | 1.39 | 6.85 | 2.96 | 0.05 |
| Oct | 4.36 | 4.38 | 4.40 | 5.07 | 142.86 | 83.10 | 1.72 | 4.94 | 2.04 | 0.05 |
| Nov | 3.75 | 3.80 | 4.70 | 4.76 | 112.13 | 52.87 | 2.12 | 4.27 | 1.80 | 0.03 |
| Dec | 3.56 | 3.44 | 4.15 | 3.89 | 91.35 | 44.93 | 2.03 | 3.87 | 1.80 | 0.06 |
| Annual | 4.79 | 4.77 | 5.01 | 5.06 | 202.08 | 123.13 | 1.79 | 5.37 | 2.26 | 0.04 |

**Table 4. The main characteristics parameters of Irbid wind speed**

| Irbid | $v_{obs}$ $ms^{-1}$ | $v_w$ $ms^{-1}$ | $\sigma_{obs}^2$ | $\sigma_w^2$ | $v^3_{avg}$ obs | $(v_{avg})^3$ obs | EPF | c $ms^{-1}$ | k | K-S Test |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 2.80 | 2.83 | 3.60 | 3.64 | 57.91 | 22.05 | 2.63 | 3.13 | 1.51 | 0.03 |
| Feb | 2.98 | 3.03 | 4.16 | 3.97 | 71.88 | 26.57 | 2.71 | 3.37 | 1.55 | 0.02 |
| Mar | 3.06 | 3.17 | 3.59 | 3.62 | 68.99 | 28.66 | 2.41 | 3.56 | 1.72 | 0.04 |
| Apr | 2.91 | 2.94 | 2.75 | 2.63 | 51.23 | 24.52 | 2.09 | 3.31 | 1.88 | 0.03 |
| May | 3.09 | 3.18 | 2.47 | 2.24 | 54.76 | 29.59 | 1.85 | 3.59 | 2.25 | 0.05 |
| Jun | 3.78 | 3.75 | 1.90 | 1.60 | 75.62 | 54.07 | 1.40 | 4.18 | 3.26 | 0.04 |
| Jul | 4.48 | 4.46 | 1.94 | 2.14 | 115.73 | 89.64 | 1.29 | 4.97 | 3.36 | 0.02 |
| Aug | 3.89 | 3.92 | 1.76 | 1.69 | 97.76 | 59.02 | 1.66 | 4.37 | 3.32 | 0.03 |
| Sept | 2.99 | 3.02 | 1.96 | 1.85 | 45.61 | 26.62 | 1.71 | 3.41 | 2.36 | 0.02 |
| Oct | 2.00 | 2.08 | 1.69 | 1.64 | 20.16 | 8.05 | 2.51 | 2.33 | 1.67 | 0.05 |
| Nov | 2.55 | 2.59 | 3.41 | 3.12 | 48.44 | 16.66 | 2.91 | 2.87 | 1.49 | 0.01 |
| Dec | 2.57 | 2.57 | 3.75 | 3.69 | 53.29 | 16.91 | 3.15 | 2.81 | 1.35 | 0.03 |
| Annual | 3.09 | 3.13 | 2.75 | 2.65 | 63.45 | 33.53 | 2.19 | 3.49 | 2.14 | 0.03 |

**Table 5. The main characteristics parameters of D.Alla wind speed**

| D.Alla | $v_{obs}$ $ms^{-1}$ | $v_w$ $ms^{-1}$ | $\sigma_{obs}^2$ | $\sigma_w^2$ | $v^3_{avg}$ obs | $(v_{avg})^3$ obs | EPF | c $ms^{-1}$ | k | K-S Test |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 2.78 | 2.84 | 7.34 | 7.40 | 107.16 | 21.46 | 4.99 | 2.90 | 1.05 | 0.03 |
| Feb | 2.32 | 2.37 | 3.70 | 3.51 | 46.10 | 12.47 | 3.70 | 2.55 | 1.27 | 0.02 |
| Mar | 2.33 | 2.47 | 3.62 | 3.76 | 47.59 | 12.59 | 3.78 | 2.66 | 1.28 | 0.03 |
| Apr | 2.66 | 2.87 | 2.04 | 2.29 | 37.93 | 18.81 | 2.02 | 3.24 | 1.98 | 0.06 |
| May | 2.51 | 2.51 | 1.63 | 1.53 | 29.01 | 15.83 | 1.83 | 2.83 | 2.13 | 0.01 |
| Jun | 2.00 | 2.04 | 1.09 | 1.06 | 15.02 | 7.94 | 1.89 | 2.30 | 2.07 | 0.01 |
| Jul | 1.81 | 1.91 | 1.08 | 1.03 | 12.39 | 5.97 | 2.07 | 2.16 | 1.96 | 0.01 |
| Aug | 1.57 | 1.61 | 0.93 | 0.89 | 8.76 | 3.84 | 2.28 | 1.80 | 1.76 | 0.01 |
| Sept | 1.66 | 1.75 | 1.10 | 1.05 | 10.97 | 4.61 | 2.38 | 1.97 | 1.77 | 0.03 |
| Oct | 2.17 | 2.22 | 2.93 | 2.80 | 34.31 | 10.18 | 3.37 | 2.42 | 1.34 | 0.02 |
| Nov | 3.29 | 3.24 | 5.93 | 5.42 | 104.21 | 35.63 | 2.92 | 3.56 | 1.41 | 0.06 |
| Dec | 2.96 | 3.00 | 6.96 | 6.41 | 108.90 | 25.94 | 4.20 | 3.18 | 1.19 | 0.03 |
| Annual | 2.34 | 2.40 | 3.19 | 3.10 | 46.86 | 14.61 | 2.95 | 2.63 | 1.60 | 0.03 |

**Table 6. The main characteristics parameters of R. Monief wind speed**

| R.Monief | $v_{obs}$ $ms^{-1}$ | $v_w$ $ms^{-1}$ | $\sigma_{obs}^2$ | $\sigma_w^2$ | $v^3_{avg}$ obs | $(v_{avg})^3$ obs | EPF | c $ms^{-1}$ | k | K-S Test |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 6.58 | 6.56 | 12.22 | 13.08 | 553.14 | 284.84 | 1.94 | 7.39 | 1.89 | 0.04 |
| Feb | 6.82 | 6.76 | 13.89 | 14.09 | 626.29 | 316.70 | 1.98 | 7.62 | 1.87 | 0.05 |
| Mar | 6.77 | 7.18 | 12.69 | 10.77 | 599.03 | 310.37 | 1.93 | 8.10 | 2.32 | 0.098* |
| Apr | 5.93 | 6.17 | 9.39 | 8.30 | 394.45 | 208.25 | 1.89 | 6.96 | 2.27 | 0.06 |
| May | 5.55 | 5.85 | 6.54 | 6.90 | 296.49 | 171.27 | 1.73 | 6.60 | 2.37 | 0.087* |
| Jun | 6.17 | 6.49 | 5.46 | 5.31 | 342.54 | 234.66 | 1.46 | 7.25 | 3.08 | 0.07 |
| Jul | 6.82 | 6.95 | 4.33 | 4.56 | 407.65 | 317.55 | 1.28 | 7.71 | 3.62 | 0.06 |
| Aug | 6.19 | 6.22 | 4.58 | 4.76 | 325.67 | 237.53 | 1.37 | 6.95 | 3.12 | 0.04 |
| Sept | 5.12 | 5.49 | 5.14 | 4.65 | 221.23 | 134.34 | 1.65 | 6.17 | 2.75 | 0.095* |
| Oct | 4.69 | 4.83 | 5.00 | 5.02 | 181.49 | 103.42 | 1.75 | 5.46 | 2.29 | 0.05 |
| Nov | 6.42 | 6.46 | 10.39 | 10.42 | 479.67 | 264.76 | 1.81 | 7.29 | 2.10 | 0.02 |
| Dec | 6.19 | 6.14 | 13.49 | 12.94 | 522.09 | 236.81 | 2.20 | 6.89 | 1.76 | 0.02 |
| Annual | 6.10 | 6.26 | 8.92 | 8.40 | 412.48 | 235.04 | 1.75 | 7.03 | 2.45 | 0.05 |

**Significant at 1% level.*

**Table 7. The main characteristics parameters of Amman wind speed**

| Amman | $v_{obs}$ $ms^{-1}$ | $v_w$ $ms^{-1}$ | $\sigma_{obs}^2$ | $\sigma_w^2$ | $v^3_{avg}$ obs | $(v_{avg})^3$ obs | EPF | c $ms^{-1}$ | k | K-S Test |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 3.00 | 3.00 | 5.41 | 5.65 | 91.24 | 26.94 | 3.39 | 3.24 | 1.27 | 0.02 |
| Feb | 3.58 | 3.59 | 7.40 | 7.24 | 152.93 | 45.99 | 3.33 | 3.91 | 1.35 | 0.02 |
| Mar | 3.43 | 3.42 | 5.54 | 5.31 | 107.63 | 40.49 | 2.66 | 3.79 | 1.51 | 0.04 |
| Apr | 3.09 | 3.14 | 4.88 | 4.80 | 86.18 | 29.49 | 2.92 | 3.46 | 1.45 | 0.03 |
| May | 3.17 | 3.36 | 3.26 | 2.99 | 68.42 | 31.78 | 2.15 | 3.79 | 2.03 | 0.06 |
| Jun | 3.62 | 3.63 | 2.78 | 2.57 | 79.39 | 47.38 | 1.68 | 4.10 | 2.42 | 0.04 |
| Jul | 3.88 | 4.04 | 2.19 | 1.73 | 84.74 | 58.56 | 1.45 | 4.50 | 3.39 | 0.07 |
| Aug | 3.09 | 3.35 | 1.92 | 2.48 | 49.70 | 29.49 | 1.69 | 3.78 | 2.25 | 0.088* |
| Sept | 2.39 | 2.51 | 2.18 | 2.43 | 33.04 | 13.71 | 2.41 | 2.80 | 1.65 | 0.07 |
| Oct | 1.99 | 2.02 | 2.02 | 2.31 | 23.58 | 7.92 | 2.98 | 2.20 | 1.34 | 0.03 |
| Nov | 2.89 | 2.96 | 7.56 | 6.11 | 165.57 | 24.15 | 6.86 | 3.15 | 1.20 | 0.05 |
| Dec | 2.74 | 2.80 | 6.18 | 6.18 | 95.34 | 20.58 | 4.63 | 2.93 | 1.13 | 0.04 |
| Annual | 3.07 | 3.15 | 4.28 | 4.15 | 86.48 | 31.37 | 3.01 | 3.47 | 1.75 | 0.04 |

**Significant at 1% level.*

The observed and theoretical Weibull mean wind speed for R.Monief and Aqaba stations are shown in Figs. 1 and 2. From these figures it is clear that Weibull model can fit the data for the months that pass the K-S test at 5% significant level better than the months that pass the K-S test at 1% significant level.

The annual mean values of the wind speed of the observed and theoretical distributions are 6.1ms$^{-1}$ and 6.26 ms$^{-1}$ for Ras.Monief, 4.79 ms$^{-1}$ and 4.77ms$^{-1}$ for Aqaba, 3.07 ms$^{-1}$ and 3.15 ms$^{-1}$ for Amman and 3.09 ms$^{-1}$ and 3.13 ms$^{-1}$ for Irbid and 2.34 ms$^{-1}$ and 2.4ms$^{-1}$ for Der Alla respectively.

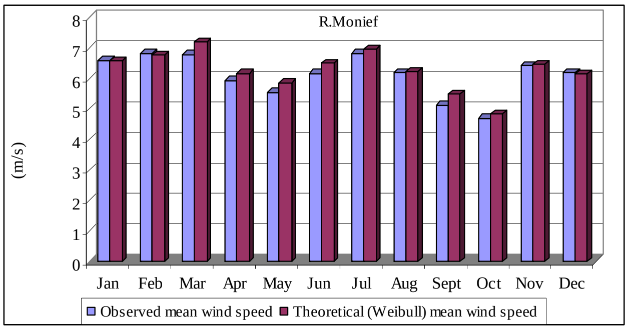


**Fig. 1. Observed and theoretical (Weibull) monthly mean wind speed for R.Monief.**

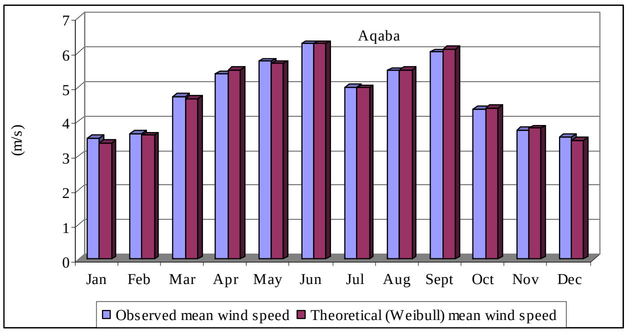


**Fig. 2. Observed and theoretical (Weibull) monthly mean wind speed for Aqaba.**

Table 8 illustrates the values of the Weibull mean wind speed over the month, season, and year. From Table 8 and Fig. 3, it can be seen that R.Monief has the highest seasonal, and annual mean wind speed followed by Aqaba, Irbid, Amman, and finally Der.Alla. For Ras.Monief, wind speed is high during all the seasons and varies from 5.59 ms$^{-1}$ in Autumn to 6.55 ms$^{-1}$ in Summer. For Aqaba, wind speed is high during Spring (5.27 ms$^{-1}$) and Summer (5.58 ms$^{-1}$) and is low during the Winter (3.48 ms$^{-1}$) and Autumn (4.76 ms$^{-1}$). For Amman, Irbid and Der Alla, in all seasons wind speed is less than *4* ms$^{-1}$ except in summer for Irbid which is *4.04* ms$^{-1}$. According to annual wind speed shown in Table 1, wind resource for Ras. Monief, Aqaba, Amman, Irbid and Der Alla are varied from very good to poor.

**Table 8: Monthly, seasonally, and annual (Weibull) mean wind speed (ms$^{-1}$) of all locations**

| Month | R.Monief | Aqaba | Amman | Irbid | D.Alla |
|---|---|---|---|---|---|
| Jan | 6.56 | 3.39 | 3.00 | 2.83 | 2.84 |
| Feb | 6.76 | 3.60 | 3.59 | 3.03 | 2.37 |
| Mar | 7.18 | 4.66 | 3.42 | 3.17 | 2.47 |
| Apr | 6.17 | 5.49 | 3.14 | 2.94 | 2.87 |
| May | 5.85 | 5.68 | 3.36 | 3.18 | 2.51 |
| Jun | 6.49 | 6.26 | 3.63 | 3.75 | 2.04 |
| Jul | 6.95 | 4.98 | 4.04 | 4.46 | 1.91 |
| Aug | 6.22 | 5.49 | 3.35 | 3.92 | 1.61 |
| Sep | 5.49 | 6.11 | 2.51 | 3.02 | 1.75 |
| Oct | 4.83 | 4.38 | 2.02 | 2.08 | 2.22 |
| Nov | 6.46 | 3.80 | 2.96 | 2.59 | 3.24 |
| Dec | 6.14 | 3.44 | 2.80 | 2.57 | 3.00 |
| Winter | 6.49 | 3.48 | 3.13 | 2.81 | 2.74 |
| Spring | 6.40 | 5.27 | 3.30 | 3.10 | 2.62 |
| Summer | 6.55 | 5.58 | 3.67 | 4.04 | 1.85 |
| Autumn | 5.59 | 4.76 | 2.50 | 2.57 | 2.40 |
| Annual | 6.26 | 4.77 | 3.15 | 3.13 | 2.40 |

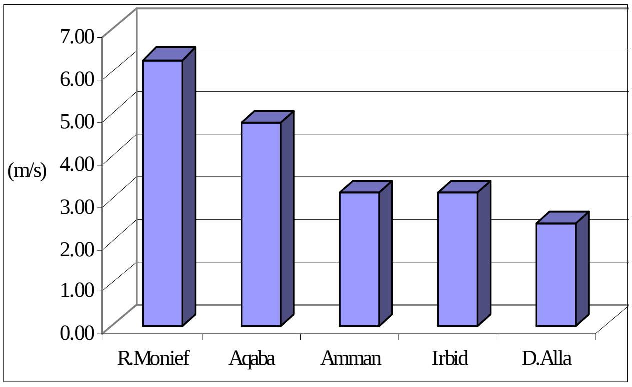


**Fig. 3. Annual Weibull mean wind speed of locations of Jordan.**

The concept of E.P.F is useful in calculating the available energy in the wind along with the knowledge of the annual or monthly wind speed. It is also useful while choosing a location with limited wind data, because long-term data from neighboring sites can be correlated with one-site short-term measurements. The annual mean values of E.P.F for Ras.Monief, Aqaba, Amman, Irbid, and Dier.Alla are 1.75, 1.79, 3.01, 2.19, and 2.95 respectively as given in tables 3-5.

Table 9 illustrates the values of the theoretical (Weibull) mean power density available during the month, season, and year. The monthly mean wind power density varies from 120.98Wm$^{-2}$ in October to 435.57 Wm$^{-2}$ in March for Ras.Monief; and from 48.34Wm$^{-2}$ in January to 215.81 Wm$^{-2}$ in June for Aqaba. For Amman, Irbid and Der Alla, monthly mean wind power density varies from 5.77 Wm$^{-2}$ to 108.82 Wm$^{-2}$. Ras.Monief has seasonal mean wind power density varies from 195.03Wm$^{-2}$ in autumn to 339.54 Wm$^{-2}$ in Winter. Aqaba has seasonal mean wind power density variation from 54.16Wm$^{-2}$ in Winter to 161.30 Wm$^{-2}$ in Spring. For Amman, Irbid and Der Alla, seasonal mean wind power density varies from 8.14 Wm$^{-2}$ to 70.49 Wm$^{-2}$.

In Table 9, the power density inferred from an actual turbine power curve is also given. The wind turbine chosen is of the horizontal type with a rated power of 300kW. The power curve of the wind turbine is given in Fig. 4 [18]. The wind speed is determined for a 10 m hub height. The rotor diameter is 33m giving a swept area of 875 m$^2$. As shown in Table 9, the agreement between the practical and theoretical values of the power density is satisfactory.

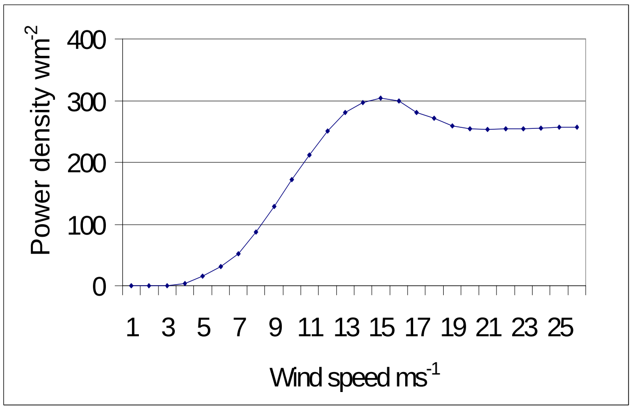


**Fig. 4. Manufacturer's power curve of a 300kW wind turbine.**

**Table 9: Monthly, seasonally, and annual mean power density Wm$^{-2}$ of all locations**

| Month | R. Monief | | Aqaba | | Amman | | Irbid | | D. Alla | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Weibull | Actual | Weibull | Actual | Weibull | Actual | Weibull | Actual | Weibull | Actual |
| Jan | 334.78 | 319.00 | 48.34 | 49.00 | 55.91 | 31.00 | 36.17 | 25.00 | 70.06 | 24.00 |
| Feb | 373.03 | 355.00 | 63.80 | 55.00 | 93.52 | 52.00 | 45.89 | 30.00 | 29.96 | 14.00 |
| Mar | 435.57 | 347.00 | 150.05 | 119.00 | 64.78 | 46.00 | 46.96 | 32.00 | 34.69 | 14.00 |
| Apr | 270.80 | 234.00 | 167.81 | 175.00 | 54.99 | 33.00 | 32.30 | 28.00 | 29.06 | 21.00 |
| May | 211.57 | 192.00 | 166.04 | 213.00 | 49.61 | 36.00 | 36.26 | 33.00 | 17.63 | 18.00 |
| Jun | 242.87 | 263.00 | 215.81 | 275.00 | 49.03 | 53.00 | 45.03 | 61.00 | 9.78 | 9.00 |
| Jul | 263.21 | 355.00 | 116.48 | 140.00 | 58.28 | 66.00 | 69.90 | 101.00 | 8.86 | 7.00 |
| Aug | 201.35 | 266.00 | 141.70 | 184.00 | 38.49 | 33.00 | 60.77 | 66.00 | 5.77 | 5.00 |
| Sep | 166.04 | 151.00 | 194.27 | 244.00 | 23.13 | 16.00 | 28.84 | 30.00 | 7.82 | 5.00 |
| Oct | 120.98 | 116.00 | 88.01 | 93.00 | 15.00 | 9.00 | 13.84 | 9.00 | 22.48 | 12.00 |
| Nov | 298.06 | 296.00 | 71.01 | 59.00 | 108.82 | 27.00 | 30.85 | 19.00 | 60.63 | 40.00 |
| Dec | 310.81 | 266.00 | 50.35 | 51.00 | 62.03 | 23.00 | 32.70 | 19.00 | 68.89 | 29.00 |
| Winter | 339.54 | 312.00 | 54.16 | 51.00 | 70.49 | 34.00 | 38.25 | 24.00 | 56.30 | 22.00 |
| Spring | 305.98 | 252.00 | 161.30 | 166.00 | 56.46 | 38.00 | 38.51 | 31.00 | 27.13 | 18.00 |
| Summer | 235.81 | 292.00 | 158.00 | 195.00 | 48.60 | 50.00 | 58.57 | 75.00 | 8.14 | 7.00 |
| Autumn | 195.03 | 178.00 | 117.77 | 117.00 | 48.98 | 16.00 | 24.51 | 18.00 | 30.31 | 15.00 |
| Annual | 261.76 | 254.00 | 118.95 | 123.00 | 57.45 | 33.00 | 40.95 | 33.00 | 24.97 | 15.00 |

As seen in Figs. 5 and 6, it is clear that the two most potential sites in this study for wind power density are Ras.Monief and Aqaba with annual power densities of 261.76 and 118.95 $Wm^{2}$ respectively, and annual wind speed of 6.26 and 4.77$ms^{-1}$ respectively.

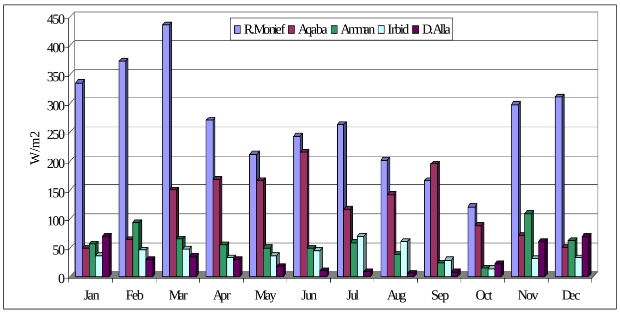


**Fig. 5. The monthly Weibull mean power density $Wm^{-2}$ of locations of Jordan.**

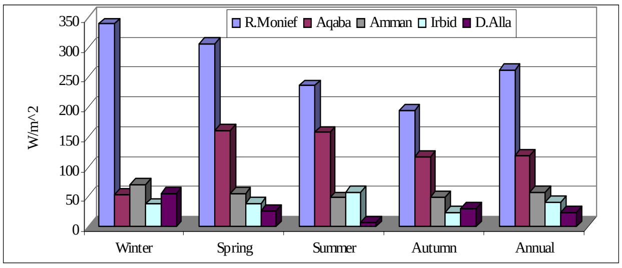


**Fig. 6. The annual and seasonal Weibull mean power density ($Wm^{-2}$) of locations of Jordan.**

The speed range over a windmill should be designed to operate the maximum wind and its structure that has to withstand depends on frequency distribution of the wind speed. Attempts have been made to fit simple distribution to the observed frequency distribution. Analysis is carried out for all sites.

**Table 10. The Annual Percentage Frequency Distribution of wind speed**

| Speed $ms^{-1}$ | RMonief (%) | Amman (%) | Aqaba (%) | Irbid (%) | D.Alla (%) |
|---|---|---|---|---|---|
| 1.0 | 1.10 | 13.05 | 4.53 | 10.37 | 21.39 |
| 2.0 | 4.10 | 21.84 | 7.48 | 20.20 | 28.63 |
| 3.0 | 8.87 | 21.39 | 12.87 | 20.41 | 22.15 |
| 4.0 | 12.29 | 15.64 | 14.94 | 18.53 | 12.75 |
| 5.0 | 13.73 | 11.71 | 15.06 | 15.70 | 6.45 |
| 6.0 | 13.18 | 7.36 | 15.24 | 8.94 | 4.23 |
| 7.0 | 13.00 | 4.47 | 11.65 | 3.68 | 1.83 |
| 8.0 | 10.67 | 1.95 | 8.61 | 1.52 | 1.03 |
| 9.0 | 6.61 | 1.13 | 4.47 | 0.40 | 0.49 |
| 10.0 | 5.72 | 0.49 | 2.98 | 0.15 | 0.52 |
| 11.0 | 3.70 | 0.49 | 1.58 | 0.09 | 0.24 |
| 12.0 | 2.72 | 0.27 | 0.43 | | 0.18 |
| 13.0 | 1.59 | 0.03 | 0.06 | | 0.09 |
| 14.0 | 1.28 | 0.09 | 0.06 | | 0.00 |
| 15.0 | 0.64 | 0.03 | 0.00 | | 0.03 |
| 16.0 | 0.40 | 0.06 | 0.00 | | |
| 17.0 | 0.18 | | 0.03 | | |
| 18.0 | 0.09 | | | | |
| 19.0 | 0.06 | | | | |
| 20.0 | 0.03 | | | | |
| 21.0 | 0.03 | | | | |
| 4-21 | 85.92 | 75.11 | 43.72 | 49.01 | 27.84 |
| 5-21 | 73.63 | 60.17 | 28.08 | 30.48 | 15.09 |
| 6-21 | 59.90 | 45.11 | 16.37 | 14.78 | 8.64 |

Table 10 lists the percentage frequency of days in the wind speed range of 1, 2, 3…21 (m/s). The distributions are based on the measurements made at the sites over the period of study using daily data. The time for which wind speed is in the range of 4 - 21 $ms^{-1}$ of the whole year are 85.92% for Ras.Monief, followed by Aqaba 75.11%, Irbid 49.00%, Amman 44.00%, and Dier.Alla 28.00%.

## 5. CONCLUSIONS

The monthly mean wind speed data of five stations in Jordan are fitted to the Weibull distribution. For Aqaba, Irbid, and Dier.Alla, the Weibull distribution passed the K-S test at 5% significant level. Ras Monief Weibull distribution passed the test for all months at 5% significant level except in March, May, and September at 1% significant level. Amman Weibull distribution passed the test for all months at 5% significant level except in August at 1% significant level. Ras Monief and Aqaba have good wind energy potential; annual wind speed of 6.26$ms^{-1}$ and 4.77$ms^{-1}$ respectively, and annual mean wind power density of 261.76$Wm^{-2}$ and 118.95$Wm^{-2}$ respectively.

Wind power density for all stations was inferred from an actual turbine power curve. The horizontal type turbine chosen has a rated power of 300kW. The rotor diameter is 33m resulting in a swept area of 875$m^2$. The power density was obtained for wind speed at a hub height of 10m. The results are found to be satisfactorily when compared to the theoretical values.

## ACKNOWLEDGEMENTS

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