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# A statistical analysis of wind speed data used in installation of wind energy conversion systems

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**Abstract**

Wind speed is the most important parameter in the design and study of wind energy conversion systems. In this study, statistical methods were used to analyze the wind speed data of Keban-Elazig in the east region of Turkey. Measured hourly time series of wind speed data were obtained from the State Meteorological Station in Keban-Elazig over a five year period from 1998 to 2002. The probability density distributions are derived from the time series data and the distributional parameters are identified. Two probability density functions are fitted to the measured probability distributions on a yearly basis.


*Keywords:* Weibull distributions; Rayleigh distributions; Weibull parameter; Wind speed data; Wind energy

## 1. Introduction

Effective utilization of wind energy entails a detailed knowledge of the wind characteristics at the particular location. The distribution of wind speeds is important for the design of wind farms, power generators and agricultural applications like irrigation. It is not an easy task to choose a site where wind energy conversion systems may be installed because many factors have to be taken into account. The most important factors are the wind speed, the energy of the wind, the generator type and a feasibility study [1]. However, wind energy is among the potential alternatives of renewable clean energy to substitute for fossil fuel based energy sources, which contaminate the lower layers of the troposphere. Because of its cleanness, wind

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## Nomenclature

| | |
|---|---|
| $A$ | area ($m^2$) |
| $c$ | Weibull scale parameter or factor (m/s) |
| $F(v)$ | cumulative distribution function |
| $f(v)$ | probability of observing wind speed |
| $h$ | height (m) |
| $k$ | Weibull shape parameter or factor in Eq. (1) (dimensionless) |
| $N$ | number of observations |
| $n$ | number of constants |
| $P$ | power of wind per unit area ($W/m^2$) |
| $P(v)$ | mean power density |
| $R$ | correlation coefficient |
| RMSE | root mean square error analysis |
| $v$ | wind speed (m/s) |
| $v_m$ | mean wind speed (m/s) |
| $v_{MP}$ | most probable wind speed (m/s) |
| $v_{\mathrm{Max}\,E}$ | wind speed carrying maximum energy (m/s) |
| $x_i$ | $i$th measured value |
| $y_i$ | $i$th calculated value |

*Greek symbols*

| | |
|---|---|
| $\rho$ | air density ($kg/m^3$) |
| $\sigma$ | standard deviations |
| $\Gamma()$ | gamma function of () |
| $\chi^2$ | chi-square |

power is sought wherever possible for conversion to electricity with the hope that air pollution will be reduced as a result of less fossil fuel burning. In some parts of the USA, up to 20% of the electrical power is generated from wind energy. In fact, after the economic crises in 1973, its importance was increased by economic limitations, and today, there are wind farms in many western European countries [2].

According to the Turkish Ministry of Energy and Natural Resources (MENR), the electric generating capacity of Turkey as of 1999 was 26,226 MWe [3]. Turkey will have to treble its installed generating capacity, to a total of 65 GWe by 2010, if Turkey's electric power consumption continues to grow at approximately 8% per year as estimated. As of 2000, electricity generation in Turkey is mainly hydroelectric (40%) and conventional thermal power plants (60%, coal, natural gas, fuel oil and Diesel powered) [3]. The current 4000 MWe gas fuelled generation capacity of Turkey will reach approximately 18,500 MWe by the year 2010 with the proposed new power plants currently under construction or in the planning stage [3]. This, however, will increase the dependency on imported natural gas, since only a tiny fraction of the natural gas consumed in Turkey is met by indigenous sources [3,4]. Turkey has to make use of its renewable resources, such as wind, solar and geothermal, not only to meet the increasing energy demand but also for environmental reasons.

Electricity generation through wind energy for general use was first realized at the Cesme Altinyunus Resort Hotel (The Golden Dolphin Hotel) in Izmir, Turkey, in 1986 with a 55 kW nominal wind power capacity [5,6]. This hotel, with 1000 beds, consumes about 3 million kW h of electrical energy annually, while the windmill installed produces 130,000 kW h per year approximately. Between 1986 and 1996, there were some attempts to generate electricity from wind, but they were never successful. In 1994, the first Build-Operate-Transfer (BOT) feasibility study for a wind energy project in Turkey was presented to the Ministry of Energy and Natural Resources of Turkey (MENR) [5,6]. Apart from the high initial investment costs in harnessing wind energy, lack of adequate knowledge on the wind speed characteristics in the country is the main reason for the failure to harvest energy from the wind. In terms of generating electricity from wind, the development of wind energy in Turkey started in 1998 when some wind plants were installed at several locations in the country. By January 1998, there were 25 applications for wind energy projects recorded at the MENR. Up to date, three wind power plants have been installed with a total capacity of about 18.9 MW [5–7]. Including the installation of a wind plant with a capacity of 1.2 MW in November 2003, the total installed capacity reached 20.1 MW. Recently, small wind turbine systems with capacities ranging from 1.5 to 5 kW have also been installed in some Turkish universities for conducting wind energy investigations as well as for lighting purposes [5–7].

In practice, it is very important to describe the variation of wind speeds for optimizing the design of the systems, resulting in less energy generating costs. The wind variation for a typical site is usually described using the so-called Weibull distribution [8,9]. In this context, over the last decade, various researchers have conducted a number of studies in order to assess wind power around the world [10–18]. Based on the studies conducted in Turkey, some researchers have performed assessments of wind power in many locations of Turkey [4,5,19–22]. In these studies, much consideration has been given to the Weibull two parameter ($k$, shape parameter, and $c$, scale parameter) function because it has been found to fit a wide collection of wind speed data. However, there is no study in the literature about wind energy conversion systems based on wind speed data for Keban-Elazig, Turkey.

The main objectives of this study are statistically to determine the wind speed data for Keban-Elazig, Turkey to be able to predict the energy output of wind energy systems.

## 2. The wind data used

In the present study, the wind speed data in hourly time series format for Keban-Elazig (38°47′N; 38° 44′E), measured between 1998 and 2002, have been statistically analyzed. The wind speed data in time series format is usually arranged in the frequency distribution format since it is more convenient for statistical analysis. The available time series data were translated into frequency distribution format. The wind speed data were recorded at a height of 10 m, continuously by a cup generator anemometer at the Keban-Elazig station of the Turkish State Meteorological Service. The continuously recorded wind speed data were averaged over 1 h periods and stored as hourly values.

In this paper, two changes on the measured and recorded data at the Keban-Elazig meteorological station were made. Firstly, monthly files were obtained for each year, with the data recorded in four columns: month, day, hour and hourly mean wind speed, because the preferred resolution of the series is 1 h. The hourly mean wind speed is the average of the 12 data corresponding to the twelve periods of 5 min that make up each hour of original data. Secondly, the lost values were also erased. Then, other data were retrieved in a spreadsheet. We used it for calculation of the parameters. The data had already been revised with an indices document in order to erase the errors that are difficult to detect. When an anemometer, obtained at the station, goes bad, either there is no data or they are incongruous. It may also happen that a damaged anemometer produces results with a value that could be true, but it is not. These data have been removed. Additionally, one year was considered as the basic unit for obtaining a set of annual parameters. We defined a complete year as having at least 90% valid data.

## 3. Theoretical analysis

### 3.1. Frequency distribution of wind speed

The wind speed probability density distributions and the functions representing them mathematically are the main tools used in the wind related literature. Their use includes a wide range of applications, from the techniques used to identify the parameters of the distribution functions to the use of such functions for analyzing the wind speed data and wind energy economics [14,15]. Two of the commonly used functions for fitting a measured wind speed probability distribution in a given location over a certain period of time are the Weibull and Rayleigh distributions. The probability density function of the Weibull distribution is given by

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

where $f(v)$ is the probability of observing wind speed $v$, $k$ is the dimensionless Weibull shape parameter (or factor) and $c$ is the Weibull scale parameter, which has a reference value in the units of wind speed.

The corresponding cumulative probability function of the Weibull distribution is given as [13,14]:

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

Determination of the parameters of the Weibull distribution requires a good fit of Eq. (2) to the recorded discrete cumulative frequency distribution. Taking the natural logarithm of both sides of Eq. (2) twice gives

$$\ln\{-\ln[1 - F(v)]\} = k\ln(v) - k\ln c \tag{3}$$

So, a plot of $\ln\{-\ln[1 - F(v)]\}$ versus $\ln v$ presents a straight line. The gradient of the line is $k$, and the intercept with the $y$-axis is $-k\ln c$.

The $k$ values range from 1.5 to 3.0 for most wind conditions. The Rayleigh distribution is a special case of the Weibull distribution in which the shape parameter is 2.0. The probability density function for the Rayleigh distribution can be simplified as

$$f(v) = \frac{2v}{c^2} \exp\left[\left(-\frac{v}{c}\right)^k\right] \tag{4}$$

The two significant parameters $k$ and $c$ are closely related to the mean value of the wind speed $v_\mathrm{m}$ as [5],

$$v_\mathrm{m} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{5}$$

where $\Gamma()$ is the gamma function of ().

As the scale and shape parameters have been calculated, two meaningful wind speeds for wind energy estimation, the most probable wind speed and the wind speed carrying maximum energy, can be easily obtained. The most probable wind speed denotes the most frequent wind speed for a given wind probability distribution and is expressed by

$$v_\mathrm{MP} = c\left(\frac{k-1}{k}\right)^{1/k} \tag{6}$$

The wind speed carrying maximum energy represents the wind speed that carries the maximum amount of wind energy and is expressed as follows [23]:

$$v_{\mathrm{Max}\,E} = c\left(\frac{k+2}{k}\right)^{1/k} \tag{7}$$

### *3.2. Wind speed variation with height*

Wind speed near the ground changes with height, which requires an equation that predicts the wind speed at one height in terms of the measured speed at another height. The most common expression for the variation of wind speed with hub height is the power law having the following form [23]:

$$\frac{v_2}{v_1} = \left\{\frac{h_2}{h_1}\right\}^m \tag{8}$$

where $v_2$ and $v_1$ are the mean wind speeds at heights $h_2$ and $h_1$, respectively. The exponent $m$ depends on such factors as surface roughness and atmospheric stability. Numerically, it lies in the range 0.05–0.5, with the most frequently adopted value being 0.14 (widely applicable to low surfaces and well exposed sites).

### *3.3. Wind power density*

It is well known that the power of the wind that flows at speed $v$ through a blade sweep area $A$ increases as the cube of its velocity and is given by [23]

$$P(v) = \frac{1}{2}\rho A v^3 \tag{9}$$

where $\rho$ is the air density for Keban-Elazig. Monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed as follows:

$$P_{\mathrm{W}} = \frac{1}{2}\rho c^3 \left(1 + \frac{3}{k}\right) \tag{10}$$

Setting $k$ equal to 2, the power density for the Rayleigh density function is found to be [3],

$$P_{\mathrm{R}} = \frac{3}{\pi}\rho v_{\mathrm{m}}^3 \tag{11}$$

However, the errors in calculating the power densities using the distributions in comparison to those using the measured probability density distributions can be found using the following equation [3]:

$$\mathrm{Error}(\%) = \frac{P_{\mathrm{W,R}} - P_{m,\mathrm{R}}}{P_{m,\mathrm{R}}} \tag{12}$$

where $P_{\mathrm{W,R}}$ is the mean power density calculated from either the Weibull or Rayleigh function used in calculation of the error and $P_{m,\mathrm{R}}$ is the wind power density for the measured probability density distribution, which serves as 'the reference mean power density'. $P_{m,\mathrm{R}}$ can be calculated from the following equation [3]:

$$P_{m,\mathrm{R}} = \sum_{j=1}^{n} \left[\frac{1}{2}\rho v_{m,j}^3 f(v_j)\right] \tag{13}$$

The yearly average error value in calculating the power density using the Weibull function is found by using the following equation

$$\mathrm{Error}(\%) = \frac{1}{12}\sum_{i=1}^{12} \left|\frac{P_{\mathrm{W,R}} - P_{m,\mathrm{R}}}{P_{m,\mathrm{R}}}\right| \tag{14}$$

### 3.4. Statistical analysis of distributions

The correlation coefficient ($R^2$), chi-square ($\chi^2$) and root mean square error analysis (RMSE) were used in statistically evaluating the performances of the Weibull and Rayleigh distributions. These parameters can be calculated as follows:

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - z_i)^2 - \sum_{i=1}^{N}(x_i - y_i)^2}{\sum_{i=1}^{N}(y_i - z_i)^2} \tag{15}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{N - n} \tag{16}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{1/2} \tag{17}$$

where $y_i$ is the $i$th actual data, $x_i$ is the $i$th predicted data with the Weibull or Rayleigh distribution, $N$ is the number of observations and $n$ is the number of constants [24]. Therefore, the best distribution function can be selected according to the highest value of $R^2$ and the lowest values of RMSE and $\chi^2$.

## 4. Results and discussion

In this study, wind speed data for Keban-Elazig, Turkey, over a five year period from 1998 to 2002 were analyzed. Based on these data, the wind speeds analyzed were processed using Statistica statistical software and Fortran computer software. The main results obtained from the present study can be summarized as follows:

Table 1
Monthly mean wind speeds and standard deviations in Keban-Elazig, Turkey, 1998–2002

| | Parameters | 1998 | 1999 | 2000 | 2001 | 2002 | Whole year |
|---|---|---|---|---|---|---|---|
| January | $v_m$ | 2.370 | 1.776 | 2.298 | 1.692 | 2.366 | 2.101 |
| | $\sigma$ | 1.314 | 0.854 | 1.199 | 0.746 | 1.115 | 1.109 |
| February | $v_m$ | 2.421 | 2.200 | 2.474 | 1.980 | 2.063 | 2.219 |
| | $\sigma$ | 1.488 | 1.474 | 1.336 | 1.228 | 1.227 | 1.344 |
| March | $v_m$ | 2.329 | 2.272 | 2.412 | 2.030 | 2.235 | 2.256 |
| | $\sigma$ | 1.455 | 1.289 | 1.370 | 1.268 | 1.372 | 1.358 |
| April | $v_m$ | 2.145 | 2.200 | 2.233 | 2.372 | 2.254 | 2.241 |
| | $\sigma$ | 1.264 | 1.146 | 1.477 | 1.385 | 1.228 | 1.307 |
| May | $v_m$ | 2.072 | 2.655 | 2.477 | 2.318 | 2.396 | 2.384 |
| | $\sigma$ | 1.129 | 1.514 | 1.282 | 1.259 | 1.192 | 1.295 |
| June | $v_m$ | 2.287 | 2.912 | 2.886 | 2.648 | 2.777 | 2.702 |
| | $\sigma$ | 1.273 | 1.728 | 1.510 | 1.422 | 1.414 | 1.493 |
| July | $v_m$ | 2.482 | 2.313 | 2.526 | 2.530 | 2.584 | 2.487 |
| | $\sigma$ | 1.228 | 1.137 | 1.141 | 1.301 | 1.437 | 1.257 |
| August | $v_m$ | 2.235 | 2.404 | 2.504 | 2.381 | 2.364 | 2.377 |
| | $\sigma$ | 1.110 | 1.221 | 1.377 | 1.152 | 1.083 | 1.196 |
| September | $v_m$ | 2.416 | 2.247 | 2.359 | 2.262 | 2.008 | 2.258 |
| | $\sigma$ | 1.334 | 1.045 | 1.214 | 1.256 | 1.041 | 1.190 |
| October | $v_m$ | 2.116 | 1.948 | 1.958 | 2.061 | 1.986 | 2.014 |
| | $\sigma$ | 1.113 | 1.008 | 1.060 | 0.998 | 1.066 | 1.051 |
| November | $v_m$ | 1.525 | 2.219 | 1.925 | 2.438 | 1.740 | 1.969 |
| | $\sigma$ | 0.790 | 1.247 | 0.898 | 1.599 | 0.839 | 1.164 |
| December | $v_m$ | 1.817 | 2.016 | 2.043 | 1.938 | 2.576 | 2.078 |
| | $\sigma$ | 1.017 | 1.157 | 1.057 | 1.046 | 1.580 | 1.215 |
| Yearly | $v_m$ | 2.184 | 2.263 | 2.340 | 2.220 | 2.283 | 2.258 |
| | $\sigma$ | 1.250 | 1.286 | 1.281 | 1.264 | 1.270 | 1.272 |

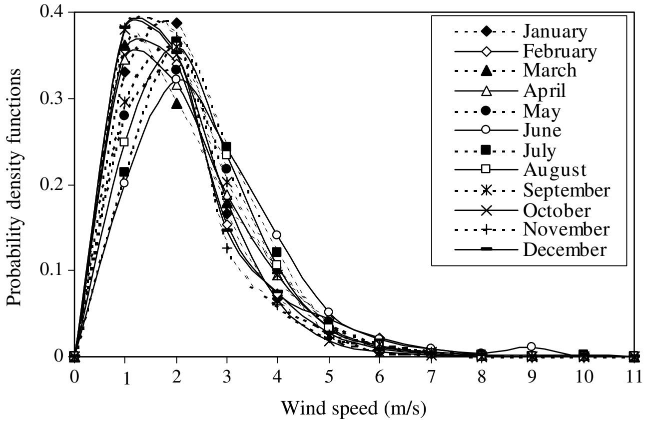


Fig. 1. Monthly wind speed probability density distributions derived from the measured hourly time series data of Keban-Elazig for whole year.

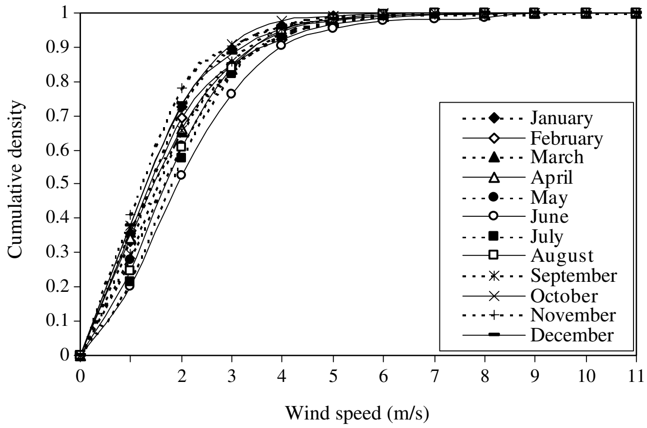


Fig. 2. Monthly wind speed cumulative probability distributions derived from the measured hourly time series data of Keban-Elazig for whole year.

The monthly mean wind speed values and the standard deviations calculated for the available time series data are presented in Table 1. It is seen in Table 1 that the highest monthly wind speeds occur in the summer months of June and July for the whole year. October and November have little wind, as indicated by the small monthly $v_m$ values of 2.014 and 1.969 m/s, respectively.

The monthly probability density and the cumulative distributions derived from the time series data of Keban-Elazig for the whole year are presented in Fig. 1 and Fig. 2, respectively. It is seen that all the curves have a similar tendency of the wind speeds for the cumulative density and probability density. The yearly probability density and cumulative distributions are seen in Fig. 3.

The monthly mean wind speeds are illustrated in Fig. 4. It is also clear from Fig. 4 that the wind speed for the whole year has the lowest value in the month of November and the maximum in the month of June, ranging from 1.969 to 2.702 m/s with an annual average of 2.258 m/s. The diurnal

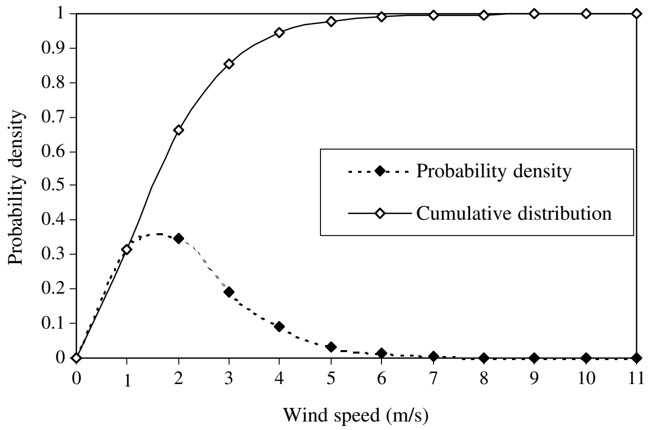


Fig. 3. Yearly wind speed probability density and cumulative probability distributions, derived from the measured hourly time series data of Keban-Elazig for whole year.

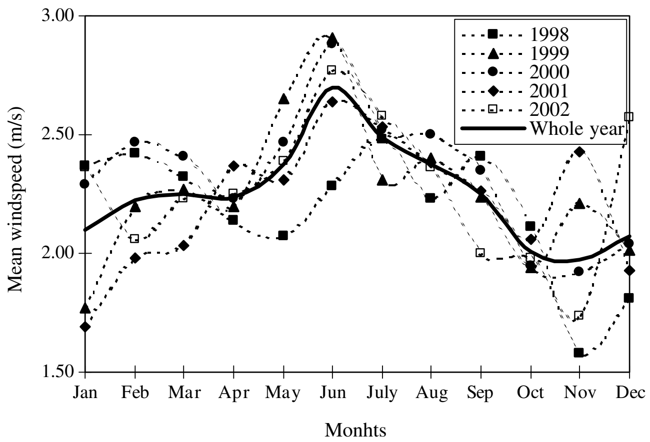


Fig. 4. Monthly mean wind speed of Keban-Elazig between 1998 and 2002 years.

variation of the wind speed at Keban-Elazig in June can be seen in Fig. 5. The diurnal wind speed has its minimum during the morning hours and maximum during the afternoon hours.

The Weibull parameters calculated analytically for the available data are presented in Table 2. It is seen from the table that while the scale parameter varies between 1.731 (November 1998) and 3.129 m/s (June 1999), the shape parameter ranges from 1.201 (November 2002) to 1.701 (February 1998) for the location analyzed. It is clear that the parameter $k$ has a much smaller variation than the parameter $c$.

In order to observe the Weibull distribution of Keban-Elazig, the Weibull probability density distributions for each of the five years were analyzed. The distributions obtained are illustrated in Fig. 6. It can be seen that the distribution is similar for a five year period and represents a narrow peak at a wind speed of around 2 m/s.

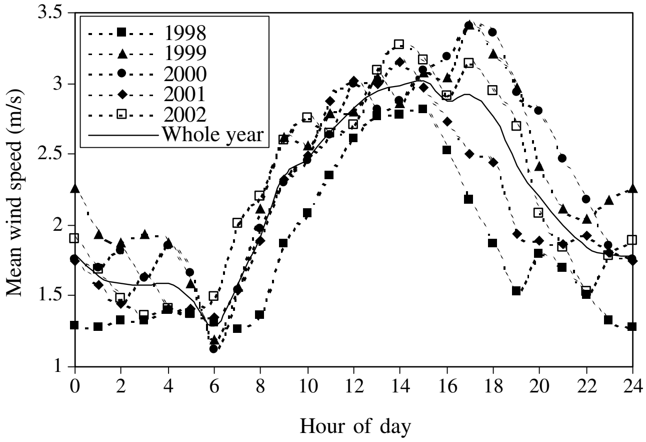


Fig. 5. Diurnal variation of wind speed in Keban-Elazig for June between 1998 and 2002 years.

For the purpose of calculating seasonal mean wind speeds, the months in each of the four seasons in the northern hemisphere are generally divided as follows: (a) winter: December, January and February; (b) spring: March, April and May; (c) summer: June, July and August and (d) autumn: September, October and November. A comparison of the seasonal Weibull probability density functions is illustrated in Fig. 7. In general, the values of the scale parameters are low during the winter and autumn and high during the summer.

The Weibull and Rayleigh approximations of the actual probability density distribution of wind speeds for the whole year are shown in Fig. 8, while a comparison of the two approximations with the actual probability distribution is given in Table 3. As can be seen in Table 3, the highest $R^2$ value was obtained by using the Weibull distribution. However, the results have shown that the RMSE and $\chi^2$ values of the Weibull distribution are lower than the values obtained by the Rayleigh distribution. As result, the Weibull approximation is found to be the most accurate distribution according to the highest value of $R^2$ and the lowest values of RMSE and $\chi^2$. Furthermore, the monthly probability density distributions obtained from the Weibull and Rayleigh distributions were compared to the measured distributions to study their suitability. The correlation coefficient values are used as the measure of goodness of fit of the probability density distributions obtained from the Weibull and Rayleigh distributions. The correlation coefficient values are presented in Fig. 9 on a monthly basis for the Keban-Elazig data. The coefficient values range from 0.9123 to 0.9531 for the Weibull distribution, while they vary between 0.6315 and 0.8693 for the Rayleigh distributions. The month to month comparison shows that the Weibull distribution returns higher coefficient values for all the months than the Rayleigh distribution, indicating a better fit to the measured probability density distributions.

The power density distributions are presented in Fig. 10. As seen in Fig. 10, these discrepancies in the probability density distributions have no effect on the wind power density, since the corresponding wind speeds are not high enough for electricity production. The most energy production is obtained at the wind speed interval of 3–4 m/s. Even though this wind speed range only makes up about 10% of the whole wind speed spectrum, over 30% of the total energy is produced

Table 2
Monthly shape parameters, $k$, and scale parameters, $c$, in Keban-Elazig, Turkey, 1998–2002

| Month | Parameters | 1998 | 1999 | 2000 | 2001 | 2002 | Whole year |
|---|---|---|---|---|---|---|---|
| January | $k$ | 1.424 | 1.452 | 1.481 | 1.212 | 1.452 | 1.281 |
| | $c$ | 2.502 | 1.928 | 2.504 | 1.807 | 2.594 | 2.236 |
| February | $k$ | 1.701 | 1.634 | 1.508 | 1.242 | 1.581 | 1.352 |
| | $c$ | 2.628 | 2.421 | 2.691 | 2.198 | 2.275 | 2.492 |
| March | $k$ | 1.621 | 1.520 | 1.680 | 1.451 | 1.487 | 1.348 |
| | $c$ | 2.528 | 2.488 | 2.628 | 2.247 | 2.461 | 2.520 |
| April | $k$ | 1.402 | 1.582 | 1.427 | 1.381 | 1.506 | 1.507 |
| | $c$ | 2.337 | 2.410 | 2.441 | 2.598 | 2.476 | 2.648 |
| May | $k$ | 1.501 | 1.301 | 1.588 | 1.401 | 1.482 | 1.447 |
| | $c$ | 2.281 | 2.872 | 2.689 | 2.531 | 2.618 | 2.648 |
| June | $k$ | 1.661 | 1.681 | 1.601 | 1.582 | 1.680 | 1.588 |
| | $c$ | 2.481 | 3.129 | 3.107 | 2.861 | 2.981 | 2.962 |
| July | $k$ | 1.301 | 1.328 | 1.204 | 1.485 | 1.402 | 1.579 |
| | $c$ | 2.701 | 2.521 | 2.738 | 2.771 | 2.783 | 2.753 |
| August | $k$ | 1.568 | 1.421 | 1.381 | 1.357 | 1.357 | 1.402 |
| | $c$ | 2.481 | 2.628 | 2.728 | 2.594 | 2.571 | 2.650 |
| September | $k$ | 1.301 | 1.281 | 1.448 | 1.249 | 1.297 | 1.568 |
| | $c$ | 2.681 | 2.438 | 2.580 | 2.479 | 2.210 | 2.521 |
| October | $k$ | 1.508 | 1.408 | 1.284 | 1.209 | 1.337 | 1.409 |
| | $c$ | 2.438 | 2.151 | 2.172 | 2.259 | 2.191 | 2.292 |
| November | $k$ | 1.309 | 1.397 | 1.391 | 1.357 | 1.201 | 1.352 |
| | $c$ | 1.731 | 2.438 | 2.138 | 2.661 | 1.968 | 2.237 |
| December | $k$ | 1.425 | 1.257 | 1.281 | 1.381 | 1.451 | 1.282 |
| | $c$ | 2.101 | 2.231 | 2.261 | 2.149 | 2.792 | 2.357 |
| Yearly | $k$ | 1.633 | 1.447 | 1.415 | 1.412 | 1.582 | 1.518 |
| | $c$ | 2.421 | 2.485 | 2.561 | 2.508 | 2.709 | 2.522 |

at this wind speed interval. Furthermore, at this wind speed interval, the time series and the model probability density distributions are very close, within 1.4%. However, even this small error in the probability density distribution leads to a much larger error in the power density distributions, as much as 15%. As seen in Fig. 10, the discrepancy between the time series and the model power density distributions is considerably large for the Rayleigh function. Even a small discrepancy in the probability density distributions for a given wind speed leads to larger errors in the corresponding power density distributions, since the wind power is dependent on the cube of the wind speed. Therefore, it is very crucial to use a probability density function that would give a good fit to the time series probability density distributions at any level of wind speed but especially at high power density wind speed levels.

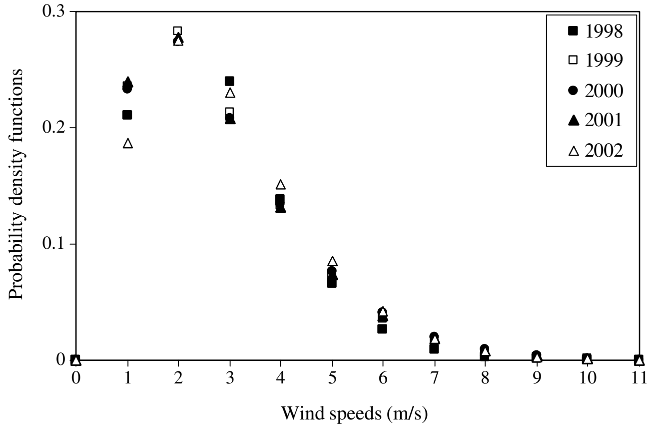


Fig. 6. Yearly Weibull probability density distributions for the period of 1998–2002 in Keban-Elazig.

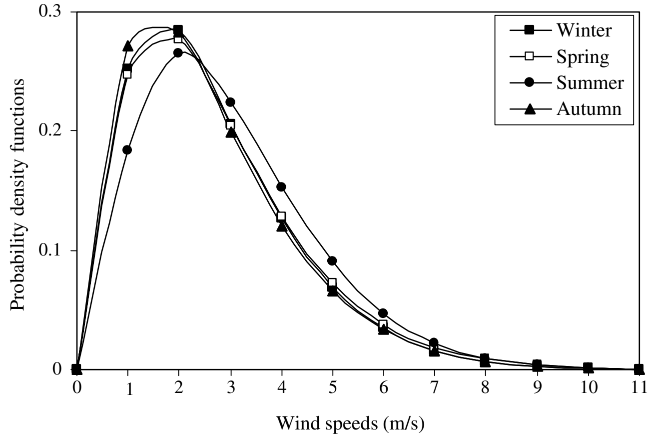


Fig. 7. A comparison of seasonal Weibull probability density function distributions in Keban-Elazig.

Fig. 11 illustrates the variation of yearly wind power density versus different hub height for the whole year, while Fig. 12 illustrates the monthly wind power density for Keban-Elazig. Fig. 11 shows that the mean wind speed and wind power density increase with the increase of hub height. Obviously, to obtain higher wind power, the higher hub heights are preferred. It is clear from Fig. 12 that in November and October, the wind power is low but is very high in June. The two curves have similar changing trends, but the rate of change is not the same. In addition, the yearly Weibull parameters, yearly wind power density and yearly mean wind speed can be obtained as shown in Table 4. It is observed that the value of wind power density is low in 1998, but it is high in 2000. Similarly, Table 5 indicates the seasonal wind power density and seasonal mean wind speed in addition to the seasonal Weibull parameters. The results show that the parameters are distinctive for the different seasons in Keban-Elazig, 1998–2002.

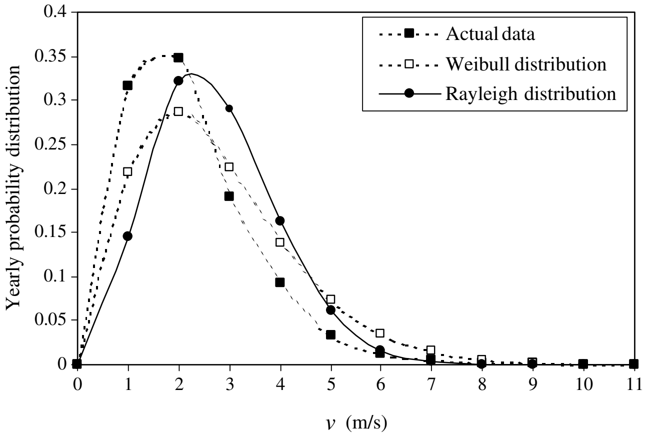


Fig. 8. Weibull and Rayleigh approximations of the actual probability distribution of wind speeds.

Table 3
Comparison of the actual probability distribution of wind speeds with Weibull and Rayleigh approximations for whole year

| $f(v)$ | | | |
|---|---|---|---|
| Wind speed (m/s) | Actual data | Weibull distribution | Rayleigh distribution |
| 1 | 0.316676 | 0.217731 | 0.145485 |
| 2 | 0.346773 | 0.287299 | 0.321328 |
| 3 | 0.190056 | 0.222828 | 0.290258 |
| 4 | 0.091959 | 0.13870 | 0.162109 |
| 5 | 0.033041 | 0.074199 | 0.061186 |
| 6 | 0.012687 | 0.035184 | 0.016151 |
| 7 | 0.004701 | 0.015054 | 0.003032 |
| 8 | 0.001711 | 0.005881 | 0.000408 |
| 9 | 0.001597 | 0.002115 | 0.003970 |
| 10 | 0.000662 | 0.000705 | 0.000028 |
| 11 | 0.000137 | 0.000219 | 0.000014 |
| $R^2$ | | 0.91370 | 0.742640 |
| RMSE | | 0.041463 | 0.064475 |
| $\chi^2$ | | 0.002101 | 0.005081 |

The power densities calculated from the measured probability density distributions and those obtained from the Weibull and Rayleigh distributions are shown in Fig. 13. The power density shows a large month to month variation. The minimum power densities occur in November and October with 9.89 and 11.59 W/m$^2$, respectively. It is interesting to note that the highest power density values occur in the summer months of June and July with the maximum value of 26.15 W/m$^2$ in June. The power densities in the remaining months are between these two groups of lows and highs. The errors in calculating the power densities using the distributions in comparison to those using the measured probability density distributions are presented in Fig. 14.

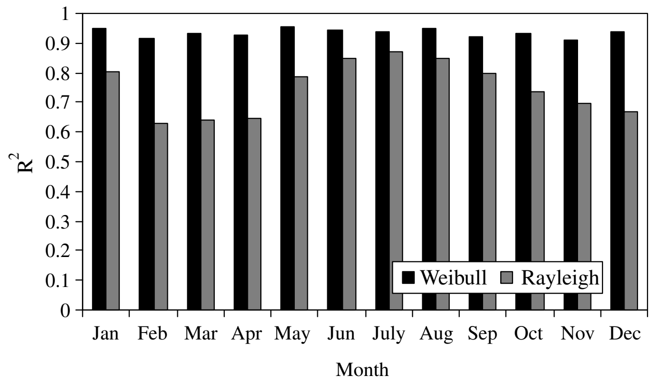


Fig. 9. Correlation coefficient values obtained in fitting the actual probability density distributions with the Weibull and Rayleigh functions.

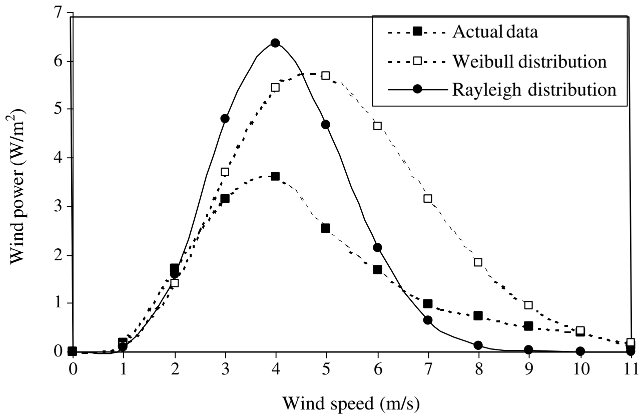


Fig. 10. Weibull and Rayleigh approximations of the actual probability distribution of wind power densities.

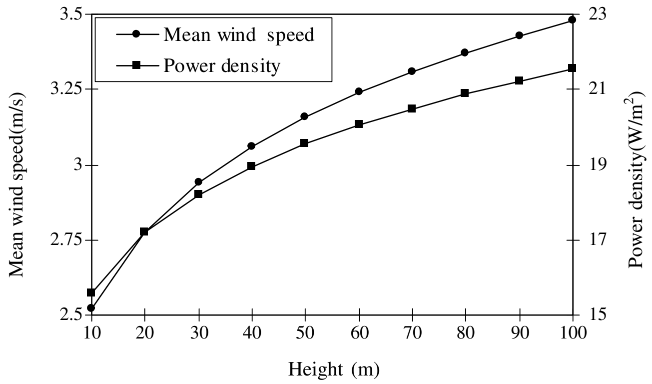


Fig. 11. Yearly power density and mean wind speed for different hub heights.

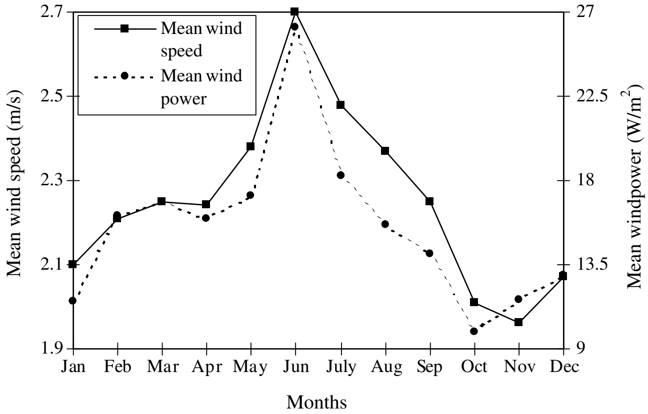


Fig. 12. Monthly wind power density and mean wind speed.

Table 4
Yearly wind characteristics in Keban-Elazig, Turkey

| Year | $v_m$ (m/s) | $k$ | $c$ (m/s) | $v_{MP}$ (m/s) | $V_{\mathrm{Max}\,E}$ (m/s) | $P$ (W/m$^2$) |
|---|---|---|---|---|---|---|
| 1998 | 2.184 | 1.633 | 2.421 | 1.355 | 3.950 | 14.366 |
| 1999 | 2.263 | 1.447 | 2.485 | 1.103 | 4.527 | 15.997 |
| 2000 | 2.340 | 1.415 | 2.561 | 1.076 | 4.773 | 16.555 |
| 2001 | 2.220 | 1.412 | 2.508 | 1.048 | 4.684 | 15.126 |
| 2002 | 2.283 | 1.582 | 2.709 | 1.439 | 4.541 | 15.922 |

Table 5
Seasonal wind characteristics in Keban-Elazig, Turkey

| Season | $v_m$ (m/s) | $k$ | $c$ (m/s) | $v_{MP}$ (m/s) | $v_{\mathrm{Max}\,E}$ (m/s) | $P$ (W/m$^2$) |
|---|---|---|---|---|---|---|
| Winter | 2.130 | 1.402 | 2.412 | 0.989 | 4.539 | 13.474 |
| Spring | 2.294 | 1.387 | 2.478 | 0.987 | 4.716 | 16.681 |
| Summer | 2.519 | 1.552 | 2.797 | 1.436 | 5.768 | 19.859 |
| Autumn | 2.080 | 1.352 | 2.356 | 0.863 | 4.572 | 11.845 |
| Whole year | 2.258 | 1.518 | 2.522 | 1.242 | 4.387 | 15.603 |

The Weibull model returns smaller error values in calculating the power density when compared to the Rayleigh model. The highest error values occur in October and November with 26.39% and 26.07% for the Weibull model, respectively. The power density is estimated by the Weibull model with a very small error value of 6.28% in April. The yearly average error value in calculating the power density using the Weibull function is 13.64%. The monthly analysis shows that the error values in calculating the power density using the Rayleigh model are relatively higher, over 25% in some months, such as November and December. Even the smallest error in

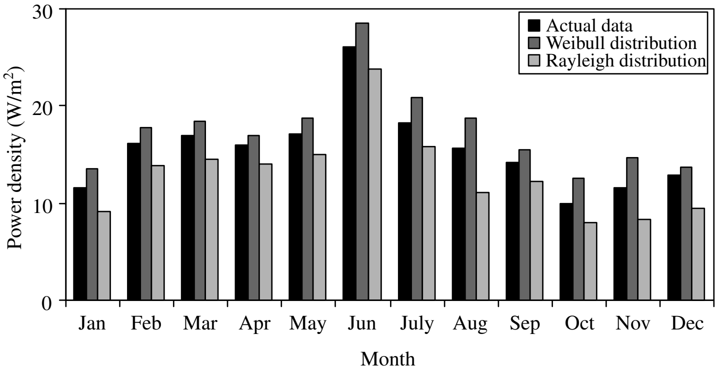


Fig. 13. Wind power density obtained from the actual data versus those obtained from the Weibull and Rayleigh models on a monthly basis.

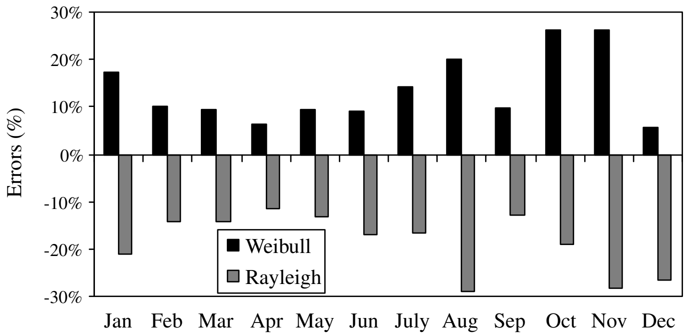


Fig. 14. Error values in calculating the wind power density obtained from the Weibull and Rayleigh models in reference to the wind power density obtained from the actual data, on monthly basis.

the power density calculation using the Rayleigh model is 11.54%. The yearly average error value in estimating the power density using the Rayleigh model is 18.60%.

## 5. Conclusions

In the present study, the hourly measured time series wind speed data of Keban-Elazig have been statistically analyzed. The probability density distributions and power density distributions have been derived from the time series data and the distributional parameters were identified. Two probability density functions have been fitted to the measured probability distributions on a monthly basis. The wind energy potential of the location has been studied based on the Weibull and the Rayleigh models. The most important outcomes of the study can be summarized as follows:

1. The Keban-Elazig station where the Turkish State Meteorological Service is located, presents poor wind characteristics. This is shown by the low monthly and yearly mean wind speed and power density values for the whole year.
2. The yearly average wind power density value is 15.603 $W/m^2$ for the whole year. Therefore, this particular site is not ideal for grid connected applications. This level of power density may be adequate for non-connected electrical and mechanical applications, such as battery charging and water pumping.
3. However, the diurnal variations of the wind speed and the wind power density may show a significant variation.
4. The Weibull distribution is better in fitting the measured monthly probability density distributions than the Rayleigh distribution for the whole year. This is shown from the monthly correlation coefficient values of the fits.
5. The Weibull distribution provided better power density estimations in all 12 months than the Rayleigh distribution.

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