



A STATISTICAL ANALYSIS OF WIND SPEED DATA AND AN ASSESSMENT OF WIND ENERGY POTENTIAL IN TAIZ-YEMEN

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ABSTRACT :

Yemen possesses a very good potential of renewable energy, such as solar and wind energy. Wind energy is an alternative clean energy source compared to fossil fuel, which pollute the lower layer of the atmosphere. In this study, statistical methods are used to analyze the wind speed data of Taiz in the southwest of Yemen. Wind speed is the most important parameter in the design and study of wind energy conversion systems. The wind speed data were obtained from the National Water Resources Information Center in Taiz (TaizNWRIC) over a four year period, 1999 to 2002. In the present study, the wind energy potential of the location is statistically analyzed based on wind speed data, measured over a period of four years. The probability distributions are derived from the wind data and their distributional parameters are identified. Two probability density functions are fitted to the measured probability distributions on a yearly basis. The wind energy potential of the location is studied based on the Weibull and the Rayleigh models.

Nomenclature:

A	Area (m²)
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
N	Number of observations
n	Number of constants
P	Power of wind per unit area (W/m²)
P (v)	Mean power density
R	Correlation coefficient
RMSE	Root mean square error
v	Wind speed (m/s)
v_m	Mean wind speed (m/s)
x_i	Ith measured value
y_i	Ith calculated value

Greek symbols:

ρ	Air density (kg/m³)
σ	Standard deviation
Γ ()	Gamma function of ()

χ^2 Chi-square

INTRODUCTION :

Increasing negative effects of fossil fuel combustion on the environment in addition to its limited stock have forced many countries to explore and change to environmentally friendly alternatives that are renewable to sustain the increasing energy demand. Changing to renewable sources and the implementation of effective conservation measures would ensure sustainability. Alternatives to conventional energy sources, especially the renewable ones, are becoming increasingly attractive because of the limited fossil fuel reserves and the adverse effects associated with their use. The renewable energy resources include solar, wind, wave, geothermal and bio-energy. All these renewable energy resources are abundant in Yemen. If these resources are well established, they can provide complete security of energy supply.

Currently, the wind energy is one of the fastest developing renewable energy source technologies across the globe. Wind energy is an alternative clean energy source compared to fossil fuel, which pollute the lower layer of the atmosphere. It has the advantage of being suitable to be used locally in rural and remote areas. The increasing demand for energy supply coupled with limited energy resources creates an urgency to find new solutions for this energy shortage.

Nowadays, wind analysis gives remarkable information to researchers involved in renewable energy studies. The use of wind energy can significantly reduce the combustion of fossil fuel and the consequent emission of carbon dioxide. Supplementing our energy base with clean and renewable sources of energy has become imperative due to the present days' energy crisis and growing environmental consciousness. Knowledge of the statistical

properties of the wind speed is essential for predicting the energy output of a wind energy conversion system. Because of the high variability in space and time of wind energy, it is important to verify that the analyzing method used for the measuring wind data will yield the estimated energy collected that is close to the actual energy collected. In recent years many efforts have been made to construct an adequate model for the wind speed frequency distribution^[1-3].

The wind speed distribution, one of the wind characteristics, is of great importance for not only for structural and environmental design and analysis, but also for the assessment of the wind energy potential and the performance of wind energy conversion system as well. Over the last two decades many researches have been devoted to develop an adequate statistical model to describe wind speed frequency distribution. The Weibull, Rayleigh and Lognormal functions are commonly used for fitting the measured wind speed probability distribution^[4].

Yemen population is about 19.5 Millions. 72.2% of the population are rurally scattered among villages. Electrification coverage percentage average is estimated to be only 20% in rural areas^[5]. The electricity is generally produced by centralized diesel generators and distributed to individual households through a local grid. This condition is a good indicator to propose wind farms combined with PV system or connected to the grid. Energy that can be captured by wind mills is highly dependent on the local average wind speed. Regions that normally present the most attractive potential are located near coasts, island areas with open terrain or on the edge of water bodies. In spite of these geographic limitations for wind energy

project settings, there is an ample terrain in most areas of the world to meet a significant portion of the local electricity needed for wind energy.

Geographic Nature of Yemen has helped to generate daily wind with reasonable duration and speed. The well known phenomena of local wind patterns are clearly realized in Yemen Sea Breezes and Mountain-valley wind which are potential areas to develop wind energy. Further study for wind availability and daily wind speed is required to precisely assist wind generation economics^[6].

Taiz city is one of the largest cities in Yemen located in the southwest of Yemen (located at 13° 35' N and 44° 01' E). Its average height from sea level is 1311 m.

The aim of the present work is to evaluate the potentiality of wind energy in Taiz area. This is done through investigating the wind characteristics at the location using statistical analysis techniques.

THEORETICAL ANALYSIS:

1-Frequency distribution of wind speed:

The wind speed probability density distributions and their functional forms represent the major aspects in wind related literature. Their use includes a wide range of applications, including identifying the parameters of the distribution functions and analyzing the wind speed data as well as wind energy economics^[3,7]. 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^[8-10]:

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

Here, $f(v)$ is the probability of observing wind speed v ; c is the Weibull scaling parameter and k is the dimensionless Weibull shape parameter.

The corresponding cumulative probability function of the Weibull distribution^[8-12] is given by

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

The Rayleigh distribution is a special case of the Weibull distribution in which the shape parameter k takes the value 2.0. From equation 1 the probability density function for the Rayleigh distribution can be simplified as^[9, 13].

$$f(v) = \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)^2\right] \dots\dots\dots(3)$$

The mean value V_m and standard deviation σ of the Weibull distribution can then be computed from^[12, 13].

$$V_m = c\Gamma\left(1 + \frac{1}{k}\right) \dots\dots\dots(4)$$

and

$$\sigma = c\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right]^{1/2} \dots\dots\dots(5)$$

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

2- Wind speed variation with height:

Wind speed near the ground changes with height. This requires an equation that predicts the wind speed at one height in terms of the measured speed at another. The most common expression for the variation of wind speed with

height is the power law having the following form^[9, 14]:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1} \right)^\alpha \dots\dots\dots(6)$$

where v_2 and v_1 are the mean wind speeds at heights h_2 and h_1 , respectively. The exponent α depends on factors such 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 which is widely applicable to low surfaces and well exposed sites^[15, 16].

3- Wind Power density function:

It is well known that the power of the wind at speed (V) through a blade sweep area (A) increases as the cube of its velocity and is given by^[9-16].

$$P(V) = \frac{1}{2} \rho A v^3 \dots\dots\dots(7)$$

where ρ is the mean air density (1.225 kg/m³ at average atmospheric pressure at sea level and at 15°C), which depends on altitude, air pressure, and temperature.

The expected monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed as follows:

$$P_w = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \dots\dots\dots(8)$$

where C is the Weibull scale parameter (m/s), and is given by

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \dots\dots\dots(9)$$

The two significant parameters k and C are closely related to the mean value of the wind speed v_m ^[13, 17].

By extracting C from Eq. (9) and setting k equal to 2, the power density for the Rayleigh model is found to be^[12, 18],

$$P_R = \frac{3}{\pi} \rho v_m^3 \dots\dots\dots(10)$$

Errors in calculating the power densities using the distributions in comparison to values of the probability density distributions derived from measured values can be found using the following equation^[7]:

$$\text{Error (\%)} = \frac{P_{W,R} - P_{m,R}}{P_{m,R}} \dots\dots\dots(11)$$

where $P_{W,R}$ is the mean power density calculated from either the Weibull or Rayleigh function used in the calculation of the error and $P_{m,R}$ is the wind power density for the probability density distribution, derived from measured values which serves as ‘the reference mean power density’. $P_{m,R}$ can be calculated from the following equation^[18].

$$P_{m,R} = \sum_{j=1}^n \left[\frac{1}{2} \rho v_m^3 f(v_j) \right] \dots\dots\dots(12)$$

The yearly average error value in calculating the power density using the Weibull function is given by

$$\text{Error(\%)} = \frac{1}{12} \sum_{i=1}^{12} \left[\frac{P_{W,R} - P_{m,R}}{P_{m,R}} \right] \dots\dots(13)$$

4-The statistical analysis of the distributions:

The square of the correlation coefficient (R^2), chi-square (χ^2) and root mean square error analysis (RMSE) are used to evaluate the performances of the Weibull and Rayleigh distributions^[19]. These parameters can be calculated as follows:

$$R^2 = \frac{\sum_{i=1}^N (y_i - z_i)^2 - \sum_{i=1}^N (x_i - y_i)^2}{\sum_{i=1}^N (y_i - z_i)^2} \dots\dots\dots(14)$$

$$\chi^2 = \frac{\sum_{i=1}^n (y_i - x_i)^2}{N - n} \dots\dots\dots(15)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (y_i - x_i)^2 \right]^{1/2} \dots\dots\dots(16)$$

where y_i is the i^{th} measured data, z_i is the mean value, 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^[7,9,19]. Therefore, the more distribution function can be selected according to the highest value of R^2 and the lowest values of RMSE and χ^2 .

RESULTS AND DISCUSSION :

Data for wind speed used in the present calculations were obtained during the period 1999–2002 from the National Water Resources Information Center, Taiz. A rotating cup type anemometer was used and the stations were positioned in open spaces free of obstacles at a height of 10 m above the ground. Wind speeds taken every 10 s. were averaged over 5 min and stored in a data-logger. The 5-min averaged data were further averaged over one hour. At the end of each hour, the hourly mean wind speed was calculated and stored sequentially in a permanent memory. Based on these data, the wind speeds were analyzed using statistical software and computer software. The main results obtained from the present study can be summarized as follows:

The Monthly mean wind speed values and the standard deviations calculated from the available data for the overall and individual four years are presented in table (1). As

indicated for the overall four years, the mean wind speeds is about 4.47 m/s. The wind speed for the whole year has the maximum monthly mean value of 5.49 m/s which arises in March, while a minimum value of 3.24 m/s occurs in October.

The monthly mean wind speeds between years 1999 to 2002 are illustrated in Fig. (1). As the figure indicates, the trends of the monthly means for the different years are similar

The variation of wind velocity is often described using the Weibull two-parameter density function. This is statistical method which is widely accepted for evaluating local wind load probabilities and considered as a standard approach. The Weibull parameters calculated analytically from the available data are presented in Table (2). As shown, while the scale parameter varies between 3.41 (October 2000) and 6.79 m/s (February 1999), the shape parameter ranges from 2.94 (Marsh 2001) to 10.78 (July 2002) for the location analyzed. It is clear that the parameter C has a smaller variation than that of the parameter k .

The monthly probability density and the cumulative distributions derived from the time series data of Taiz for the whole years are presented in Fig. (2) and Fig. (3), respectively. The yearly probability density and cumulative distributions are shown in Fig. (4).

In order to observe the Weibull distribution of Taiz, the Weibull probability density distributions for each of the four years were analyzed. The distributions obtained are illustrated in Fig. (5). It can be seen that the distribution is similar for a four year period and represents a narrow peak at a wind speed of about 4.7 m/s.

The Weibull and Rayleigh approximations of the actual probability density distribution of wind speeds for the whole years are shown in

Fig.(6), while a comparison of the two approximations with the actual probability distribution is given in Table (3).

The correlation coefficient values are used as the measures of the fitness of the probability density distributions obtained from the Weibull and Rayleigh distributions. The parameters for the statistical analysis correlation coefficient, R^2 , the root mean square error, RMSE, and Chi-square error, are given in Table (4). As can be seen in Table (4) the value of correlation coefficient for weibull is higher the Rayleigh. The correlation coefficient values are presented in Fig. (7) on a monthly basis for the location data.

The correlation coefficient values range from 0.90 to 0.99 for the Weibull distribution, while they vary between 0.55 and 0.75 for the Rayleigh distributions. The average of the monthly values is 0.95 for the Weibull model and 0.64 for the Rayleigh model. The month to month comparison shows that the Weibull model retains higher coefficient values for all the months indicating better fitness to the measured probability density distributions.

However, the results have shown that the RMSE and χ^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 χ^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 power densities calculated from the measured probability density distributions and those obtained from the Weibull and Rayleigh distributions are shown in Fig. (8). The power density shows a large month to month variation. The minimum power densities occur in September and October with 25.5 and 27.0 W/m^2 , respectively. The highest power density values occur in the spring months of March and April with the maximum value of 140.3 W/m^2 in March. The power densities in the remaining months lie between the lowest and highest power density values previously mentioned.

Errors in calculating the power densities using the distributions in comparison to those using the measured probability density distributions are presented in Fig. (9). The highest error values occur in May and September with 12.9% and 14.8% for the Weibull model, respectively. The power density as estimated by the Weibull model has a very small error value 2.6% in March. The monthly analysis shows that the highest error values using the Rayleigh model occur in April and September with 14.4% and 10.8% respectively, whereas the smallest error in the power density calculation using the Rayleigh model is 5.5% in October. The yearly average error value in the power density calculation using the Weibull function is 7.5%. While the yearly average error value in estimating the power density using the Rayleigh model is 7.8%.

Table (1): Monthly mean wind speeds and standard deviations in Taiz, Yemen, 1999–2002

Years	1999		2000		2001		2002		Whole year	
Parameters	v_m	σ	v_m	σ	v_m	σ	v_m	σ	v_m	σ
January	2.05	1.13	4.50	1.31	4.13	0.72	4.54	1.31	4.54	1.12
February	6.02	1.37	4.58	0.98	4.74	1.37	4.51	0.92	4.96	1.16
March	5.42	1.61	5.71	1.91	5.10	1.89	5.74	1.91	5.49	1.83
April	5.21	1.28	4.75	1.70	5.10	1.81	5.6	1.94	5.17	1.68
May	4.10	0.55	4.22	1.01	3.58	0.68	3.58	0.68	3.87	0.73
June	4.00	0.54	4.28	0.66	4.65	0.86	4.65	0.86	4.40	0.73
July	5.37	0.99	4.71	1.67	4.96	1.22	5.00	0.56	5.01	1.11
August	4.83	0.84	4.96	0.88	4.82	1.30	4.68	0.70	4.82	0.93
September	3.34	0.55	3.13	0.94	3.22	0.55	3.34	0.55	3.26	0.65
October	3.09	1.04	3.11	0.78	3.47	0.65	3.30	1.11	3.24	0.90
November	4.35	0.51	4.65	1.30	4.25	0.99	3.86	0.83	4.28	0.91
December	4.78	0.97	4.32	0.99	5.21	1.46	4.00	0.74	4.58	1.04
Yearly	4.63	0.95	4.41	1.18	4.44	1.13	4.39	1.01	4.47	1.35

Table (2) : Monthly shape parameters ,k, and scale parameters, c, in Taiz, 1999–2002

Years	1999		2000		2001		2002		Whole year	
Parameters	C	k	C	k	C	k	C	k	C	k
January	5.66	5.05	5.00	6.82	4.66	6.67	5.08	3.82	5.10	4.84
February	6.79	4.99	4.79	5.34	5.35	6.85	5.09	5.62	5.55	4.95
March	6.12	3.74	6.37	3.28	5.75	2.94	6.44	3.28	6.17	3.31
April	5.88	4.60	5.32	3.05	5.75	3.08	6.32	6.22	5.69	4.24
May	4.63	8.86	4.79	4.72	4.04	6.07	4.04	6.67	4.37	6.43
June	4.51	8.80	4.56	7.61	5.25	6.25	5.25	6.25	4.90	7.23
July	6.06	6.27	5.27	3.08	5.60	4.59	5.64	10.78	5.64	6.18
August	5.45	6.68	5.32	6.54	5.44	5.15	5.82	7.87	5.37	6.31
September	3.80	7.09	3.47	3.69	3.63	6.82	3.77	7.59	3.67	3.17
October	3.50	3.26	3.41	4.49	3.92	6.17	3.72	3.27	3.64	4.30
November	4.91	10.26	5.13	3.99	4.80	4.87	4.36	5.31	4.80	6.12
December	5.40	5.65	4.32	4.95	5.88	3.98	4.51	6.25	5.10	5.21
Yearly	5.23	6.27	4.83	4.55	4.96	4.95	4.96	5.99	4.99	5.44

Table (3) : Comparison of the actual probability distribution of wind speeds derived from measured data with Weibull and Rayleigh approximations for whole year

J	v_j	$v_{m,j}$	Actual data	Weibull distribution	Rayleigh distribution
1	0-1	0.5	0.00038	0.00004	0.0399
2	1-2	1.5	0.0079	0.0052	0.1198
3	2-3	2.5	0.0685	0.0049	0.1954
4	3-4	3.5	0.2472	0.1934	0.2425
5	4-5	4.4	0.3721	0.3745	0.2137
6	5-6	5.4	0.2556	0.3349	0.0944
7	6-7	6.4	0.0733	0.0707	0.0111
8	7-8	7.4	0.0088	0.0013	0.00013
9	8-9	8.4	0.0004	5×10^{-7}	3.3×10^{-8}
10	9-10	9.5	6×10^{-6}	1×10^{-13}	1.2×10^{-12}
11	10-11	10.5	4×10^{-8}	7×10^{-24}	0
12	11-12	11.5	0	0	0

Table (4) : The statistical analysis parameters for monthly wind speed distributions in Taiz

		January	February	March	April	May	June
R^2	Weibull	0.97	0.97	0.99	0.94	0.90	0.90
	Rayleigh	0.72	0.61	0.73	0.62	0.61	0.55
χ^2	Weibull	0.00051	0.00048	0.00027	0.00043	0.0030	0.0031
	Rayleigh	0.0069	0.0072	0.0025	0.0037	0.0144	0.0159
RMSE	Weibull	0.0213	0.0210	0.0049	0.0198	0.0527	0.0532
	Rayleigh	0.0797	0.0810	0.0475	0.0851	0.1148	0.1210

		July	August	September	October	November	December
R^2	Weibull	0.91	0.93	0.95	0.99	0.93	0.97
	Rayleigh	0.60	0.55	0.63	0.75	0.64	0.61
χ^2	Weibull	0.0016	0.0015	0.0016	0.00029	0.0015	0.00058
	Rayleigh	0.0077	0.0109	0.0151	0.0076	0.0103	0.0085
RMSE	Weibull	0.0385	0.0366	0.0378	0.0163	0.0373	0.0231
	Rayleigh	0.0843	0.1000	0.1175	0.0835	0.0969	0.0883

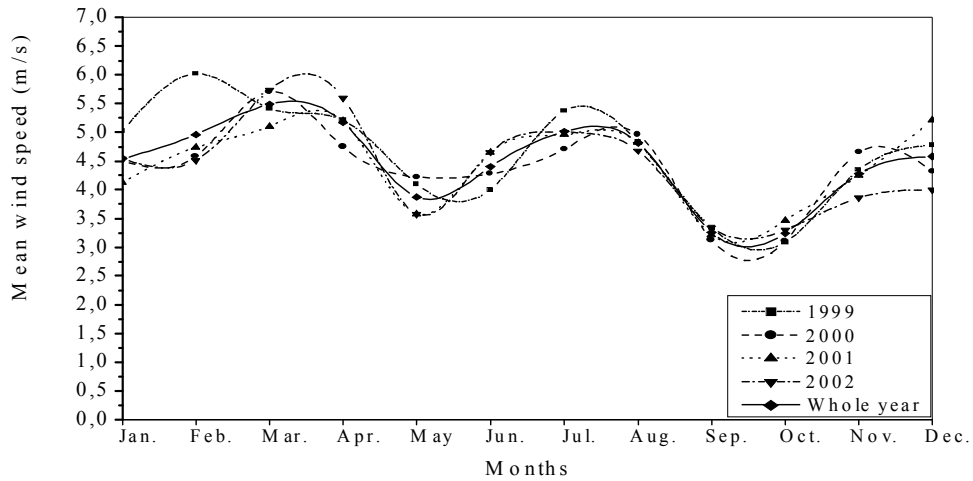


Fig. (1) : Monthly mean wind speed of Taiz 1999 and 2002

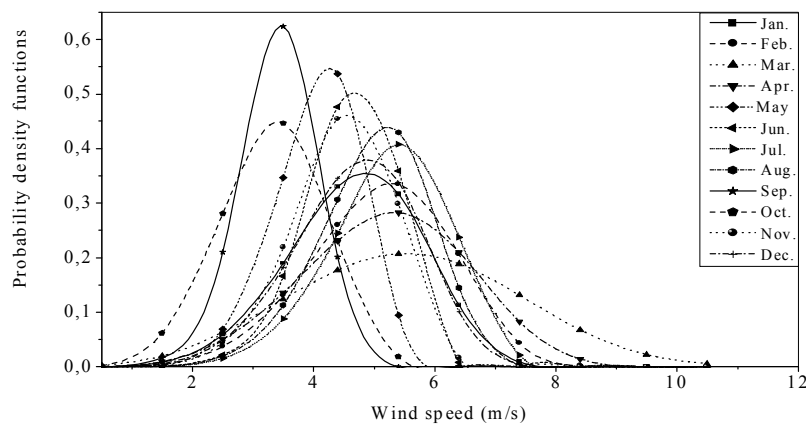


Fig. (2): Monthly wind speed probability density distributions derived from the measured data of Taiz for whole years

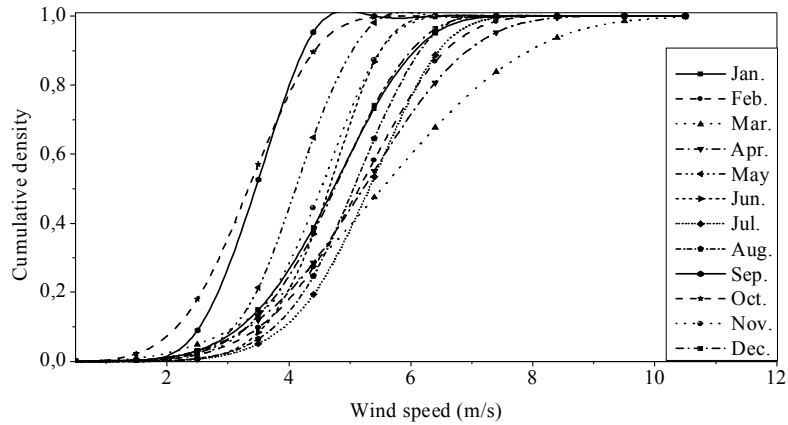


Fig. (3): Monthly wind speed cumulative probability distributions derived from the measured data of Taiz for whole years.

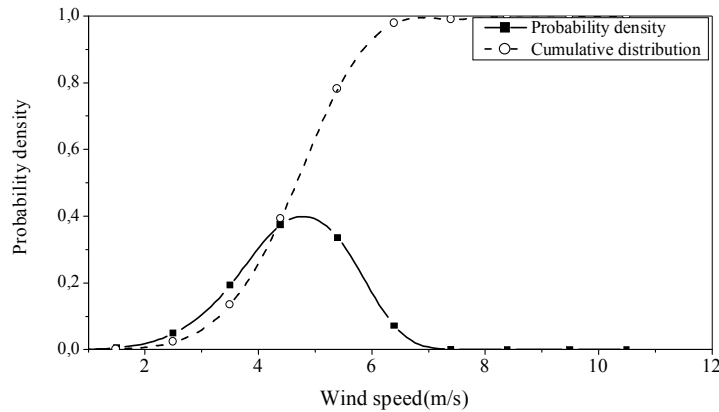


Fig. (4): Yearly wind speed probability density and cumulative probability distributions, derived from the measured data of Taiz for a whole years

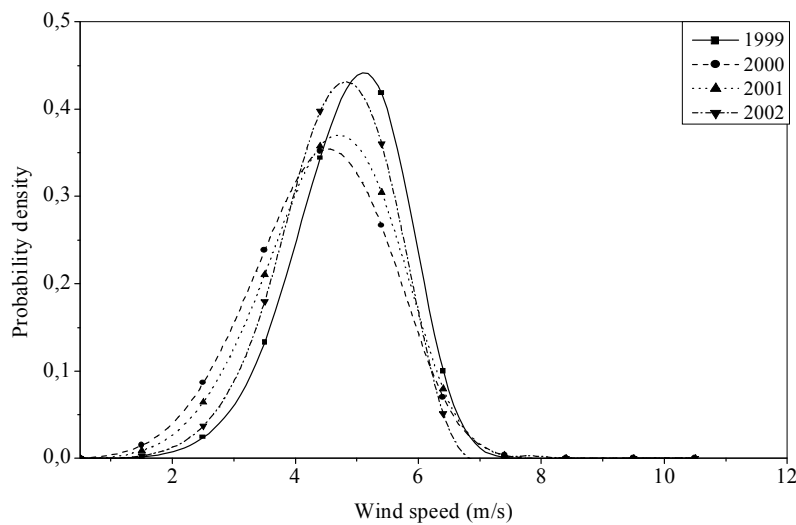


Fig. (5): Yearly Weibull probability density distributions for the period of 1999–2002 in Taiz

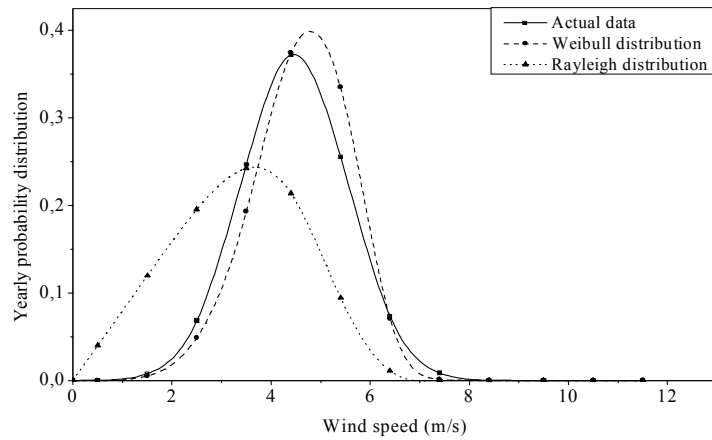


Fig. (6): Weibull and Rayleigh approximations of the actual probability distribution of wind speeds

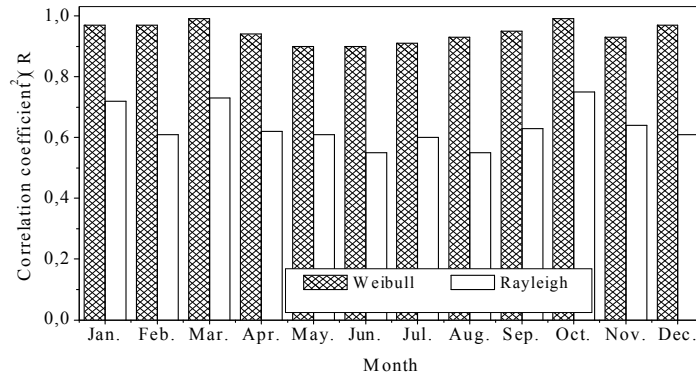


Fig. (7): Correlation coefficient values obtained by fitting the actual probability density distributions with the Weibull and Rayleigh functions

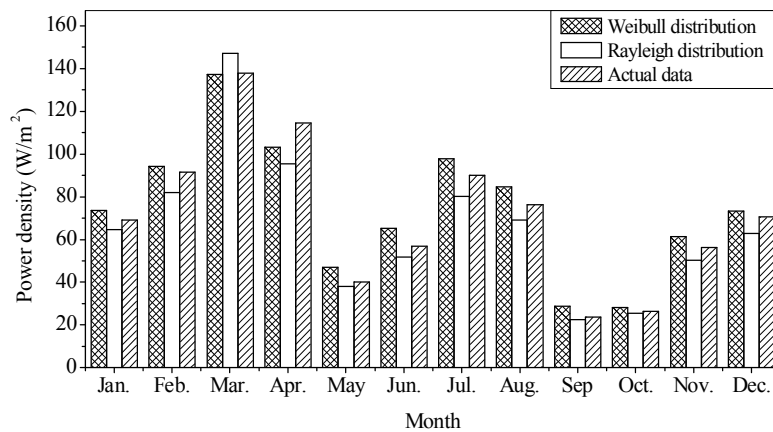


Fig. (8): Wind power density obtained from the actual data versus those obtained from the Weibull and Rayleigh models on a monthly basis.

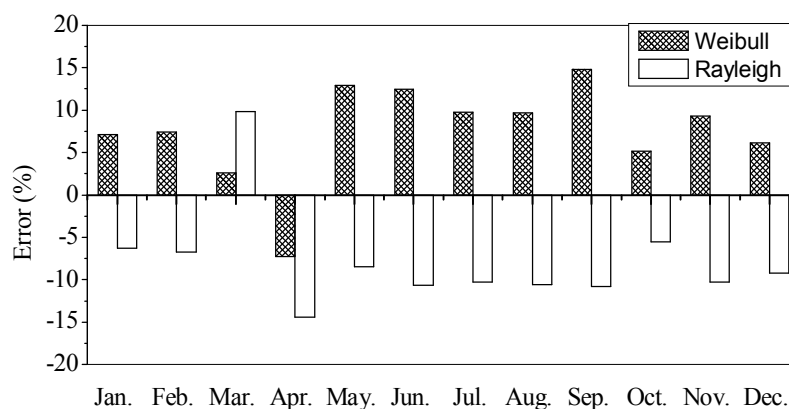


Fig. (9): Error values in calculating the wind power density on monthly basis obtained from the Weibull and Rayleigh models in reference to the wind power density obtained from the measured data

CONCLUSIONS:

Wind characteristics of Taiz have been analyzed statistically. Wind speed data were collected for a period of four years (1999–2002). The probability density distributions and power density distributions were 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. Based on the Weibull and Rayleigh models, the wind energy potential of the location has been studied. The most important outcomes of the study can be summarized as:

- 1-The Weibull distribution is fitting the measured monthly probability density distributions better than the Rayleigh distribution for the whole years. This is shown from the monthly correlation coefficient values.
- 2-The Weibull distribution provides better power density estimations in eleven months than the Rayleigh distribution.
- 3-The mean value of wind speed and energy intensity measured at the location reveals that the current technology does not provide

economical electricity production from wind power and that the measurements should be evaluated in the long term in accordance with technological developments and reduction in the cost of turbines. The result derived from this study encourages utilization of the wind energy potential in this location.

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التحليل الإحصائي لبيانات سرعة الرياح وتقييم طاقة الرياح في تعز - الجمهورية اليمنية مهبوب البحيري

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اليمن لديها إمكانيات جيدة من الطاقات المتجددة مثل الطاقة الشمسية وطاقة الرياح، وتعتبر طاقة الرياح من المصادر النظيفة بيئياً وأحد المصادر البديلة للوقود الأحفوري الذي يعد مصدراً رئيسياً لتلويث البيئة وخصوصاً الطبقة السفلى للغلاف الجوي (التروبوسفير)، حيث أن بيانات سرعة الرياح هي العامل الأهم لتصميم أنظمة تحويل هذه الطاقة، ففي هذه الدراسة تركز على التحليل الإحصائي لبيانات سرعة الرياح لمدينة تعز الواقعة جنوب غرب اليمن، والتي تم الحصول عليها من المركز الوطني للموارد المائية في تعز لفترة أربع سنوات من 1999 إلى 2002م، وبجانب التحليل الإحصائي للبيانات المقاسة في فترة أربع سنوات تناولت الدراسة التوزيع الاحتمالي لهذه البيانات، ومعرفة قيم الكميات الخاصة بالتوزيع، وتبين أن الكثافة الاحتمالية تتلاءم مع التوزيع الاحتمالي القياسي السنوي، وكذلك تم دراسة طاقة الرياح للموقع استناداً على نموذج Weibull و Rayleigh.