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Assessment of Wind Energy Potential In Zwara, Libya

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Abstract: To assess the wind energy potential at any site, the wind power density should be estimated; it evaluates the wind resource and indicates the amount of available wind energy. The purpose of this study is to estimate the monthly and annual wind power density based on the Weibull distribution using wind speed data collected in Zwara, Libya during 2007. The wind date are measured at the three hub heights of 10m, 30m, and 50m above ground level, and recorded every 10 minutes. The analysis showed that the annual average wind speed are 4.51, 5.86, 6.26 m/s for the respective mentioned heights. The average annual wind power densities at the mentioned heights were 113.71, 204.19, 243.48 , respectively.

تقييم إمكانات طاقة الرياح في زوارة ، ليبيا.

الحسن طيابين، فتحى العكاري، على جويد، اشرف زغوان و رحاب عبدالله

ملخص: لتقييم إمكانية طاقة الرياح في أي موقع، يجب تقدير كثافة قدرة الرياح؛ فهي تعمل على تقييم مورد الرياح وتشير إلى

* *Corresponding author*

كمية طاقة الرياح المتاحة في الموقع. تستهدف هذه الدراسة حساب كثافة قدرة الرياح الشهرية والسنوية بالاعتماد على توزيع ويبل باستخدام بيانات سرعة الرياح التي تم تجميعها في زوارة-ليبيا خلال عام 2007. تم قياس سرعة الرياح عند ثلاثة ارتفاعات وهي 10 و 30 و 50م فوق مستوى سطح الأرض، ومُسجلة كل 10 دقائق. أظهرت نتائج التحليل بأن المتوسط السنوي لسرعة الرياح في الموقع هو 6.26 ، 4.51،5.86 م/ث، للارتفاعات المذكورة على الترتيب. وكانت متوسط الكثافة السنوية لقدرة الرياح عند الارتفاعات المذكورة 243.48 ، 204.19، 113.71 واط/م^2، على التوالي..

Keywords: ***Weibull distribution; most probable wind speed; wind rose; hub height; capacity factor; wind power classification; mean net energy output***

Nomenclature

A	Turbine swept rotor area ( )	P_R	Turbine rated power (W)
c	Weibull scale parameter (m/s)	T	Time (in hours)
CDF	Cumulative density function	υ	Wind velocity (m/s)
C_f	Capacity factor	υ_{ci}	Turbine cut-in speed (m/s)
E_D	Wind energy density ()	υ_{co}	Turbine cut-off speed (m/s)
f(υ)	Probability of having a speed of υ	υ_m	Mean wind speed (m/s)
F(υ)	Probability of having a speed of υ	υ_{ME}	Wind speed carrying maximum energy (m/s)
h	Height (m)	υ_{MF}	Most probable wind speed (m/s)
k	Dimensionless Weibull shape parameter	υ_r	Turbine rated (nominal) speed (m/s)
P_D	Wind power density	α	Ground friction coefficient
PDF	Probability density function	Γ	Gamma function
$P_{e, avg}$	Power produced by turbine (W)	ρ	Air density (kg/)
PNL	Battelle-Pacific Northwest Laboratory	σ	Standard deviation of wind speed

1. INTRODUCTION

Increased global energy demands and huge increases in energy consumption have led to the rapid depletion of fossil fuels. Significant environmental problems also result from the combustion of fossil fuels including the emission of carbon dioxide and other hazardous gases. As a result, the world has focused on alternative renewable energy sources, especially wind and solar energy, in order to generate electricity more safely. Wind energy has become one of the fastest growing energy resources in the world, and one of the cleanest when compared to fossil fuels, which pollute the environment. A wind turbine converts wind speed into electricity. Before installing a specific turbine at any site, clearly the available wind power at the site must first be assessed, as appropriate for turbine installation. This study focuses on an estimation of the amount of wind power available at identified locations in Libya, followed by an estimation of the net energy output from selected turbines in these locations.

Several studies have investigated wind power density and wind energy potential. Elmabruk et al. [1] estimated the wind energy in certain locations in Libya, including Derna, Musrata, Zwara, and Sebha, using wind speed data measured at longer time intervals, of 3-hours. The study focused on the VentisV-12 wind turbine with a rated power of 500 kW, in order to calculate the annual net energy output and annual capacity factor; the results indicate that wind energy in Libya is available in identified locations, and that the site of Derna has the maximum annual net energy output and annual capacity factor. Hasan et al. [2] evaluated the annual, monthly and the seasonal performance of the wind resource at the Zawiya region in northwest of Libya. The wind data are measured at height of 50 m above the ground level. The results showed that the annual average wind speed is 6.14 m/s, and the annual energy production of 750 kw wind turbine is 2.70 Gwh/year.

Ouammi et al. [3] determined the monthly and seasonal wind speed distribution, wind directions, and wind power density in order to assess the wind energy available at four locations in the Liguria region of Italy. Their results show that the Capo Vado site is the most productive, with the monthly mean wind speed variation from 2.80 to 9.98 m/s at a hub height of 10 m; in addition, the monthly wind power densities vary from 90.71 to 1177.97 . Dahmouni et al. [4] estimated wind energy potential based on the wind speed data collected in Borj-Cedria, Tunisia. Here the authors estimated the seasonal average wind velocity and seasonal wind power density. They then estimated the net energy output of seven types of 1.5 MW wind turbines. This seasonal net energy output varies from 613 kWh to 1.123 MWh per season. The authors concluded that the Vensys 70 wind turbine generator is the most appropriate type for the characteristics of their studied site. Adaramola et al. [5] studied the potential wind energy and economic viability of using a wind turbine generator to generate electric power on the coast of Ghana. Wind speed is described by the Weibull distribution. The net output energy and cost of electric power produced from wind turbine generators were determined. Their results show that the wind resource in the region under investigation can be classified as class 2 or less.

Although several studies have been reported in the field of wind energy potential [1, 6-8], there has not been a representation of the wind rose, which is a chart indicating the distribution of the wind in different directions. Accurate measurement of the direction of the wind is essential to avoid any obstacles to the wind flow from a specific side [9]. Many other studies [3, 5, 10, 11] have used approximations in their calculations to estimate the parameters of the Weibull probability function. Whereas the standard deviation method, based on a numerical technique, is a more precise method to estimate the parameters of the Weibull distribution [12]. The other studies [1, 13] have used a graphical method to estimate the Weibull parameters. The graphical method was found to be inefficient in determining the Weibull parameters [14]. The estimation method of distribution parameters is the most critical and important step in forming the distribution. The graphical method could also be performed by hand with minimal computation. However, it is also less precise than the standard deviation method, and it is the least effective method to fit the Weibull distribution [12, 15, 16]. Elmabruk et al. [1] did not present wind energy density in their study. The wind energy density is the most successful method in assessing the wind potential of any location as it shows how much energy is available at a location selected for electricity production using wind turbine [10, 11].

This paper estimates the mean power density and the energy density at a selected site, based on the Weibull probability function. It will also investigate the effect of height on mean power density and energy density. In addition, an estimation of the net energy output from a specified turbine and its capacity factor will be simulated. The MATLAB script file program is used for the simulation.

2. DATA COLLECTION AND CASE STUDY REGION

Short-term time series of 10-minutes measured wind speed data were used for assessment of wind energy potential by estimating the wind power density. Data were measured at three different hub heights of 10m, 30m, and 50m above ground level during 2007 in Zwara (Latitude 32.93 N and Longitude 12.10 E) which located at the northwestern coast of Libya as shown in Figure 1.

3. MATHEMATICAL MODEL

Power from a wind turbine is proportional to the air density, the rotor swept area and the cube of wind speed. Furthermore, it depends on the power coefficient of the rotor, and the transmission efficiency and loads. But the wind speed is the most critical factor affecting the power produced from a wind turbine generator, due to the cubic relationship between wind speed and power. Thus, a small variation in the velocity will result in a significant change in the power. Since wind speed is a stochastic phenomenon, describing its behavior using probability density function (PDF) is needed. This computation is the first necessary step, and it provides the most critical estimate in the assessment of wind energy potential.

Figure (1). Localization of the site used in this study located in Zwara, the northwestern coast of Libya.

Teyabeen [17] utilized several types of probability density functions to characterize wind speed distribution at the Zwara city; the study proved that the Weibull probability density function provides the best fit for measured wind speed data. Thus, the estimation of wind energy potential in this paper will focus only on the Weibull distribution.

For any given wind speed data at a specific location, two important factors must be known: the average value and the standard deviation of wind speed. They provide important information on the wind resource. The average wind speed gives an indication of the wind energy potential at a specific location. It can be calculated by [9, 17]:

$$\upsilon_m = \frac{1}{n}\sum_{i=1}^{n}\upsilon_i \quad (1)$$

where (m/s) is the wind velocity, and is the number of wind speed data. The second important factor is the standard deviation of wind speed, , which describes the deviation of individual wind speeds from the mean value; it is given by [9, 17]:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\upsilon_i - \upsilon_m)^2} \quad (2)$$

3.1 Weibull distribution

The Weibull probability density function is expressed as [1, 3, 4, 7-11, 13, 17]

$$f(\upsilon) = \left(\frac{k}{c}\right)\left(\frac{\upsilon}{c}\right)^{k-1} e^{-\left(\frac{\upsilon}{c}\right)^k} \quad (3)$$

where is the probability of observing wind speed, indicating the probability of wind at the given velocity; , is the shape parameter (dimensionless), and is the scale parameter (in m/s). The cumulative distribution function of Weibull is the integration of the probability density function, indicating the probability that the wind speed is equal to or less than . It is given by [9, 14, 17]:

$$F(\upsilon) = 1 - e^{-\left(\frac{\upsilon}{c}\right)^k} \quad (4)$$

The mean wind speed of the Weibull probability density function (also known as the expected value of wind speed) is given by [9, 17-19]:

$$\upsilon_m = c\Gamma\left(1+\frac{1}{k}\right) \quad (5)$$

where is the gamma function, defined as [9, 17]:

$$\Gamma(t) = \int_0^\infty x^{t-1}e^{-x}dx \quad (6)$$

The standard deviation of the Weibull distribution is given as [9, 17, 19]

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

The Weibull distribution parameters, , and , must be estimated in order to deal with the Weibull distribution. In this paper, the standard deviation method, a numerical method that uses mathematical iterations, is introduced to determine the Weibull parameters. The expressions in equations (5) and (7) indicate to [17]:

$$\left(\frac{\sigma}{\upsilon_m}\right)^2 = \frac{\Gamma\left(1+\frac{2}{k}\right)}{\Gamma^2\left(1+\frac{1}{k}\right)} - 1 \quad (8)$$

Once and are estimated from the wind speed data obtained at a site, then can be determined numerically using (8). Once is determined, the other parameter, , is given as [9, 17-19]:

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

3.2 Extrapolation of wind speed

In most cases, the hub height of the wind turbine to be installed at a site is different from the height of the available wind speed data measured at that site. The available wind speeds must therefore be modified to the hub height of the wind turbine using the following power exponent function [20-22]:

$$\frac{\upsilon}{\upsilon_r} = \left(\frac{h}{h_r}\right)^\alpha \quad (10)$$

where (m/s) is the wind velocity at the hub height (in m), (in m/s) is the wind velocity at the reference hub height (in m), and (dimensionless) is the power law exponent, which represents the surface roughness coefficient, and is given by [18, 20, 21]:

$$\alpha = \frac{0.37 - 0.088\ln(\upsilon_r)}{1 - 0.088\ln\left(\frac{h_r}{10}\right)} \quad (11)$$

In this study, the surface roughness coefficient is 0.12 [1].

3.3 Mean wind power density and mean energy density

Wind power density is a useful way to evaluate the wind resource at any location; it indicates the amount of energy available at a location suitable for conversion by a wind turbine [11]. The power available in the wind, , flowing with velocity (m/s) through a swept area of wind turbine rotor blade, (), at any given site can be expressed as [3, 11, 22]:

$$P(\upsilon) = \frac{1}{2}\rho A \upsilon^3 \quad (12)$$

Where is the air density at the site (in this study, it is assumed to be 1.225). The total energy per unit rotor contributed by all possible wind speeds at a site is expressed as [9]:

$$E_D = T\int_0^\infty P_A f(\upsilon)d\upsilon \quad (13)$$

where is the power available in the wind per unit area. The equation (13) can be expressed as [9]:

$$E_D = \frac{\rho}{2}c^3\Gamma\left(\frac{3}{k}+1\right)T \quad (14)$$

where represents the mean wind energy density (in Watts hour per square meter).

Since , then [7, 9, 11, 22]:

$$P_D = \frac{\rho}{2}c^3\Gamma\left(\frac{3}{k}+1\right) \quad (15)$$

In the equation (15), represents the mean wind power density (in).

In addition to the two important factors, the mean and standard deviation of wind speed, there are two other factors relating to wind energy estimation: the most probable (frequent) wind speed , and the wind speed carrying the maximum energy . The most frequent wind speed corresponds to the peak of the probability density function , and can be estimated by differentiating the probability density function, then equalling the result to zero, ; thus can be expressed as [9]:

$$\upsilon_{MF} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \quad (16)$$

The definition of energy per unit rotor area and time, , thus can be found by letting , it expressed as [9]:

$$\upsilon_{ME} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (17)$$

3.4 Wind power Classification

Both the average wind velocity and power density are used for the classification of the wind resource. The classification scheme for wind power density has been developed by the Battelle - Pacific Northwest Laboratory (PNL) [21]. This classification is a numerical classification, which ranks the wind power density from Class 1 (the lowest) to Class 7 (the highest). Each class represents a range of mean wind speeds and a range of wind power densities at specified heights above the ground [3, 5 ,7, 10, 22-27].

3.5 Wind turbine energy output and capacity factor

The energy generated from a wind turbine depends on both the characteristics of the wind site and the parameters of the wind turbine. Hence, it is necessary that the site characteristics and the turbine characteristics which should be properly matched. Thus the cut-in wind speed , rated wind speed , cut-off wind speed , and the rated power of the wind turbine must be appropriate for the site characteristics in order to maximize the energy output from a wind turbine. The response of the wind turbine to wind speed at any site can be evaluated by the quantity of mean electric power () and the conversion efficiency (which is known as a capacity factor) of the turbine. The mean electric power generated from a wind turbine can be estimated based on the parameters of the Weibull probability function using the following expression [5, 11, 28, 29]:

$$P_{e,avg} = P_R \left(\frac{e^{-\left(\frac{\upsilon_{ci}}{c}\right)^k} - e^{-\left(\frac{\upsilon_r}{c}\right)^k}}{\left(\frac{\upsilon_r}{c}\right)^k - \left(\frac{\upsilon_{ci}}{c}\right)^k} - e^{-\left(\frac{\upsilon_{co}}{c}\right)^k} \right) \quad (18)$$

The mean net output energy per year from the selected turbine can then be:

$$E_{out} = P_{e,avg} \times T \quad (19)$$

Where is the total hours per year. The capacity factor of a wind turbine at any given site is defined as the ratio of actual power produced by the wind turbine over a period of time to the energy that it could have produced. It can be estimated as [5, 9, 11, 28-33]

$$C_f = \frac{E_{out}}{P_R \times T} \quad (20)$$

4. RESULTS AND DISCUSSION

In this study, wind speed data collated in Zwara, Libya over one year during 2007 were analyzed using the Weibull distribution.

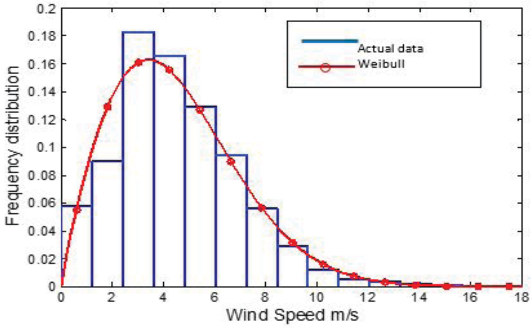
4.1 Frequency distribution of wind speed

The annual wind speed histogram and the Weibull distribution with parameters derived from measured wind speed at heights of 10, 30, and 50 m, are plotted and shown in Figure 2. As mentioned in the previous section, the peak of the curve of probability density function indicates the most frequent wind speed. Therefore it can be clearly seen from Figure 2, that the wind speed corresponding to the peak of the distribution curve is almost equal to the most frequent bin of the histogram. The expected annual values of the most frequent wind speed are 3.41, 5.21, and 5.65 m/s at heights of 10, 30, and 50 m, respectively, as are presented in Tables 1, 2, and 3.

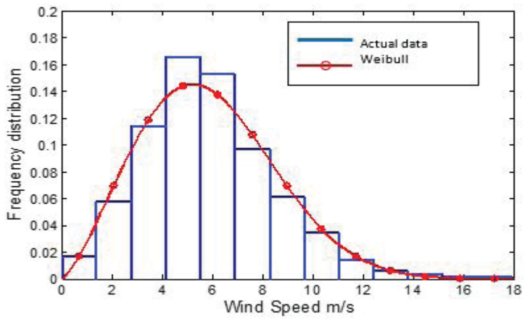
Table (1). Statistical analysis of wind speed, power density, and energy density at height of 10 m.

Month	υ_m (m/s)	σ (m/s)	k	c (m/s)	υ_{MF} (m/s)	υ_{ME} (m/s)	P_D (W/m²)	No. hours	E_D (kWh/m²)
Jan	4.04	2.35	1.77	4.54	2.84	6.96	88.18	744	65.61
Feb	5.16	3.13	1.69	5.78	3.40	9.17	194.21	672	130.51
Mar	4.61	2.45	1.96	5.20	3.61	7.44	117.00	744	87.05
Apr	6.05	2.19	3.00	6.78	5.92	8.04	190.90	720	137.45
May	4.56	2.03	2.39	5.14	4.10	6.63	94.52	744	70.32
Jun	4.78	2.15	2.36	5.39	4.27	6.99	110.01	720	79.21
Jul	4.58	2.13	2.27	5.17	4.00	6.83	100.05	744	74.44
Aug	4.48	1.84	2.61	5.04	4.19	6.27	84.11	744	62.58

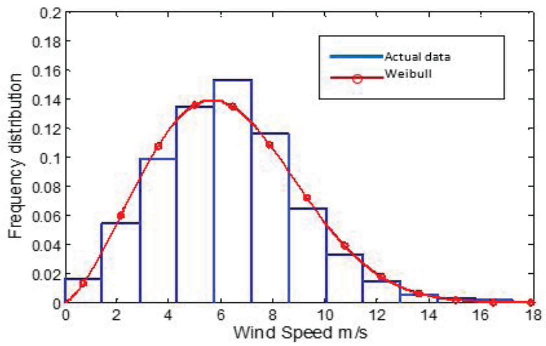
Sep	4.96	2.05	2.59	5.58	4.62	6.96	114.68	720	82.57
Oct	4.91	2.40	2.15	5.54	4.14	7.52	128.97	744	95.95
Nov	3.73	1.78	2.21	4.21	3.21	5.64	55.24	720	39.77
Dec	2.41	3.15	1.10	2.50	0.28	6.41	41.21	744	30.66
Annual	4.51	2.48	1.89	5.08	3.41	7.44	113.71	8760	996.1



(a)



(b)



(c)

Figure (2). Annual histogram of wind speed and Weibull distribution, (a) at 10m, (b) at 30m, and (c) at 50 m.

Table (2). Statistical analysis of wind speed, power density, and energy density at height of 30 m.

Month	υ_m (m/s)	σ (m/s)	k	c (m/s)	υ_{MF} (m/s)	υ_{ME} (m/s)	P_D (W/m^2)	No. hours	E_D (kWh/m^2)
Jan	5.16	2.62	2.06	5.82	4.22	8.09	155.73	744	115.86
Feb	6.41	3.43	1.94	7.23	4.98	10.42	318.09	672	213.76
Mar	5.84	2.68	2.31	6.59	5.16	8.63	204.36	744	152.04
Apr	7.74	2.74	3.08	8.66	7.62	10.19	393.54	720	283.35
May	5.60	2.30	2.61	6.30	5.24	7.83	164.28	744	122.22
Jun	6.09	2.48	2.63	6.85	5.71	8.49	210.23	720	151.37
Jul	5.31	2.38	2.37	5.99	4.75	7.75	150.52	744	111.99
Aug	5.70	2.28	2.69	6.41	5.39	7.88	170.08	744	126.54
Sep	6.15	2.30	2.89	6.90	5.96	8.28	204.57	720	147.29
Oct	6.19	2.60	2.54	6.97	5.72	8.76	226.20	744	168.29
Nov	5.05	1.89	2.89	5.66	4.89	6.79	112.91	720	81.30
Dec	5.20	2.80	1.93	5.86	4.01	8.47	170.36	744	126.75
Annual	5.86	2.65	2.34	6.61	5.21	8.61	204.19	8760	1788.7

Table 3. Statistical analysis of wind speed, power density, and energy density at height of 50 m.

Month	υ_m (m/s)	σ (m/s)	k	c (m/s)	υ_{MF} (m/s)	υ_{ME} (m/s)	P_D (W/m^2)	No. hours	E_D (kWh/m^2)
Jan	5.60	2.76	2.13	6.32	4.69	8.62	193.13	744	143.69
Feb	6.87	3.50	2.05	7.75	5.59	10.80	369.50	672	248.30
Mar	6.34	2.74	2.47	7.15	5.80	9.09	248.66	744	185.00
Apr	8.11	2.81	3.15	9.06	8.03	10.59	446.75	720	321.66
May	5.99	2.41	2.67	6.74	5.65	8.31	198.55	744	147.72
Jun	6.60	2.70	2.62	7.43	6.18	9.23	268.88	720	193.59
Jul	5.39	2.41	2.37	6.08	4.82	7.87	157.40	744	117.11
Aug	6.01	2.49	2.58	6.77	5.60	8.46	205.28	744	152.73
Sep	6.39	2.27	3.06	7.15	6.28	8.43	222.06	720	159.88
Oct	6.61	2.59	2.75	7.43	6.30	9.06	261.76	744	194.75
Nov	5.66	2.16	2.83	6.35	5.44	7.67	161.05	720	115.96
Dec	5.71	2.96	2.01	6.44	4.57	9.08	216.34	744	160.96
Annual	6.26	2.76	2.41	7.06	5.65	9.07	243.48	8760	2132.88

4.2 Wind rose

The Wind Rose provides information about wind speed and wind direction in a combined form. It is a graphical tool (chart) used to give a view of how wind velocity and wind direction are distributed at a specified site. The chart is divided into a number of equally spaced clockwise sectors representing different directions, where the first sector indicates north.

In this study, the wind rose is constructed by dividing the chart into 12 sectors, and all values of wind speed data measured at ten minutes intervals and the wind direction at a height of 50 m, were used. Figure 3 shows the chart of the Wind Rose, and Table 4 illustrates the percentage of time that wind velocity and direction remained at the different wind speed bins for the site under investigation. For each sector, the value presented in each wind speed bin represents the percentage of all wind speed data recorded at the site under investigation.

Figure 3 shows that for the studied site, most of the wind blows from the East and the Northeast (sectors 3 and 4). Table 4 also illustrates that the wind speeds in both sectors 3 and 4 represent 31.17% of all wind speeds in all sectors (directions). The results in Table 4 illustrates that for 66.87% of the time, the wind velocity is higher than 5 m/s, whereas wind velocity higher than 9 m/s is represented 14.60% of the time and wind velocity less than 3 m/s is represented 11.27% of the time.

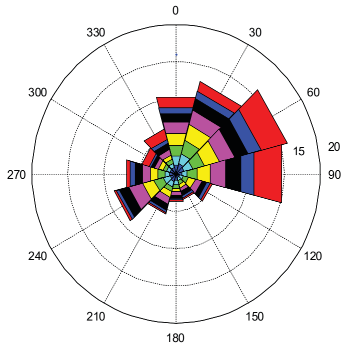


Figure (3). Wind Rose chart for the studied site at a height of 50 m above the ground

Table (4). Percentage of wind speed distribution, and wind direction at different speed bins at a height of 50 m.

	Wind speed bins								
	0≤υ<3	3≤υ<4	4≤υ<5	5≤υ<6	6≤υ<7	7≤υ<8	8≤υ<9	υ≥9	Sum. %ge
Sector 1	1.25	1.18	1.51	1.65	1.62	1.13	0.86	1.37	10.57
Sector 2	1.41	1.32	1.89	2.23	1.97	1.55	1.06	1.37	12.80
Sector 3	1.19	1.22	1.70	2.13	2.21	1.95	1.86	3.72	15.97
Sector 4	0.79	0.82	1.41	1.90	2.21	2.21	1.90	3.97	15.20
Sector 5	0.57	0.52	0.73	0.96	0.96	0.70	0.44	0.30	5.20
Sector 6	0.57	0.40	0.52	0.50	0.46	0.61	0.36	0.20	3.61
Sector 7	0.84	0.64	0.53	0.44	0.51	0.48	0.19	0.15	3.78
Sector 8	1.05	0.76	0.65	0.82	0.94	0.83	0.36	0.20	5.60
Sector 9	0.88	1.04	1.29	1.63	1.95	1.41	0.42	0.32	8.94
Sector 10	0.93	0.69	0.95	1.07	1.15	1.06	0.78	0.50	7.14
Sector 11	0.88	0.50	0.49	0.65	0.60	0.46	0.29	1.06	4.93
Sector 12	0.91	0.53	0.57	0.59	0.81	0.84	0.56	1.44	6.26
Sum. %ge	11.27	9.62	12.24	14.57	15.39	13.23	9.08	14.60	100

4.3 Mean wind speed, mean power density and mean energy density

The average value and standard deviation of wind speed are estimated from the available data for each of twelve months and over the year at three mentioned heights using expressions (1) and (2), respectively, and the mean wind power density is estimated using the expression in equation (15). The monthly variation and annual values of mean wind speed , mean power density , at heights of 10 m, 30 m, 50 m are presented in Tables 1, 2, and 3, respectively, and shown in Figure 4. The monthly mean wind speeds vary between 2.41 m/s in December and 6.05 m/s in April at height of 10 m, and vary between 5.05 m/s in November and 7.74 m/s in April at height of 30 m, and vary between 5.39 m/s in July and 8.11 m/s in April at height of 50 m. Consequently, the monthly mean power density varies between 41.21 in December and 194.10 in February at a height of 10 m, and varies between 112.91 in November and 393.54 in April at a height of 30 m, and varies between 157.40 in July and 446.75 in April at a height of 50 m.

Based on the classification scheme of wind power which was introduced by the Battelle-Pacific Northwest Laboratory (PNL) [23], the annual mean power density at a height of 10 m falls into class 2 ; whereas most of the monthly mean power densities fall into class 1 and class 2 , except in February, and April, when they fall into class 3 , as illustrated in Table 1. At a height of 30 m, most of the monthly mean power densities fall into class 2 , except in February, and April, where they fall into class 3 and class 4 , respectively, as illustrated in Table 2. However, the annual mean power density at this height falls into class 2 , as shown in Table 2. At a height of 50 m, the annual mean power density falls into class 2 , whereas most of the monthly mean power density falls into class 1 and class 2 , except in April, where it falls into class 4 , as illustrated in Table 3. As can be clearly seen from Figure 4, at any fixed month, the wind power density at a height of 50 m is greater than the wind power density at lower heights.

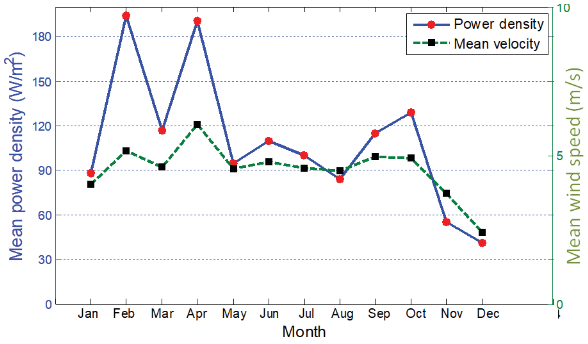
The monthly variation of the most frequent wind velocity , and wind speed carrying maximum energy , as well as the annual values of these factors at heights of 10, 30, and 50 m are also represented in Tables 1, 2, and 3, respectively. The annual values of at heights of 10, 30, and 50 m are 3.41, 5.21, 5.65 m/s, respectively, as illustrated in Figure 1. The annual values of at heights of 10, 30, and 50 m are 7.44, 8.61, 9.07 m/s, respectively.

The annual values and monthly variations in wind energy density are presented in Tables 1, 2, and 3. As shown in Figure 5. These figures vary between 30.66 in December and 137.45 in April at heights of between 81.30 . A variation exists between November and April, at heights of 30m and 50m respectively, wind speeds vary between 115.96 in November and 321.66 in April. However, the annual mean energy densities at heights of 10, 30, and 50 m are 996.1, 1788.7, 2132.88 , respectively. Figure 5 shows that the highest value of wind energy density occurs in April for all hub heights.

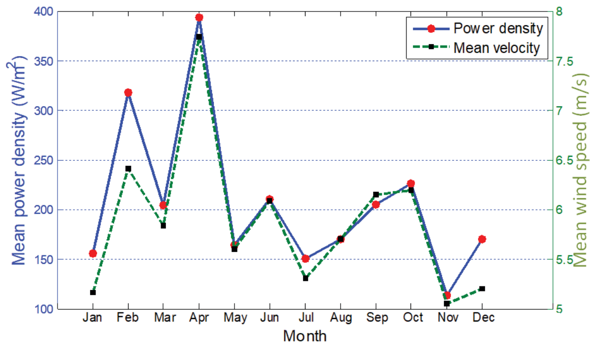
4.4 Net output energy and capacity factor

This section considers the net energy output from a wind turbine and its capacity factor. Many wind turbine generators are available with different operating characteristics. In this paper, four types of small to medium sized wind turbines were selected in order to simulate their response to wind speed at the studied site. Their power range was recorded from 330 to 1500 kW [34, 35]. These wind turbines are E-33 330 kW, E-53 800 kW, LTW80 1000 kW, and LTW80 1500 kW. Their characteristics are shown in Table 5 and Figure 6. For the studied site, the annual net energy produced by selected turbines and their capacity factors are simulated based on the Weibull distribution using expressions (19) and (20), respectively, where the wind speeds are extrapolated according to the hub heights of wind turbines using expression (10). Figure 7, and Figure 8 show the performance of the selected turbines at the studied location.

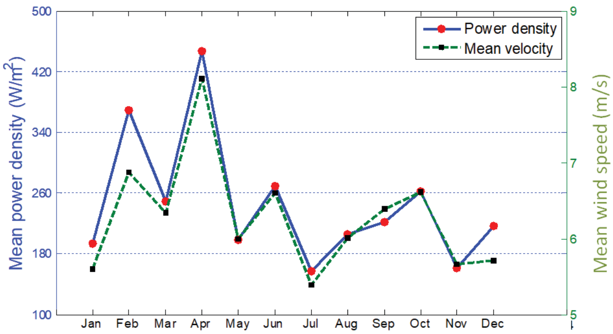
Selected turbines (E-33 330 kW, E-53 800 kW, LTW80 1000 kW, and LTW80 1500 kW), produce an energy output of 969.12 MWh, 1549.29 MWh, 3486.57 MWh, and 5155.70 MWh, per year, respectively. Their capacity factors are 33.02%, 21.83%, 39.80%, 39.24%, respectively.



(a)



(b)



(c)

Figure 4. Monthly variation of mean wind speed and wind power density at (a) 10 m, (b) 30 m, (c) 50 m.

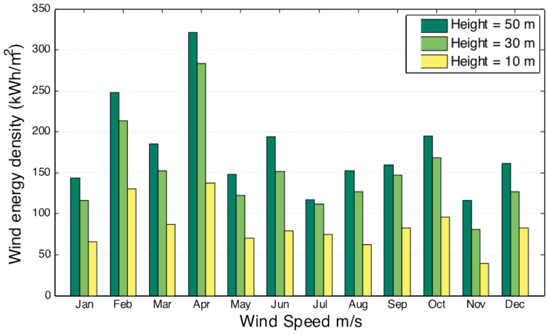


Figure (5). Monthly variation of mean wind energy density at heights of 10, 30, and 50 m above the ground.

Table 5. Specifications of wind turbines used in the analysis.

S. No.	Manufacturer	Model	P_R (kW)	υ_{ci} (m/s)	υ_r (m/s)	υ_{co} (m/s)	Tower height (m)
T1	ENERCON	E-33 330 kW	330	3	13	25	44
T2	ENERCON	E-53 800 kW	810	2	13	25	50
T3	LEITWIND	LTW80 1000 kW	1000	3	12	25	65
T4	LEITWIND	LTW80 1500 kW	1500	3	12	25	60

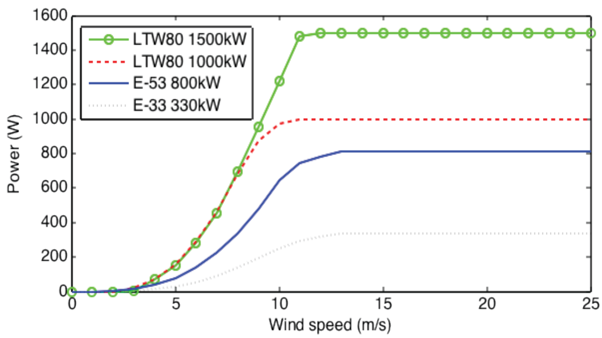


Figure (6). Power curves of the selected wind turbines.

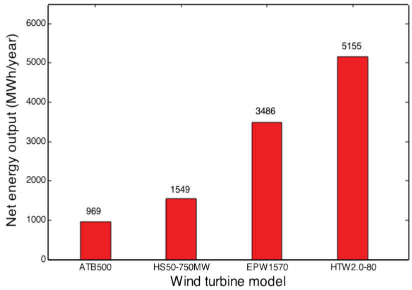


Figure (7). Annual mean net energy output of wind turbines.

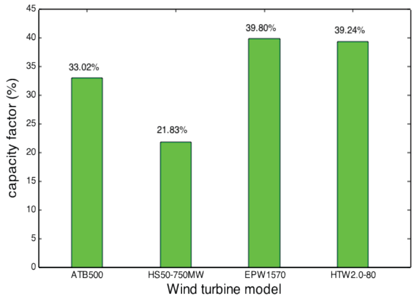


Figure (8). Capacity factor of wind turbine models.

CONCLUSIONS

Based on the detailed statistical study of wind power and energy potential at heights of 10 m, 30 m, and 50 m in Zwara, Libya during 2007, it can be concluded that:

- When the hub height is increased from 10 m to 30 m, the annual mean energy density increases by 79.57%, compared to an increase of only 19.24% when the hub height is increased from 30 m to 50 m.
- Based on the classification scheme of wind power density developed by the Battelle-Pacific Northwest Laboratory (PNL), the site under investigation has wind resources falling into class 2. Thus it can be considered suitable for small-scale applications.

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