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Assessment of Wind Energy Potential for Selecting Small-Scale Wind Turbines in Low Wind Locations in Libya: A Comparative Study

Youssef Kassem[1,2,]*, and Hüseyin Çamur[1], Mohamed A. AbuGharara[1]

[1]*Department of Mechanical Engineering, Engineering Faculty, Near East University, 99138 Nicosia (via Mersin 10, Turkey),*

[2]*Department of Civil Engineering, Civil and Environmental Engineering Faculty,*
Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus.

**Correspondence Author*

Abstract:

In this paper, ten distribution functions are used to analyze the characteristics of wind speed in three selected regions (Tripoli, Nault, and Esspeea) in Libya. The monthly wind speed data are used and measured at 10m height. The results indicated that the mean monthly wind speeds in the studied regions are within the range of 2.121 m/s to 4.349 m/s at 10m height. Annual distribution parameters are calculated for each distribution using the Maximum likelihood method. Kolmogorov–Smirnov (KS) statistic is determined to evaluate the distribution suitability to fit the actual wind speed data. In addition, the wind power density in each region is calculated. The results showed that Nault has the highest mean actual wind power (50.3W/m2) compared with Tripoli (30.972W/m2) and Esspeea (5.844W/m2). Moreover, since the hub height of many wind turbines is higher than the measurement height, the distribution parameters and wind power density are estimated at various heights using power law method. The result demonstrated that small-scale wind turbines can be exploited by the wind in different regions. Consequently, the present value cost method (PVC) is used to evaluate the energy cost of electricity using various wind turbine models. Economically, the lowest value of electricity cost was obtained from Finn Wind Tuule C 200 with a value of 0.001427 $/kW for Tripoli, 0.0010 $/kW for Nault and 0.013194$/kW for Esspeea.

Keywords: Economic analysis; Libya; horizontal axis wind turbines; statistical distribution; vertical axis wind turbine; wind speed characteristics

1. INTRODUCTION

The increases of populations and energy demand have increased in recent years the significance of renewable energy as an alternative source. Renewable energy sources are considered clean alternatives to fossil fuels that can provide sustainable energy solutions [1-3]. Renewable energies such as wind energy are recognized as alternative resources for generating electricity in the future [4]. A key advantage of wind energy is that they avoid carbon dioxide emissions [5]. Wind energy can be converted directly into electricity using wind turbines [6]. It now used extensively for meeting the electricity demand in many countries such as India [7], Pakistan [8], Turkey [9] and Saudi Arabia [10].

Wind speed characteristics are the most factor to investigate the wind potential at a specific location [11]. Several scientific researchers have been investigated the wind potential in different regions. For instance, Alayat et al. [12] evaluate the wind potential and estimate the electricity cost per kWh using small-scale vertical axis wind turbine at eight selected regions in Northern Cyprus. The results showed that Aeolos-V2 with a rating of 5kWuse could be suitable for generating electricity in the studied locations. Kassem et al. [12] evaluated the economic feasibility of 12MW grid-connected wind farms and PV plants for producing electricity in Girne and Lefkoşa in Northern Cyprus. The authors concluded that PV plants are the most economical option compared to wind farms for generating electricity in the studied regions. Azad et al. [13] investigated the wind energy assessment at different hub heights in desired locations using the Weibull distribution function. The results showed that the wind power sources in the site are categorized as poor. Albani and Ibrahim [15] analyzed the wind energy potential at three coastal locations in Malaysia. They concluded that the production of wind energy is only feasible and practical at certain locations in Malaysia. Belabes et al. [16] evaluated the wind potential at six selected sites in North of Algeria. They concluded that wind power project is not economically in North of Algeria due to its high generation prices. Ohunaki and Akinnawonu [17] evaluated the wind potential at Jos in Nigeria using long-term wind speed data. They found that the selected site is suitable for wind turbine applications.

Libya is a North African country bordered by the Mediterranean Sea to the north, Egypt to the east, Sudan to the southeast, Chad and the Niger to the south, Algeria to Tunisia to the west (Davies, 2009). It has an area of nearly 1.8 million square kilometers (700,000 square miles) and Libya is the fourth largest country in Africa and occupies the 17th largest country in the world. Ranking ninth among 10 countries with the world's largest proven oil reserves (Hubbard, 2014). The increases of populations and energy demand have increased in recent years the significance of renewable energy as an alternative source.

In this regard, this paper aims to investigate wind energy potential at three selected regions in Libya. The wind speed data were taken from meteorological service for various periods and measured at 10m height. Ten distribution functions are used to determine the wind power density of the selected regions. In the present study, the parameters of these distribution functions are calculated using the Maximum Likelihood method. Power law model is used to calculate wind power density at different heights. Moreover, economic evaluation for a small-scale wind turbine using the present value cost method (PVC) has been made. To the best of author's knowledge, this is the first study to carry out such an analysis the wind speed at three selected regions in Libya.

The rest of the paper is structured as follows: Section 2 presents overall information about the collected wind data, wind data adjustment, and analysis procedure. Section 3 describes the wind speed characteristics at the studied locations and analyzes the wind power densities at different heights to evaluate wind energy potential in detail. It also discusses the economic evaluation and the performance of small-scale vertical axis wind turbines. Section 4 presents the discussions, and section 5 provides significant conclusions.

2. MATERIALS AND METHODS

In this section, the statistical analysis of wind speed measured at a height of 10m at three regions in Libya is discussed. Ten distributions are used to determine the wind power density in the studied regions. The power law method is utilized to estimate the wind speed at various hub heights. The annual energy outputs, capacity factors, and electricity-generated cost were derived for small-scale wind turbines of various sizes and type. Figure 1 illustrates the procedure analysis of the current study.

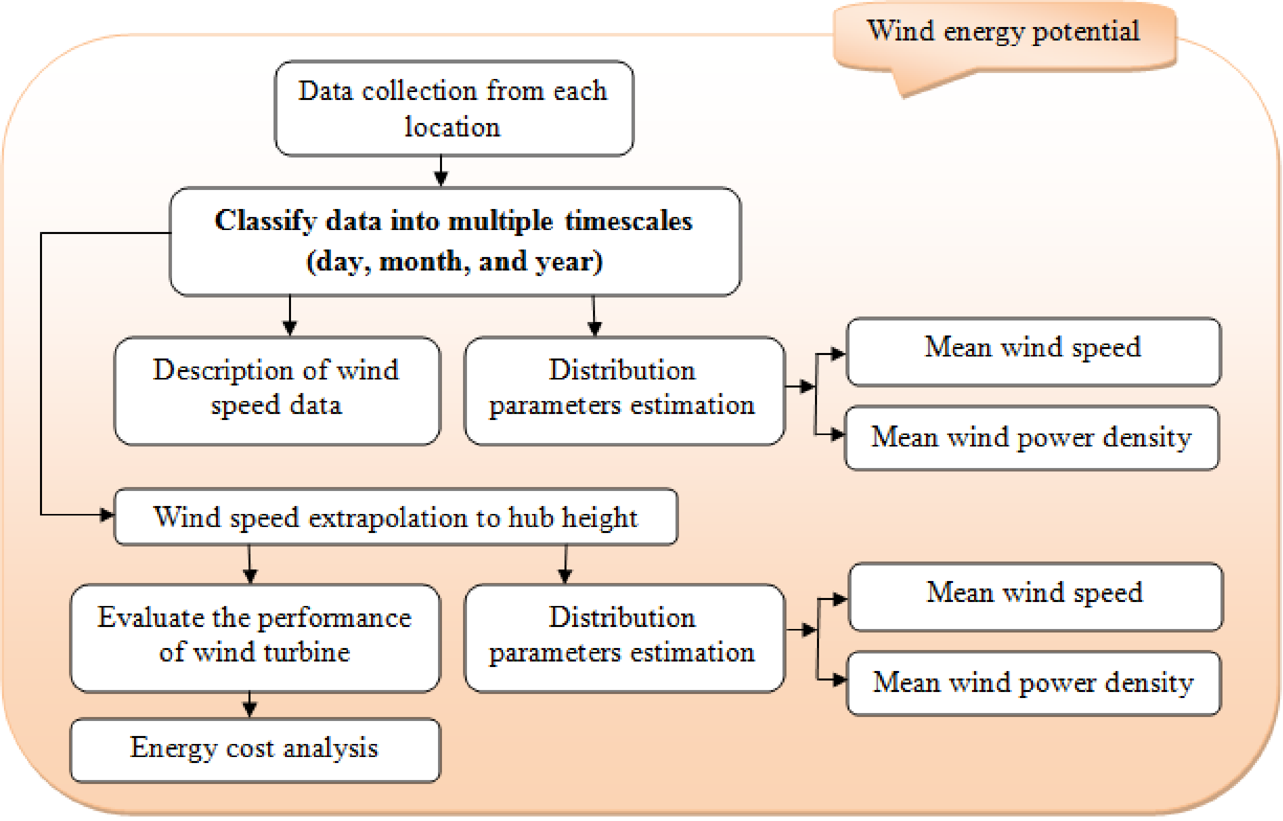

Figure 1. The flowchart for analysis steps of the study

2.1. Measurement data

The wind speed data of three selected regions were taken from meteorological service in Libya. The data are measured at the height of 10m. In this study, monthly wind speed is used to investigate the monthly wind speed data at the selected regions. The information and location of the selected regions are shown in Table 1 and Figure 2.

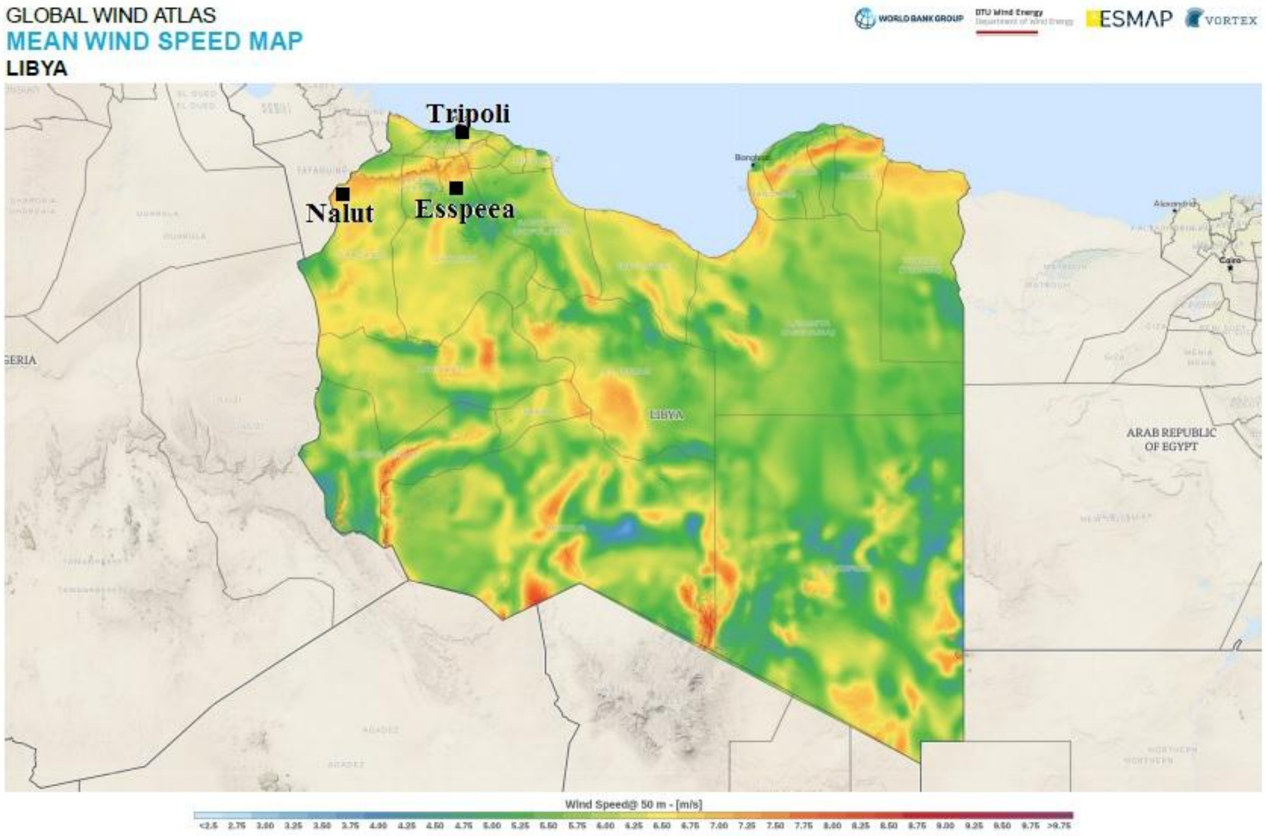

Figure 2. Wind Atlas map of Libya at 50m height

Table 1. information from three selected regions

Station	Longitude (°E)	Latitude (°N)	Altitude [m]	Period records	Measured height [m]	Year
Tripoli	32.892	13.173	81	1981-2010	10	30
Nault	31.874	10.979	568	1981-2010	10	30
Esspeea	32.892	13.173	73	1993-2009	10	17

2.1.1. Tripoli

Tripoli is the capital of Libya and its largest city. It has a population of (940,653) thousand in 2012, located in the north-west of Libya. The city is built on a rocky top overlooking the Mediterranean Sea opposite the southern tip of the island of Sicily. It is bordered by the Tajoura area, west of Janzur, south of the Suwani area, and the Mediterranean Sea to the north.

2.1.2. Nault

Nalut Libyan city, the center of the province of Nalut in the mountain "Nafusa mountain", located 276 kilometers from the capital city of Tripoli, at latitude (31.52) and on a longitude (10.59) degree. Nalut is one of the third largest mountain ranges after Green and Yefran, the last of these cities in the West. The importance of the city dates back to its position on the coastline between the Sahel and the Sahara and its proximity to the Tunisian-Algerian border.

2.1.3. Esspeea

Esspeea is a residential and agricultural area of Libya located south of Tripoli on the outskirts of the town of Qasr Ben Ghachir in the north, and up to the mountain of Gharyan in the south and its elevation from the sea surface is about 73 meters and has a semi-rocky climate. It is less than 40 kilometers south of Tripoli.

2.2. Probability distribution functions

Probability density function (PDF) and cumulative distribution function (CDF) are the most common functions used to analyze the wind speed characteristics. Table 2 is tabulated the PDF and CDF functions used for evaluating the wind speed characteristics in this study. The parameters of these functions are calculated using the maximum likelihood method. In order to obtain the distribution parameters, Easy fit, and Matlab R2015a software have been used.

Table 2. Expressions of statistical distributions used in this study [17, 20-24].

Distribution function	**PDF**	**CDF**
Weibull (W)	$PDF = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^{k}\right)$	$CDF = 1 - exp\left(-\left(\frac{v}{c}\right)^{k}\right)$
Gamma (G)	$PDF = \frac{v^{\beta-1}}{\alpha^{\beta}\Gamma(\beta)} exp\left(-\frac{v}{\beta}\right)$	$CDF = \frac{\gamma\left(\beta, \frac{v}{\alpha}\right)}{\Gamma(\beta)}$
Lognormal (LN)	$PDF = \frac{1}{v\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{ln(v)-\mu}{\sigma}\right)^{2}\right]$	$CDF = \frac{1}{2} + erf\left[\frac{ln(v)-\mu}{\sigma\sqrt{2}}\right]$
Logistic (L)	$PDF = \frac{exp\left(-\frac{v-\mu}{\sigma}\right)}{\sigma\left\{1 + exp\left(-\frac{v-\mu}{\sigma}\right)\right\}^{2}}$	$CDF = \frac{1}{1 + exp\left(-\frac{v-\mu}{\sigma}\right)}$
Log-Logistic (LL)	$PDF = \left(\left(\frac{\beta}{\alpha}\left(\frac{v}{\alpha}\right)^{\beta-1}\right) \Big/ \left(1+\frac{v}{\alpha}\right)^{\beta}\right)^{2}$	$CDF = \frac{1}{\left(1+\frac{v}{\alpha}\right)^{-\beta}}$
Inverse Gaussian (IG)	$PDF = \left(\frac{\lambda}{2\pi v^{2}}\right)^{1/2} e^{\left[\frac{-\lambda(v-\mu)^{2}}{2\mu^{2}v}\right]}$	$CDF = \Phi\left(\sqrt{\frac{\lambda}{v}}\left(\frac{v}{\mu}-1\right)\right) + exp\left(\frac{2\lambda}{\mu}\right)\Phi\left(-\sqrt{\frac{\lambda}{v}}\left(\frac{v}{\mu}+1\right)\right)$
Generalized Extreme Value (GEV)	$PDF = \frac{1}{\alpha}\left[1 - \frac{\zeta(v)-\mu}{\alpha}\right]^{\frac{1}{\zeta}-1} exp\left[-\left(1 - 1 - \frac{\zeta(v)-\mu}{\alpha}\right)^{\frac{1}{\zeta}}\right]$	$CDF = exp\left[-\left(1 - 1 - \frac{\zeta(v)-\mu}{\alpha}\right)^{\frac{1}{\zeta}}\right]$
Nakagami (Na)	$PDF = \frac{2m^{m}}{\Gamma(m)\Omega^{\mathrm{m}}} v^{2m-1} e^{\left(-\frac{m}{\Omega}G^{2}\right)}$	$CDF = \frac{\gamma\left(m, \frac{m}{\Omega}v^{2}\right)}{\Gamma(m)}$
Normal (N)	$PDF = \frac{1}{\sqrt{2\pi\sigma^{2}}} exp\left(-\frac{v-\mu}{2\sigma^{2}}\right)$	$CDF = \frac{1}{2}\left[1 + erf\left(\frac{v-\mu}{\sigma\sqrt{2}}\right)\right]$
Rayleigh (R)	$PDF = \frac{2v}{c^{2}} e^{-\left(\frac{v}{c}\right)^{2}}$	$CDF = 1 - exp\left[-\left(\frac{v}{c}\right)^{2}\right]$

W	**k**	Shape parameter	LL	$\boldsymbol{\beta}$	Shape parameter	Na	$\boldsymbol{m}$	Shape parameter
	c [m/s]	Scale parameter		$\boldsymbol{\alpha}$	Scale Parameter		$\boldsymbol{\Omega}$	Scale parameter
G	$\boldsymbol{\beta}$	Shape parameter	IG	$\boldsymbol{\lambda}$	Shape parameter	N	$\boldsymbol{\sigma}$	Standard deviation
	$\boldsymbol{\alpha}$	Scale Parameter		$\boldsymbol{\mu}$	Mean parameter		$\boldsymbol{\mu}$	Mean parameter
LN	$\boldsymbol{\sigma}$	Shape parameter	GEV	$\boldsymbol{\mu}$	Location Parameter	R	**c [m/s]**	Scale parameter
	$\boldsymbol{\mu}$	Scale Parameter		$\boldsymbol{\zeta}$	Scale Parameter			
L	$\boldsymbol{\mu}$	Location Parameter		$\boldsymbol{\alpha}$	Shape Parameter			
	$\boldsymbol{\sigma}$	Scale Parameter						

2.3. Wind power density (WPD)

The theoretically available kinetic energy that wind possesses at a certain location can be expressed as the mean wind power density (WPD). In other words, it is the maximum available wind power at each unit area. The mathematical expression for wind power density is given with the following relations [25, 26]:

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

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

Moreover, the mean wind power density can be estimated using Eq. (3) [11].

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

where P is wind power density in W, A is swept area in m^2, ρ is air density (ρ =1.225 kg/m^3) $f(v)$ is the probability density function (PDF), $\bar{P}$ the mean wind power density in W and $\bar{v}$ is the mean wind speed in m/s.

2.4. Wind speed variation

Power law model is widely used to estimate the wind speed (v) at a different hub height of wind turbine (z) [11, 20]. It is expressed as

$$\frac{v}{v_{10}}=\left(\frac{z}{z_{10}}\right)^{\alpha} \tag{4}$$

where v_{10} is the wind speed at original height z_{10}, and α is the surface roughness coefficient (Eq. (5)).

$$\alpha=\frac{0.37-0.088ln(v_{10})}{1-0.088ln(z_{10}/10)} \tag{5}$$

2.5. The energy output of wind turbines

The wind turbine can produce a useful power when the wind speed reaches to cut-in wind speed (v_{ci}) of the turbine. After that, the power starts to increase until the wind speed achieves the rated wind speed (v_r), at this speed the power is equal to the rated power of wind turbine (P_r). The power generation stops when the wind speed greater than the wind cut-off wind speed (v_{co}) in order to prevent damage to the wind turbine. Consequently, the power generation of wind turbine (P_{wt}) and the total power generated (E_{wt}) over a period (t) can be expressed as [25]

$$P_{wt(i)}=\begin{cases} \mathrm{P_r}\dfrac{v_i^2-v_{ci}^2}{v_r^2-v_{ci}^2} & v_{ci}\le v_i\le v_r \\ \dfrac{1}{2}\rho A C_p v_r^2 & v_r\le v_i\le v_{co} \\ 0 & v_i\le v_{ci}\ and\ v_i\ge v_{co} \end{cases} \tag{6}$$

$$E_{wt}=\sum_{i=1}^{n}P_{wt(i)}\times t \tag{7}$$

where C_p is the performance coefficient, which can be estimated as

$$C_p=2\frac{P_r}{\rho A v_r^3} \tag{8}$$

The total energy generated (E_{wt}) by the operation of the wind turbine over a period (t) can be determined as [25].

Finally, the capacity factor (CF) of a wind turbine can be estimated as [25]:

$$CF=\frac{E_{wt}}{P_r.t} \tag{9}$$

2.6. Economic analysis of wind turbines

The wind power project cost depends on three main factors: capital cost (I), operation and maintenance system cost (C_{omr}) and the turbine life (n) [27,28]. Several methods are used to estimate the cost of the wind power project. The most common method used to calculate the wind energy cost is the present value of costs (PVC) method [29]. It is expressed as

$$PVC=\left[I+C_{omr}\left(\frac{1+i}{r-i}\right)\times\left[1-\left(\frac{1+i}{1+r}\right)^n\right]-S\left(\frac{1+i}{1+r}\right)^n\right] \tag{10}$$

where r is the discount rate, i is the inflation rate and S is the scrap value of the turbine price and civil work.

The cost energy cost per kWh (CE) can be estimated as [29]:

$$EGC=\frac{PVC}{t\times P_r\times CF} \tag{11}$$

3. RESULTS

3.1. Description of wind speed data

The descriptive statistics of each studied region in terms of mean, maximum, median, standard deviation (SD), the coefficient of variation (Cv), skewness, and kurtosis are presented in Table 3. It is found the mean wind speed values are ranged from 2.121 m/s to 4.349 m/s at 10m height. The maximum and minimum mean wind speeds were recorded in Nault and Esspeea with a value of 4.349m/s and 2.121 m/s, respectively. In addition, the variation coefficients are moderately high and ranged from 10.33 to 15.36. It is also found that annual values of skewness are positive which indicated that all distributions are right-skewed except Nault. One of the most important factors that explain the wind speed at a specific region is the altitude of the region above ground level (Ouarda et al., 2015). For this study, the largest median wind speed occurred at Nault, which is located at the latitude of 568m (see Table 1). While the lowest median wind speed has occurred at Esspeea (altitude above the ground level is 73m)

Table 3. Descriptive statistics of wind speed series

Station	height [m]	Maximum [m/s]	Mean [m/s]	Median [m/s]	SD [m/s]	C_v	Skewness	Kurtosis
Tripoli	10	4.649	3.698	3.626	0.498	13.47	0.82	-0.44
Nault	10	4.843	4.349	4.538	0.449	10.33	-0.36	-1.83
Esspeea	10	2.7992	2.121	2.088	0.3257	15.36	0.87	0.46

Figure 3 shows the seasonally wind speed data for three selected sites. During the winter season, the maximum and minimum wind speeds were occurred in 2003 and 1989, respectively, at Tripoli. In addition, for Nault site, the highest and lowest wind speed was recorded in 1987 and 1997, respectively. For Esspeea site, the minimum wind speed was recorded in 2008 with a value of 1.2m/s. In spring season, the wind speed values were varied from 3.2m/s to 4.9m/s for Tripoli, 3.5m/s to 6.1m/s for Nault and 2.0m/s to 3.2 m/s for Esspeea. In the summer season, the wind speed level was reached 4.6m/s in 2003 at Tripoli, 5m/s in 1987 at Nault and 2.7m/s in 1993 at Esspeea. For the autumn season, the wind speed values were ranged from 2.3 and 4.4 for Tripoli, 2.8 and 5.2 m/s for Nault and 1.3 and 2.7m/s for Esspeea. Generally, Figure 3 gives the following findings:

1) The highest values of the mean monthly wind speed of all stations occurred during winter and spring seasons;
2) For all seasons, Nault has the maximum values of mean monthly wind speed.

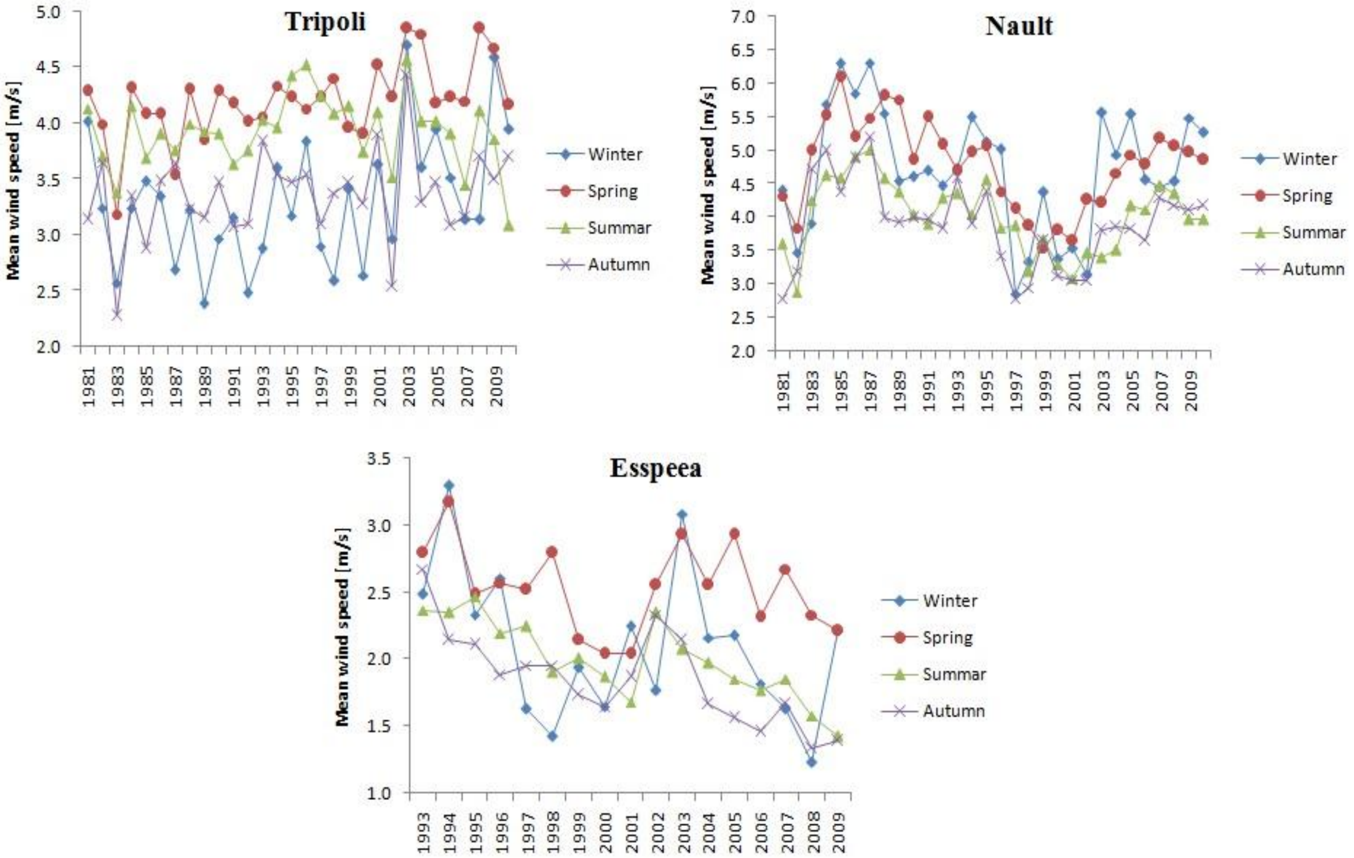

Figure 3. Seasonally wind speeds for three studied sites

The monthly wind speeds for all selected sites are shown in Figure 4.

Figure 4 shows the monthly wind speed at the selected sites. It is noticed that monthly wind speed is ranged from 1.70 and 4.7 m/s. The highest and lowest wind speeds are obtained in May at Tripoli and October at Esspeea, respectively. In addition, it is found that Nault has the maximum yearly wind speeds compared to other sites.

3.2. Distribution function parameters at 10m height

As mentioned previously, the Maximum like-hood method was used to determine the parameters of ten distribution functions. Therefore, the mean, variance and the parameters of each distribution function are tabulated in Table 4. Additionally, Figure 5 illustrates the PDF and CDF for each site. Moreover, in order to select the best distribution that provides a good fit to actual wind speed data, the Kolmogorov-Smirnov test (KS) was used. The result of KS with the ranked distribution function is listed in Table 5. The lowest value of KS for distribution function is considered as the best distribution for analyzing the wind speed. It is found that Generalized Extreme Value distribution has the lowest KS compared to other distributions. Moreover, it is noticed that Rayleigh distribution function cannot be used to evaluate the wind potential in the studied Location, as shown in Table 5 and Figure 5.

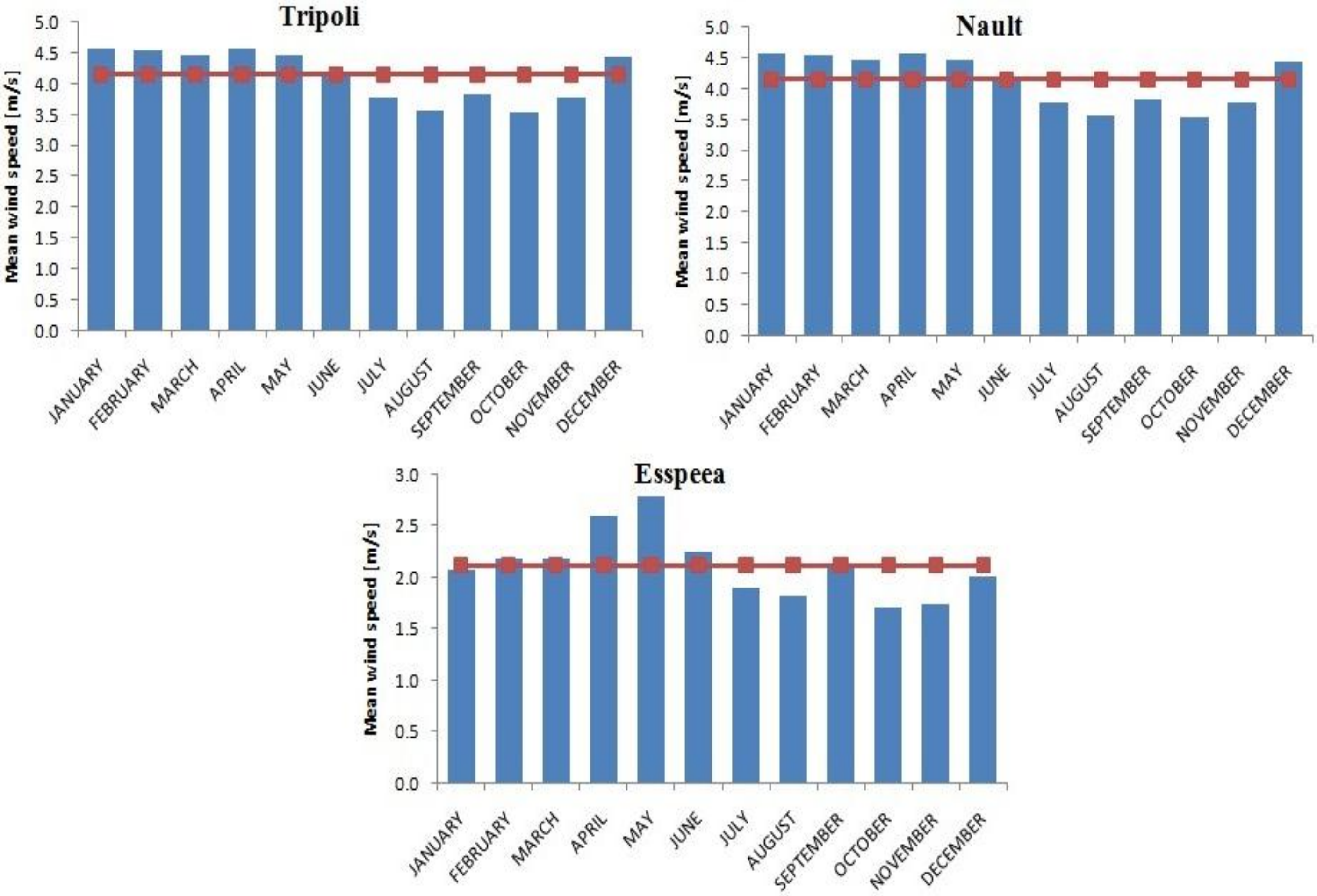

Figure 4. Monthly wind speed

Table 4. Parameter values of different distribution functions over the investigated period at 10 m height

Model	Parameters	Tripoli	Nault	Esspeea
Actual	**mean**	3.698	4.349	2.121
Gamma	**Mean**	3.708	4.342	2.121
	Variance	0.208	0.188	0.092
	β	65.978	100.531	48.764
	α	0.056	0.043	0.044
Generalized Extreme Value	**Mean**	3.715	4.294	2.121
	Variance	0.306	0.324	0.107
	ζ	0.164	-1.122	0.052
	α	0.328	0.537	0.237
	μ	3.463	4.322	1.971
Inverse Gaussian	**Mean**	3.708	4.342	2.121
	Variance	0.206	0.191	0.091
	μ	3.708	4.342	2.121
	λ	247.257	427.983	104.424
Logistic	**Mean**	3.658	4.369	2.092
	Variance	0.245	0.236	0.101
	μ	3.658	4.369	2.092
	σ	0.273	0.268	0.175
Log-Logistic	**Mean**	3.674	4.379	2.105
	Variance	0.237	0.252	0.100
	β	1.293	1.470	0.733
	α	0.072	0.063	0.082
Lognormal	**Mean**	3.710	4.344	2.123
	Variance	0.226	0.209	0.100
	σ	1.303	1.463	0.742
	μ	0.128	0.105	0.148
Nakagami	**Mean**	3.709	4.341	2.122
	Variance	0.212	0.184	0.094
	m	16.355	25.682	12.080
	Ω	13.969	19.033	4.597
Normal	**Mean**	3.708	4.342	2.121
	Variance	0.237	0.199	0.106
	μ	3.708	4.342	2.121
	σ	0.487	0.446	0.326
Rayleigh	**Mean**	3.312	3.866	1.900
	Variance	2.998	4.084	0.987
	c	2.643	3.085	1.516
Weibull	**Mean**	3.696	4.354	2.111
	Variance	0.294	0.169	0.134
	c	3.922	4.531	2.261
	k	8.101	12.920	6.759

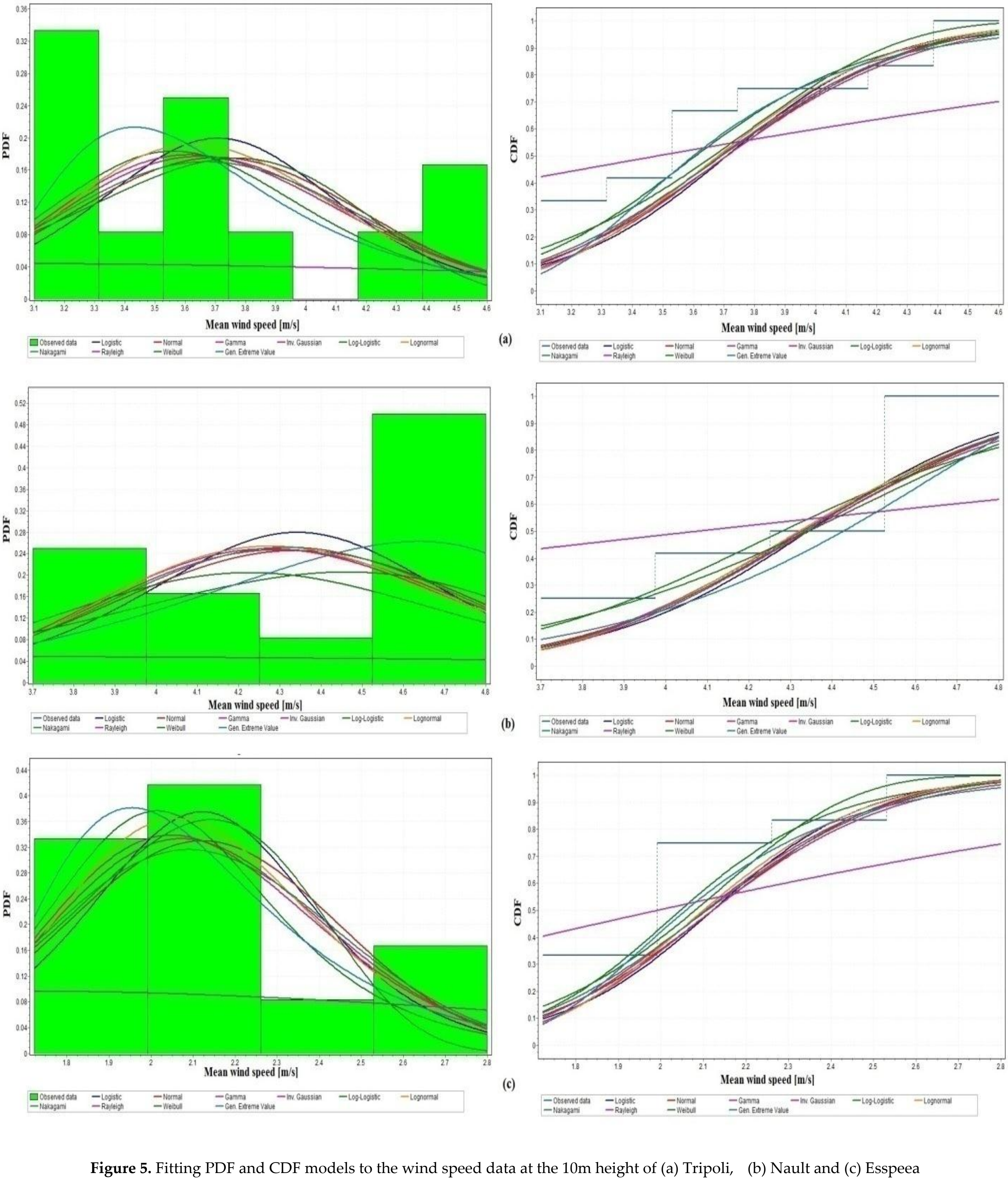

Figure 5. Fitting PDF and CDF models to the wind speed data at the 10m height of (a) Tripoli, (b) Nault and (c) Esspeea

Table 5. Results of goodness-of-fit and the selected distribution (in bold) for each Location at 10m height

Site	Model	Kolmogorov Smirnov test	Ranked
Tripoli	Gamma	0.15889	2
	Generalized Extreme Value	**0.13161**	**1**
	Inverse Gaussian	0.17625	8
	Logistic	0.17587	7
	Log-Logistic	0.16840	5
	Lognormal	0.15844	3
	Nakagami	0.16550	4
	Normal	0.17535	6
	Rayleigh	0.42239	10
	Weibull	0.18045	9
Nault	Gamma	0.29280	6
	Generalized Extreme Value	**0.25502**	**1**
	Inverse Gaussian	0.27995	4
	Logistic	0.31106	9
	Log-Logistic	0.26614	3
	Lognormal	0.29910	8
	Nakagami	0.29645	7
	Normal	0.28908	5
	Rayleigh	0.43470	10
	Weibull	0.26051	2
Esspeea	Gamma	0.15277	6
	Generalized Extreme Value	**0.11781**	**1**
	Inverse Gaussian	0.17278	9
	Logistic	0.14870	4
	Log-Logistic	0.13747	3
	Lognormal	0.13469	2
	Nakagami	0.16203	7
	Normal	0.16789	8
	Rayleigh	0.40397	10
	Weibull	0.15032	5

3.3. Distribution function parameters at various heights

Generally, the value of wind speed depends on the measurement height. Therefore, in order to yield an accurate determination of wind energy potential, the winds speed is calculated at different wind turbine hub height using Eq. (4) and (5). As results, the monthly wind speed at different height is evaluated and illustrated as shown in Figure 6. It noticed that as the height above the ground increases, the wind speed would increase.

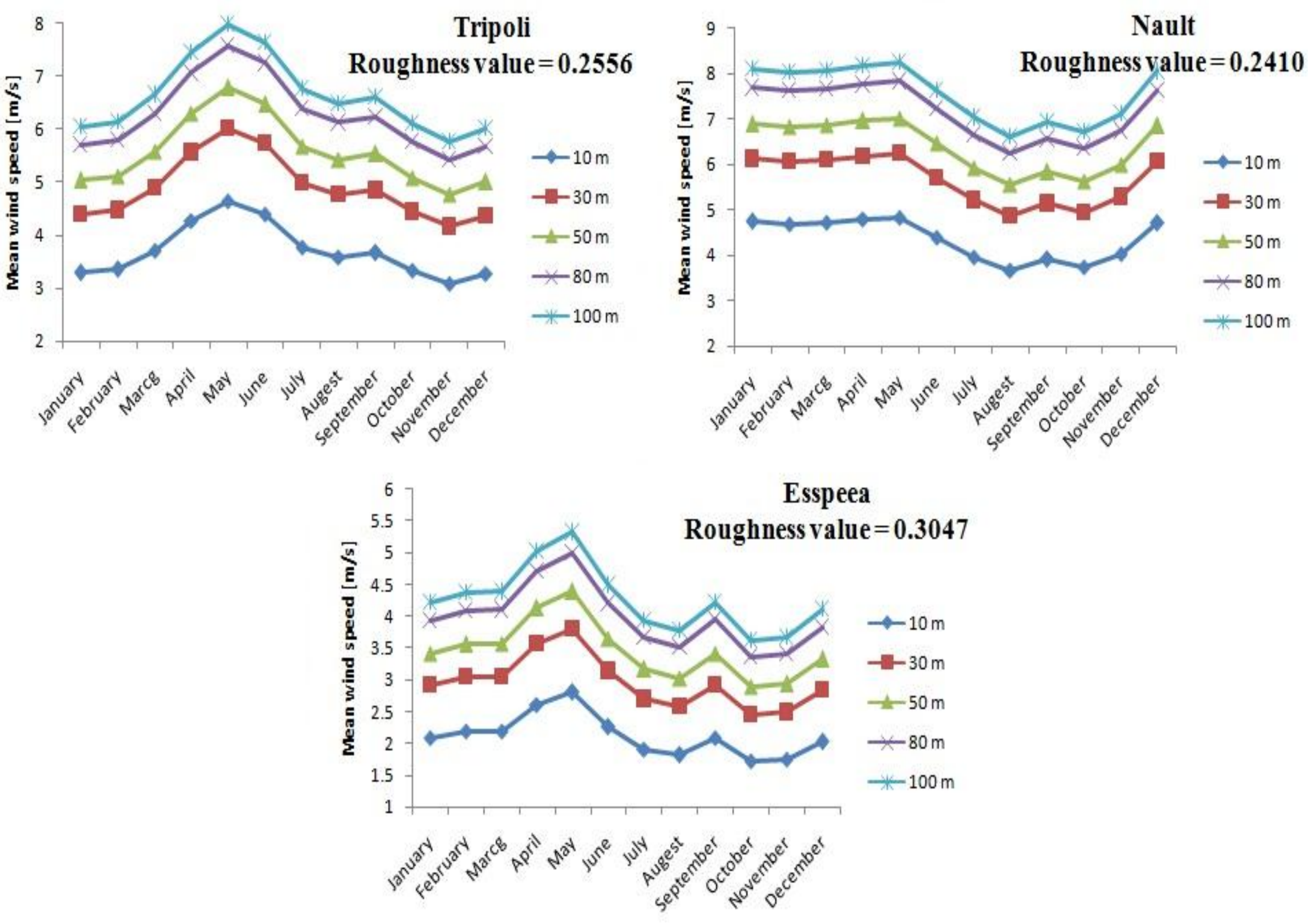

Figure 6. Monthly mean wind speed profile at various heights

Data collected from each site at a height of 10m have been extrapolated to various heights, which is characterized as a good to very good wind resource height in the literature (Mostafaeipour, 2010). In order to ensure the Generalized Extreme Value as the best distribution to study the wind speed characteristics for all studied site, Table 7 tabulates the parameters of ten distributions at various heights. In addition, goodness-of-fit statistics in terms of the Kolmogorov-Smirnov tests for each distribution function are summarized in Table 8. It is observed that Generalized Extreme Value can be used to study the wind speed distribution at any heights for all selected sites.

Table 7. Parameter values of different distribution functions over the investigated period at various heights

Hub height		**30 m**			**100 m**		
Model	**Parameters**	**Tripoli**	**Nault**	**Esspeea**	**Tripoli**	**Nault**	**Esspeea**
Actual	**mean**	4.889	5.663	2.959	6.642	7.563	4.263
Gamma	**Mean**	4.889	5.663	2.959	6.642	7.563	4.263
	Variance	0.309	0.263	0.146	0.443	0.367	0.236
	β	77.419	121.759	59.843	99.533	155.980	76.928
	α	0.063	0.047	0.049	0.067	0.048	0.055
Generalized Extreme Value	**Mean**	4.901	5.661	2.958	6.653	7.611	4.261
	Variance	0.482	0.383	0.166	0.664	0.447	0.263
	ζ	0.189	-1.063	0.039	0.176	-1.052	0.024
	α	0.389	0.602	0.301	0.471	0.653	0.387
	μ	4.587	5.677	2.772	6.283	7.626	4.028
Inverse Gaussian	**Mean**	4.889	5.663	2.959	6.642	7.563	4.263
	Variance	0.305	0.268	0.145	0.438	0.372	0.234
	μ	4.889	5.663	2.959	6.642	7.563	4.263
	λ	383.279	678.238	178.820	669.008	1163.330	331.151
Logistic	**Mean**	4.826	5.693	2.924	6.567	7.599	4.220
	Variance	0.359	0.333	0.160	0.514	0.465	0.258
	μ	4.826	5.693	2.924	6.567	7.599	4.220
	σ	0.330	0.318	0.220	0.395	0.376	0.280
Log-Logistic	**Mean**	4.843	5.704	2.939	6.585	7.611	4.237
	Variance	0.345	0.352	0.158	0.496	0.487	0.254
	β	1.570	1.736	1.069	1.879	2.025	1.437
	α	0.066	0.057	0.074	0.059	0.050	0.065
Lognormal	**Mean**	4.891	5.665	2.961	6.644	7.566	4.265
	Variance	0.333	0.293	0.158	0.479	0.406	0.256
	σ	1.581	1.730	1.077	1.888	2.020	1.443
	μ	0.118	0.095	0.134	0.104	0.084	0.118
Nakagami	**Mean**	4.890	5.663	2.960	6.642	7.563	4.263
	Variance	0.314	0.260	0.149	0.450	0.362	0.240
	m	19.145	30.999	14.819	24.618	39.598	19.048
	Ω	24.227	32.327	8.910	44.572	57.563	18.418
Normal	**Mean**	4.889	5.663	2.959	6.642	7.563	4.263
	Variance	0.352	0.281	0.167	0.502	0.392	0.268
	μ	4.889	5.663	2.959	6.642	7.563	4.263
	σ	0.593	0.530	0.409	0.709	0.626	0.518
Rayleigh	**Mean**	4.362	5.039	2.645	5.917	6.724	3.803
	Variance	5.199	6.937	1.912	9.565	12.353	3.952
	c	3.480	4.020	2.111	4.721	5.365	3.035
Weibull	**Mean**	4.871	5.677	2.945	6.618	7.580	4.243
	Variance	0.451	0.242	0.216	0.658	0.340	0.356
	c	5.153	5.890	3.137	6.962	7.834	4.493
	k	8.652	14.119	7.483	9.801	15.995	8.477

Table 8. Results of goodness-of-fit and the selected distribution (in bold) for each Location at various heights

hub height		**30 m**		**100 m**	
Site	**Model**	**Kolmogorov Smirnov test**	**Ranked**	**Kolmogorov Smirnov test**	**Ranked**
Tripoli	Gamma	0.16724	2	0.16801	3
	Generalized Extreme Value	**0.13893**	**1**	**0.13889**	**1**
	Inverse Gaussian	0.18331	8	0.18210	7
	Logistic	0.19623	9	0.19625	9
	Log-Logistic	0.15330	3	0.15330	2
	Lognormal	0.18279	7	0.18279	8
	Nakagami	0.17172	4	0.17040	4
	Normal	0.18089	6	0.17818	6
	Rayleigh	0.43374	10	0.44648	10
	Weibull	0.17419	5	0.17419	5
Nault	Gamma	0.27786	6	0.27754	5
	Generalized Extreme Value	**0.23233**	**1**	**0.23223**	**1**
	Inverse Gaussian	0.26602	4	0.26705	4
	Logistic	0.29607	9	0.29626	9
	Log-Logistic	0.25920	3	0.25920	3
	Lognormal	0.28501	8	0.28501	8
	Nakagami	0.28047	7	0.27988	7
	Normal	0.27363	5	0.27382	5
	Rayleigh	0.44052	10	0.45238	10
	Weibull	0.25111	2	0.25111	2
Esspeea	Gamma	0.15180	6	0.15073	6
	Generalized Extreme Value	**0.11755**	**1**	**0.11726**	**1**
	Inverse Gaussian	0.16983	9	0.16660	9
	Logistic	0.14590	4	0.14287	4
	Log-Logistic	0.13747	3	0.13747	3
	Lognormal	0.13469	2	0.13469	2
	Nakagami	0.16037	7	0.15847	7
	Normal	0.16528	8	0.16246	8
	Rayleigh	0.41711	10	0.43165	10
	Weibull	0.15032	5	0.15032	5

3.4. The wind power density at various heights

The values of wind power density at 10m height for each studied site were estimated using Eq. (4) and tabulated in Table 9. It can be seen that Nault has the highest mean actual wind power (50.3/m^2) compared with Tripoli (30.972W/m^2) and Esspeea (5.844W/m^2). When the Generalized Extreme Value distribution is used, the estimated power density at an extrapolated height of 10m and was varied from 5.843 to 48.493W/m^2. The highest calculated power density values are 48.493 W/m^2 at Nault, while the minimum WPD was observed at Esspeea with 5.843 W/m^2. For comparison purposes, the calculated annual WPD at various is presented in Table 9.

The kinetic energy potential of the wind at each site is characterized by the mean power density ranges given in the literature [30, 31]. Among the sites investigated in this study, the maximum estimated power density became prominent in the Nault site, where the highest density is 264.998 W/m^2 at a height of 100m (Table 9). According to the results listed in Tables 9 and the wind power classification [30, 31], all of the locations chosen for investigation indicate poor wind energy potential. Therefore, high capacity wind turbines (MWs) are not feasible to be investigated in these sites. Nevertheless, small-scale wind turbines can be used to gather the wind energy potential in these locations.

Table 9. Mean wind power density in W/m^2 of all selected regions at various heights

Hub height	**10 m**			**30 m**			**100 m**		
Model	**Tripoli**	**Nault**	**Esspeea**	**Tripoli**	**Nault**	**Esspeea**	**Tripoli**	**Nault**	**Esspeea**
Actual	30.975	50.382	5.844	71.585	111.238	15.871	179.444	264.998	47.445
Gamma	31.235	50.128	5.847	71.585	111.238	15.871	179.444	264.999	47.445
Generalized Extreme Value	31.409	48.493	5.843	72.086	111.108	15.854	180.378	270.092	47.381
Inverse Gaussian	31.235	50.128	5.847	71.585	111.238	15.871	179.444	264.999	47.445
Logistic	29.990	51.069	5.607	68.835	113.017	15.305	173.492	268.795	46.015
Log-Logistic	30.364	51.431	5.715	69.559	113.679	15.544	174.916	270.016	46.575
Lognormal	31.285	50.207	5.859	71.682	111.381	15.899	179.637	265.260	47.511
Nakagami	31.254	50.120	5.853	71.622	111.225	15.883	179.505	264.978	47.468
Normal	31.235	50.128	5.847	71.585	111.238	15.871	179.444	264.999	47.445
Rayleigh	22.258	35.399	4.202	50.838	78.360	11.339	126.861	186.191	33.696
Weibull	30.928	50.551	5.763	70.793	112.052	15.644	177.505	266.726	46.777

3.5. Economic analysis of electricity generation potential

In this study, the performance of two types of a wind turbine, namely a horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) was investigated. Generally, HAWTs are the most commonly used for generating electricity today. However, vertical axis wind turbines are good for low wind speed and can be installed on the rooftop of the building or on top of communication towers. The characteristic of the selected small-scale wind turbines is presented in Table 10.

The total energy power of wind turbine in kW, capacity factor and the electricity cost of each wind turbine were calculated using Eq. (7), (10) and (12), respectively.

Table 11 shows the effect of hub height on the annual energy and capacity factor from the chosen wind turbine. For a horizontal axis wind turbine, it is found that Finn Wind Tuule C 200 with 3kW rated has the minimum of annual energy and capacity factor corresponding to the hub height (27m) for all regions. For a vertical axis wind turbine, Winddam with 4kW was found to be most efficient with a maximum of annual energy and capacity factor corresponding to various hub heights.

Economically, the lowest value of electricity cost was obtained from Finn Wind Tuule C 200 with a value of 0.001427 $/kW for Tripoli, 0.0010 $/kW for Nault and 0.013194$/kW for Esspeea as shown in Table 11. Most of the roof's building on these regions are flat and the majority of the people in these regions probably can be used vertical axis wind turbine. Thus, it would be recommended for the selected regions to adapt turbine model Winddam (VWAT).

Table 10. Characteristics of the selected wind turbine

Turbine type	**Model**	**P_r[KW]**	**Hub height [m]**	**v_{ci} [m/s]**	**v_r [m/s]**	**v_{c0}[m/s]**
HAWT	**Finn Wind Tuule C 200**	3	27	1.9	10	-
HAWT	**Aircon10**	10	12/18/24/30	2.5	11	32
VAWT	**Winddam**	4	12/18/24/30	2.5	12	-
VAWT	**Windside (WS-12)**	8	12/18/24/30	2	20	-

Table 11. Electricity production and financial indices in three regions

Region	Model	Hub height [m]	Total energy power of wind turbine [kW]	CF [%]	COEG [c$/kWh]
Tripoli	Windside (WS-12)	12	146.814	76.466	0.011563
		18	167.028	86.994	0.010164
		24	219.345	114.242	0.007740
		30	263.620	137.302	0.006440
	Winddam	12	162.418	169.186	0.005226
		18	191.474	199.452	0.004433
		24	266.674	277.785	0.003183
		30	330.314	344.077	0.002570
	Aircon10	12	487.432	203.097	0.004354
		18	574.631	239.430	0.003693
		24	800.312	333.463	0.002652
		30	991.302	413.043	0.002141
	Finn Wind Tuule C 200	27	446.121	619.613	0.001427
Nault	Windside (WS-12)	12	229.607	119.587	0.007394
		18	256.220	133.448	0.006626
		24	324.498	169.010	0.005232
		30	381.705	198.805	0.004448
	Winddam	12	281.424	293.149	0.003016
		18	319.677	332.997	0.002655
		24	417.820	435.229	0.002032
		30	500.048	520.884	0.001697
	Aircon10	12	844.577	351.907	0.002513
		18	959.379	399.741	0.002212
		24	1253.915	522.464	0.001692
		30	1500.690	625.287	0.001414
	Finn Wind Tuule C 200	27	636.854	884.519	0.001000
Esspeea	Windside (WS-12)	12	4.226	2.201	0.401759
		18	5.148	2.681	0.329761
		24	11.959	6.229	0.141954
		30	20.841	10.855	0.081459
	Winddam	12	1.370	1.427	0.619762
		18	2.696	2.808	0.314882
		24	7.782	8.106	0.109080
		30	14.276	14.870	0.059460
	Aircon10	12	4.110	1.713	0.516281
		18	8.090	3.371	0.262306
		24	23.354	9.731	0.090867
		30	42.842	17.851	0.049532
	Finn Wind Tuule C 200	27	48.250	67.014	0.013194

4. CONCLUSIONS

In this paper, the wind speed characteristics and wind power potential at three locations in Libya: Tripoli, Nault, and Esspeea for various periods were investigated. Moreover, the capabilities of a horizontal axis wind turbine and a vertical axis wind turbine to generate power at the selected locations were examined and compared their functionality in the urban environment. The following are the major conclusion from the analysis:

- Annual mean wind speed for the three regions considered in this study is ranging from 2.1 to 4.1 m/s at 10 m, which indicates that the investigated regions have low wind energy potential.
- Among the studied locations, it was noticed that Nault has the highest winds. The wind power analysis shows that Nault is the best location for harvesting wind energy.
- As a result, the annual wind power values were ranged from 5.844W/m^2 to 30.975W/m^2 at 10m height and 15.871W/m^2 to 71.585W/m^2 at 30m height. These values demonstrated that the wind power potential of these regions could be possible to exploit the wind power using small-scale wind turbines at the region.
- Based on the results, it was concluded that VAWT with a comparable rated output would produce more power in the urban environment than a HAWT due to less noisy and higher efficiency in the urban environment.
- In comparison, it was found that Winddam with a power rating of 4kW had the lowest energy production cost among the considered vertical axis wind turbine. In addition, it was observed that Finn Wind Tuule C 200 with a power rating of 3kW had the lowest energy production cost among the considered horizontal axis wind turbine.

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Conflicts of Interest:

The authors declare no conflict of interest.

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