Technical and Economical Evaluation and GHG Analysis of Wind Power Generation in Four Sites Using Different Weibull Parameters

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Abstract- Four sites close to the Libyan coast were selected for technical and economical assessment of wind power generation using real measured wind data. The assessment was carried out using the Weibull distribution function and the Weibull parameters were calculated using three different methods; graphical method (GM), empirical method (EM) and maximum likelihood method (MLM). Error analyses using various techniques were conducted to check for the validity of the different Weibull methods used. The technical assessment includes the calculations of the annual energy production (AEP), capacity factor (C_f) and greenhouse gas emission (GHG) reduction. The estimated annual energy production was used in the calculation of the present value of cost which estimates the cost of each kWh of electricity produced by a certain wind turbine. The effect of the annual greenhouse gas emission reduction on the cost analysis was also considered. The results have shown the electricity cost of all the sites is below the world average electricity price. Using different Weibull parameters have noticeable effects on the technical and economical estimations of wind power production. The MLM method yields higher AEP estimation compared to the other methods for all the sites. On the other hand, GM method gives less estimation for the AEP compared to the other methods for all the sites. Adding the GHG reduction income into the electricity cost calculations decreases it by an average of 18%.

Keywords Wind energy, Weibull distribution, wind assessment, annual energy production, present value of cost, GHG.

1. Introduction

The demand for energy increases due to the daily increase in population and industry. Fossil-fuel based energy sources have negative effects on the environment and they are running out. The greenhouse gases, such as carbon dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O), are the main factors of increasing the global warming [1, 2]. Those gases arise from burning fossil fuels. Alternative renewable sources must be developed to decrease the emission of greenhouse gases. Wind energy is one of the renewable energy sources which are rapidly growing in most of the countries due to its relatively low cost [3].

Before the installation of a wind farm, a detailed analysis of the wind energy potential of the site including the calculation of the annual energy production and cost analysis should be conducted. Such feasibility study is vital to minimize the investment risk [4]. Most of the methods used in literature to determine the wind energy potential are based on the probability distribution functions (PDF). Weibull function is a commonly used one in wind energy literature [5-10].

Other methods are based on the assessment of hybrid systems. Sadati et al. [11] have conducted a performance analysis of photovoltaic (PV), parabolic trough collector (PTC) and wind energy systems for a 10MW power plants in

Multan, Pakistan. They concluded that the PV and PTC systems are more feasible for energy production than the wind energy system in that region.

Sadati et al. [12] have performed a feasibility study for a grid connected PV-wind battery hybrid system on a Mediterranean island. Their results of the energy production, net present cost and levelized cost of electricity have shown that the solar and wind energy systems can be used synergistically the studied island.

Many works have been performed for wind energy assessment in different sites. Bhuiyan et al. [13], have carried out a wind energy assessment in Kuakata, Bangladesh using the Wind Energy Assessment software of IUT. They have implemented both of Rayleigh and Weibull methods in the calculation of wind energy production. They have also emphasized on the effects of wind energy on the green house gases reduction.

Okechukwu et al. [14] have conducted a wind resource assessment in Port Harcourt, Nigeria. Their assessment was based on Weibull probability distribution function. The results revealed high wind energy potential in the analyzed site.

Olaofe [15], has studied the offshore wind energy assessment in the southwest coast of Nigeria using a high resolution satellite observations. The author found that the Weibull method gave better fitting for the offshore wind speed than the Rayleigh method.

Pachauri and Chauhan [16] have explored the wind technology assessment in India. They have in details presented the challenges, wind power development and marketing the small wind turbines in India.

Gualtieri [17] has developed an integrated wind resource assessment for wind farm planning. The tool is used to calculate many parameters such as mean wind speed, power density, Weibull parameters and annual energy production. The same author has upgraded this tool in [18]. The new upgrades include (but not limited to) the calculation of the wind power density function, estimation of the wind speed extrapolation to a specific hub height and uncertainty assessment for annual energy production.

Meißner et al. [19] have implemented the artificial neural networks (ANN) for wind power forecast. Their results obtained from using pure ANN and a hybrid method based on both ANN and computational fluid dynamics were validated against a SCADA data of a wind farm located in a complex terrain in Italy. The results showed that their methods are promising for future applications.

Libya is a rapidly growing consumer of energy and the demand for electricity increases by 10% -15% every year [20]. Libya is one of the highest electricity consumption per capita in Africa. The consumption has increased from 2.60 kWh in 2000 to 4.60kWh in 2009 [21]. The general wind map based on satellite data shows that the wind energy potential in Libya is high. The average wind speed is between 6-7.5 m/s at 40m height [22].

There are few studies about wind energy in Libya; El-Osta et al. [23] have selected a small wind farm of 1.5MW to be a pilot wind project. They have investigated different sites in Tripoli. Zwara site was chosen as the site of the project. The analysis was conducted using WASP software. The average wind speed was found as 6.9m/s at 10m height with an available power of 399 W/m^2. Their results were promising for the wind farm project.

El-Osta and Khalifa [24] have conducted a pre-feasibility study for a 6MW wind farm in Zwara site. They have used the RETScreen software for the economic evaluation of the project. Their results show that the project is feasible.

El-Osta et al. [25] conducted a study to evaluate the wind potential at the central region of the Libyan coast and to predict the capacity credit of wind power for different penetration levels. Their results have shown that an area of less than 1% of the total Libyan area is able to supply the total electric energy demand. They concluded that the wind potential in Libya is very high and promising.

Ahmed M. A. Mohammed et al. [21] have investigated the utilization of renewable energy in Libya. They concluded that Libya is rich in renewable energy including wind energy but needs more comprehensive energy strategy and more financial and educational investment.

M. S. Elmnefi and A. M. Bofares [20] have obtained wind speed measurements for 12 months period at Benina site in Libya. The results showed an average wind speed of about 11 m/s at 10m height which indicates the high wind energy potential in Benina site. Other studies for the wind potential in Iran [26], Italy [27], Ankara [28], Algeria [29] and India [30] have also been performed.

In this study, technical and economic assessments for four different cities located close to the Libyan coast have been conducted. Two of the sites, Tolmeita and Almqrun, are located in the eastern side of the coast where the other two sites, Alazeeziya and Tarhuna, are located in the western side of the coast. The Weibull parameters were estimated using three different methods; graphical method, empirical method and maximum likelihood method. The Weibull distribution results obtained from each method were fitted against the actual data. Error analysis by calculating the Determination of coefficient (R2), root mean square error (RMSE), mean bias error (MBE) and mean bias absolute error (MAE) is also done to check for the validity of the computed Weibull distributions. The technical assessment includes the calculation of the annual energy production, capacity factor and greenhouse gas emission reduction (GHG). While the economic assessment includes cost analysis for the produced electricity in $ cent/kWh and the calculation of the GHG reduction income and its effect on the produced electricity cost. The effects of different Weibull parameters on the analysis are also addressed in this study.

2. Wind Data

The knowledge of the characteristics of the wind regimes in any location is important in the evaluation and usage of wind resources. The present study is to carry out wind energy assessment for 4 different sites.

The data were obtained from the Meteorological Authority and New & Renewable Energy Authority in Libya. Table 1 shows the physical features of the meteorological stations.

Table 1. Physical features of the meteorological stations

Station (Site)	Latitude	Longitude	Altitude (m)
Tolmeita	32.42178°	20.56388°	80
Almqrun	31.43784°	20.14928°	65
Alazeeziya	32.31550°	13.01030°	180
Tarhuna	32.26020°	13.38040°	398

The real wind data measured at 60m height is used in this investigation. The mean wind speed, V_m, is the most commonly used indicator of wind energy potential. It is defined in Eq (1) as [31]:

$$V_m = \frac{1}{N}\sum_{i=1}^{N} v_i \tag{1}$$

Where, v_i, is the hourly measured wind speed and, N, is the number of measured hourly wind speed data. Tables 2 shows the monthly and annual averages of the measured wind speeds in each site. From this table, a maximum average value of 11.5 m/s was recorded at Tarhuna in April while a minimum average value of 3.01 m/s was measured Tolmeita in August. Figure 1 shows a comparison of the monthly mean wind speeds between the sites. The figure shows that Tarhuna and Alazeeziya have the highest mean wind speeds along the year and their highest wind speeds were recorded in April. On the other hand, Tolmeita has the lowest wind speeds compare to the other sites all over the year.

The measured annual wind speed frequency curves are plotted for all the sites in Fig. 2. From Fig. 2 we notice that the distribution curves of the sites have similar trends. They increase to reach a peak value and decrease after that. The peak value is close to the annual mean speed of the corresponding site. The peak value of the frequency ranges between 12 % and 16 %.

Table 2. Average wind speeds.

Site	Monthly Average Wind Speeds (m/s)												Annual Averages (m/s)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Tolmeita	7.25	5.57	5.96	6.27	4.23	3.64	3.16	3.01	5.00	4.82	6.02	7.45	5.22
Almqrun	6.12	6.04	6.86	7.04	6.59	6.26	6.53	5.91	5.89	5.12	5.72	6.71	6.24
Alazeeziya	6.63	8.19	8.15	9.52	7.44	7.94	6.15	7.11	6.48	7.47	7.12	7.39	7.97
Tarhuna	6.74	8.78	8.39	11.5	8.48	8.98	7.44	7.88	7.84	8.47	7.31	6.68	8.70

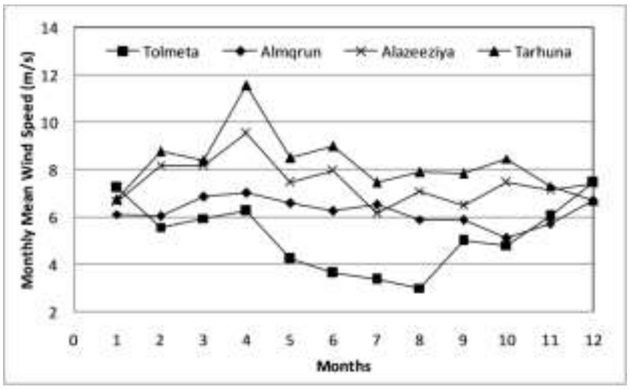

Fig. 1. Monthly variation of wind speeds for the selected sites.

3. Analysis Method

3.1 Probability Density Function and Weibull Parameters

To calculate the annual energy production, information about the Probability Density Function (PDF) and Cumulative Distribution Function (CDF) should be known. PDF is used for fitting the calculated data with the actual ones while CDF is used in the annual energy production calculations.

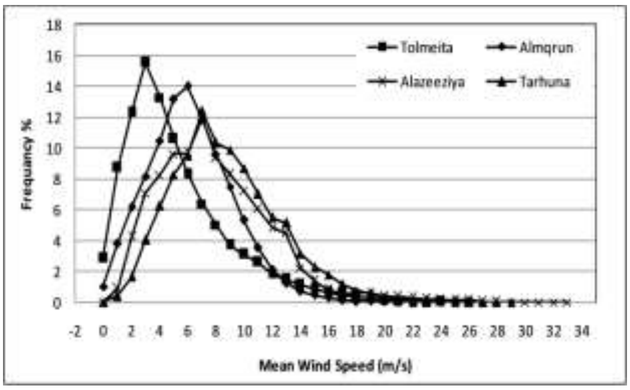

Fig. 2. Measured annual frequency distribution.

Typically the PDF is given by the Weibull distribution, which considers some corrections to account for the site conditions (e.g. landscape, vegetation and obstacles). Those corrections are modeled through a shape factor, *k*, and a scale factor, *c*, as shown in equations 2 and 3 [31].

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

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

Where, $PF(v)$, is the probability density function, $F(v)$, is the cumulative distribution function and, v, is the wind speed. In this study the Weibull distribution which has been used in many other works [32-35] will be used. First the Weibull parameters, *k* and *c*, must be found for each site. There are different ways to estimate the Weibull parameters. Three methods will be used in this study. Those methods are graphical method, empirical method and maximum likelihood method.

Graphical Method (GM):

The graphical method is used to estimate the Weibull parameters from the measured wind speed data. Eq. (3) can be written as:

$$1 - F(v) = exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{4}$$

Taking the double logarithmic transformation of Eq. (4), we obtain Eq. (5) as:

$$ln[-ln(1 - F(v))] = k\ lnv - k\ lnc \tag{5}$$

Plotting, *ln[-ln(1-F(v))]*, versus, *lnv*, will yield approximately a straight line. The gradient of the line is, *k*, parameter and the intercept with y-axis is, *–k ln(c)*.

Empirical Method (EM)

The empirical method is considered as special case of the moment method, where the Weibull parameters, *k*, and, *c*, are given by equations 6 and 7 as shown below [36]:

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \tag{6}$$

$$c \approx \frac{V_m\, k^{2.6674}}{0.184 + 0.816\, k^{2.73855}} \tag{7}$$

Where, σ, is the standard deviation of the observed data defined in Eq. (8) [8].

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(v_i - V_m)^2} \tag{8}$$

Maximum Likelihood Method (MLM)

This method is a mathematical expression known as a likelihood function of the wind speed data in time series format which is used to estimate the parameters, *k* and, *c*, by equations 9 and 10 [32].

$$k = \frac{\pi}{\sqrt{6}}\left[\frac{N(N-1)}{N(\sum ln^2(v_i)) - (\sum ln(v_i))^2}\right]^{0.5} \tag{9}$$

$$c = \left(\frac{\sum (v_i)^k}{N}\right)^{\frac{1}{k}} \tag{10}$$

3.2 Error Analysis

The error analysis is carried out to verify the accuracy of the Weibull distributions which are obtained by the different methods mentioned in the previous section. To do so, the coefficient of determination, R^2, the Root Mean Square Error, RMSE, the Mean Bias Error, MBE, and the Mean Bias Absolute Error, MAE, are calculated.

The coefficient of determination, R^2, is the square of the ratio between the Weibull frequencies to the actual frequencies. It is defined in Eq. (11) [1, 5, 37, 38]

$$R^2 = \frac{(\sum_{i=1}^{N}(y_i - z_i)^2 - \sum_{i=1}^{N}(y_i - x_i)^2)}{\sum_{i=1}^{N}(y_i - z_i)^2} \tag{11}$$

Where, *N*, is the number of observations (number of actual data), y_i, is the actual frequency, x_i, is the Weibull frequency and, z_i, is the average wind speed.

The root mean Square Error, RMSE, is a measure of the residuals between Weibull frequency and the actual frequency. It is defined in Eq. (12) as [1, 38, 39]:

$$RSME = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2} \tag{12}$$

The Mean Bias Error, MBE, is a measure of how closely the Weibull frequencies match with the actual frequencies. It is calculated from Eq. (13) [1, 5, 37-39].

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(y_i - x_i) \tag{13}$$

Similarly, the Mean Bias Absolute Error, MAE, is another measure found from Eq. (14) [1, 5, 37, 38].

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - x_i| \tag{14}$$

3.3 Annual Energy Production and Capacity Factor

The annual energy production calculations are very vital in the evaluation of any wind energy project. The long-term wind speed distribution is combined with the power curve of a specific wind turbine to give the energy generated at each wind speed and hence the total energy generated overall the year. The annual energy production (AEP) can be expressed mathematically as follow [40]. The probability that a wind speed, v_0, will fall between two wind speeds, v_i, and v_{i+1}, is obtained from the cumulative distribution function as in Eq. (15).

$$F(v_i < v_0 < v_{i+1}) = exp\left[-\left(\frac{v_i}{c}\right)^{k}\right] - exp\left[-\left(\frac{v_{i+1}}{c}\right)^{k}\right] \tag{15}$$

The total annual energy production is calculated as:

$$AEP = \sum_{i=1}^{N-1} \frac{1}{2}[P(v_{i+1}) + P(v_i)] \cdot F(v_i < v_0 < v_{i+1}) \cdot 8760 \quad (16)$$

Where, $P(v_i)$, is the power output of a certain wind turbine at wind speed, v_i, and, 8760, is the number of hours in the year. Another important measure for the wind turbine productivity is the capacity factor, C_f, which is defined as the ratio of the actual annual energy generated to the annual energy produced by the wind turbine if it had run at its rated power. The capacity factor is calculated from Eq. (17):

$$C_f = \frac{\text{energy generated per year (Kwh)}}{\text{wind turbin rated power (kw)x8760}} \quad (17)$$

3.4 Cost Analysis

The cost analysis is conducted by using the present value of costs (PVC) formula given in [41] and used by many researchers [42, 43]. PVC formula estimates the cost per kWh of electricity produced by a wind turbine. The PVC is given in Eq. (18).

$$PVC = I + C_{omr}\left[\frac{1+i}{r-i}\right] \times \left[1 - \left[\frac{1+i}{1+r}\right]^t\right] - S\left[\frac{1+i}{1+r}\right]^t \quad (18)$$

Where;

t: Turbine life time

I: Investment = turbine cost + 20% of the turbine cost for civil work

C_{omr}: Operation, Maintenance and Repair cost = 25% of the annual cost of the turbine

i: Inflation rate

r: Interest rate

S: Scrap value = 10% of the investment

After calculating the PVC, the cost of each kWh produced by the turbine in, USD cent/kWh, is calculated as in Eq. (19).

$$kWh\ cost = \frac{PVC}{AEP \times t} \times 100 \quad (19)$$

3.5 Greenhouse Gases (GHG) Reduction Calculation

The annual GHG emission reduction is calculated in terms of the tons of carbon dioxide (tCO2) per year that would be equivalent to the emission reduction by using energy from wind turbines. The GHG reduction, Δ_{GHG}, is calculated by using Eq. (20) which is used by RETScreen software [44].

$$\Delta_{GHG} = (e_{base} - e_{prop})E_{prop}(1 - \lambda_{prop})(1 - e_{cr}) \quad (20)$$

Where, e_{base}, is the base case GHG emission factor (tCO_2/MWh), e_{prop}, is the proposed case GHG emission factor (tCO_2/MWh) and, E_{prop}, is the proposed case annual electricity produced (MWh). E_{prop}, is the annual electricity produced by the wind turbine in the different sites calculated previously. λ_{prop}, is the fraction of the electricity loss in transmission and distribution (T&D losses) for the proposed case and, e_{cr}, is the GHG emission reduction credit transaction fee.

To see the GHG reduction effect on the cost analysis, we need to know the price of tons of CO_2. Using the same cost analysis stated before and adding the GHG reduction effect, the new electricity cost is calculated form Eq. (21).

$$kWh\ cost = 100 \times \frac{PVC_{without\ GHG} - price\ of\ annual\ GHG\ red. \times\ t}{AEP \times t} \quad (21)$$

4. Results and Discussion

4.1 Weibull Parameters

The Weibull parameters are calculated using the three different methods mentioned before. The results corresponding to the graphical method for each site are obtained from the plots shown in Fig. 3. The Weibull parameters results for the different sites calculated from the different methods are shown in Table 3. The results obtained in Table 3 show that there are differences among the, *k*, and, *c*, values obtained by the different methods. MLM method results in higher values for the Weibull parameters for all the sites studied while the GM method results in lower values for the Weibull parameters. This difference in the results will affects the technical and economical predictions as shown in the next sections.

4.2 Probability Density and Cumulative Distribution Function

The probability density function and cumulative distribution function are calculated by substituting the Weibull parameters, *k*, and, *c*, into equations 2 and 3. The probability density function indicates the frequency of the wind blowing at a certain speed. The calculated probability density function using Weibull parameters computed from different methods are fitted against the frequency of the actual wind data in Fig. 4. Figure 4 shows that for the sites were the wind speed is low (Tolmeita and Almqrun) the computed PDF deviates from the actual data. For the other two sites (Alazeeziya and Tarhuna), where the wind speed is high, it is noticed that the computed probability density function matches well with the actual data for all the used methods with the MLM giving better agreement with the actual data for all the sites.

4.3 Error Analysis Results

The errors associated with the different Weibull methods are calculated using equations 11-14 and the error results are shown in Table 4. The small values for RSME, MBE and MAE verifies that the methods for calculating the Weibull parameters in this study are accurate and can be used for wind energy assessment. Also the R^2 values are close to 1.0 for all the methods in all the sites which proves the accuracy of the used methods once more.

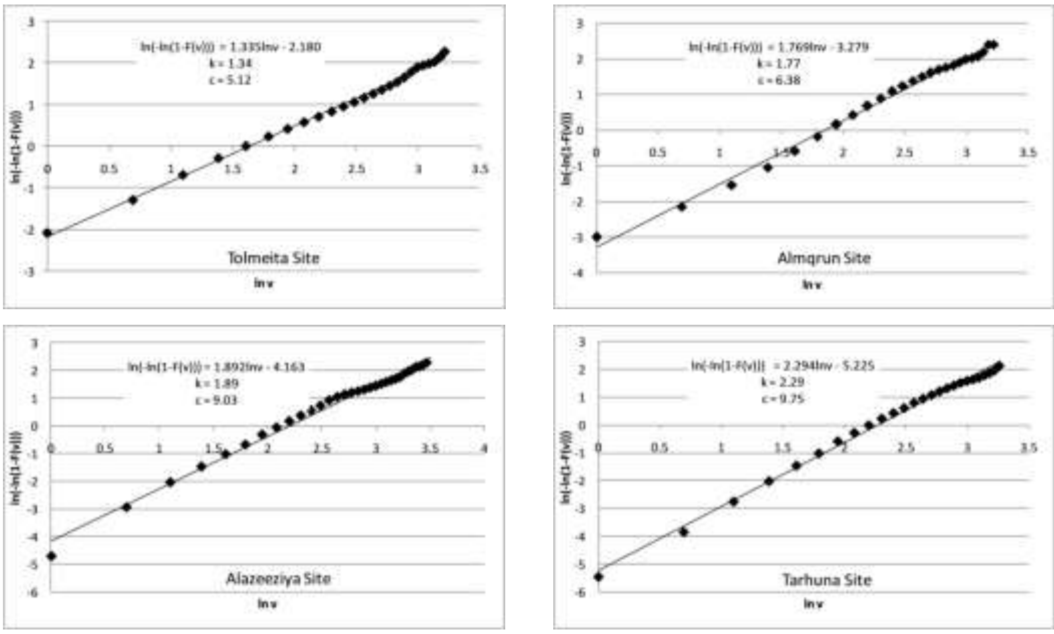

Fig. 3. Graphical method to estimate the Weibull parameters.

Table 3. Weibull Parameters estimated by three different.

Site	Method					
	GM		EM		MLM	
	k	c	k	c	k	c
Tolmeita	1.34	5.12	1.43	5.75	1.72	6.09
Almqrun	1.77	6.38	2.13	7.05	2.12	7.06
Alazeeziya	1.89	9.03	2.04	9.00	2.29	9.27
Tarhuna	2.29	9.75	2.42	9.81	2.64	10.02

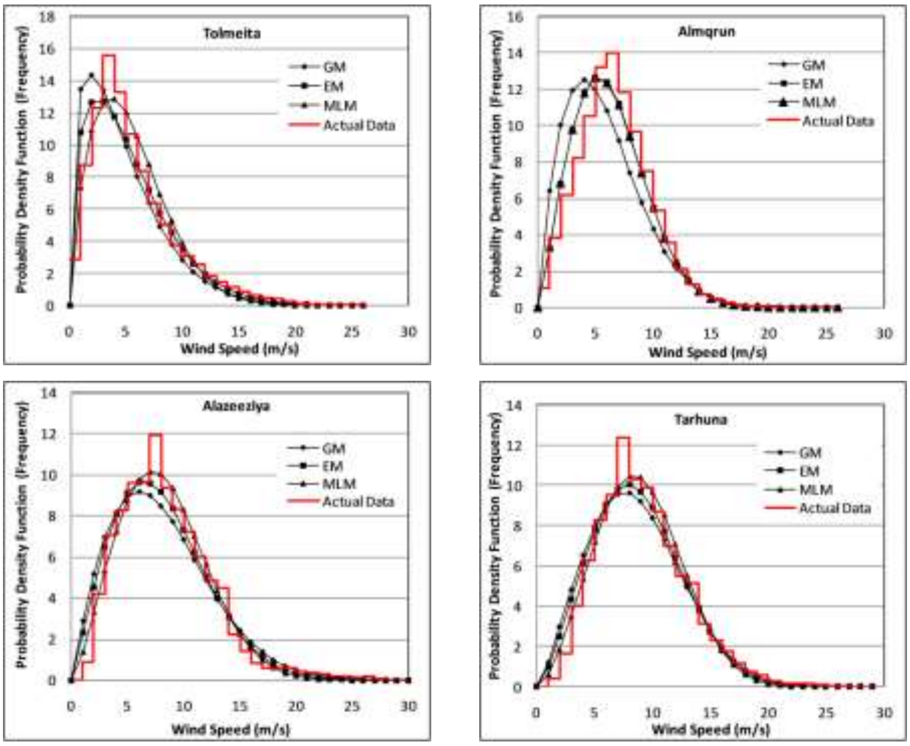

Fig. 4. Comparison of the probability density functio.

Table 4. Error analysis results.

Site	Method	R^2	RSME	MBE	MAE
Tolmeita	GM	0.99287	0.02877	7.81E-05	0.00034
	EM	0.99576	0.02218	5.25E-05	0.00027
	MLM	0.99335	0.02778	2.07E-05	0.00041
Almqrun	GM	0.98842	0.03603	1.64E-05	0.00050
	EM	0.99837	0.01353	4.04E-06	0.00018
	MLM	0.99831	0.01376	4.18E-06	0.00019
Alazeeziya	GM	0.99831	0.01938	5.81E-06	0.00028
	EM	0.99905	0.01457	3.38E-06	0.00021
	MLM	0.99863	0.01746	1.18E-06	0.00031
Tarhuna	GM	0.99821	0.01606	1.06E-06	0.00022
	EM	0.99860	0.01421	5.88E-07	0.00019
	MLM	0.99781	0.01780	1.83E-07	0.00027

4.4 Annual Energy Production and Capacity Factor Results

To calculate the annual energy production, AEP, and the capacity factor, C_f, information about a certain wind turbine must be available including the power curve. In this study the selected model wind turbine is Enercon E53-800 kW. This turbine has a relatively low rated wind speed and an available hub height of 60m (the same height at which the measured wind data are available). The technical specifications and the power curve of this wind turbine are given in Table 5 and Fig. 5 respectively [45].

Table 5. Technical specifications of the model wind turbine.

Item	Description
Turbine Model	Enercon E53-800 kW
Configuration	Three blade, horizontal axis
Rated Power	800 kW
Cut-in wind speed	2 m/s
Rated wind speed	12 m/s
Cut-out wind speed	28 – 34 m/s
Rotor Speed	12 – 28.3 RPM
Rotor diameter	52.9 m
Swept area	2,198 m^2
Hub height	60 m
Estimated unit price	1,230,000 USD

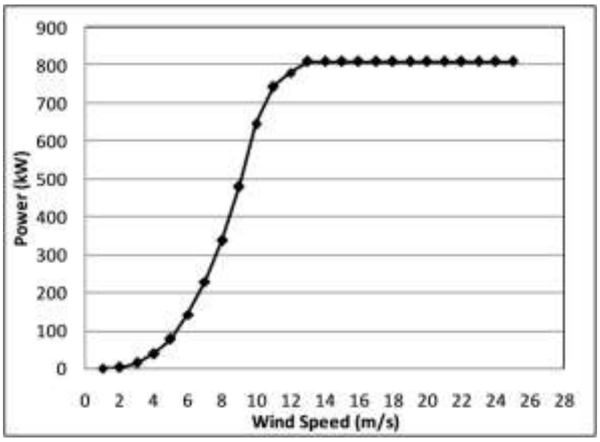

Fig. 5. Power curve of the model wind turbine.

Using equations 15-17, the annual energy production and capacity factor can be calculated. The results for AEP and C_f are shown in Table 6 for the different Weibull methods.

Comparison of the annual energy production among the sites is shown in Fig. 6. Table 6 and Fig. 6 show that, for the low wind speed cases (Tolmeita and Almqrun), EM and MLM methods yield close estimations for AEP to each other. On the other hand, at high wind speeds (Alazeeziya and Tarhuna), GM and EM give close results to each other.

As seen in Table 6, the capacity factor for Alazeeziya and Tarhuna is very high. This high value in C_f means that the wind in those sites used to blow at a speed close to the rated speed of the wind turbine. In fact, from the wind data of the sites, the frequency of wind speeds above 10 m/s was around 30 % for Alazeeziya and 35% for Tarhuna. On the other hand, for Tolmeita and Almqrun sites, the wind speed frequency for speeds above 10 m/s were only 9.5% and 11% respectively.

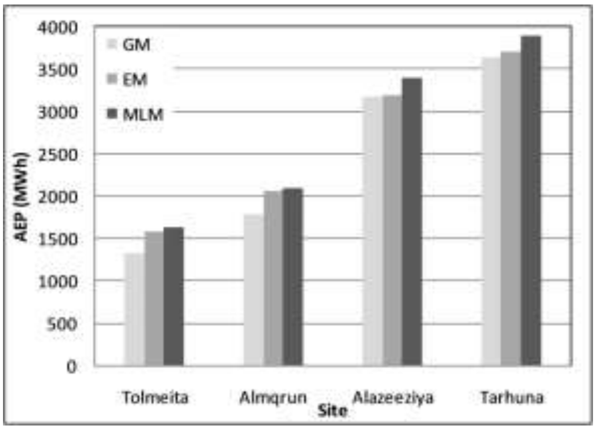

Fig. 6. Comparison of AEP among the sites using different Weibull methods.

4.5 Present Value Cost and Electricity Price

To calculate the present value cost, PVC, the values of the different terms in Eq. (18) should be known. In this study those values have been calculated based on the values in [38]. The calculated and assumed terms are listed in Table 7.

Those values are used for all the studied sites in this paper. The turbine cost was estimated according to [46] as 1600 USD/kW. The cost of each kWh produced by the turbine in, USD cent/kWh, is calculated from Eq. (19). The results of the electricity price for each site are shown in Table 8.

Table 6. Annual energy production and capacity factor for all sites.

Site	GM		EM		MLM	
	AEP (kWh)	C_f (%)	AEP (kWh)	C_f (%)	AEP (kWh)	C_f (%)
Tolmeita	1326254	18.92	1579265	22.54	1635920	23.34
Almqrun	1779710	25.40	2069157	29.53	2087639	29.79
Alazeeziya	3174948	45.30	3194849	45.59	3389674	48.37
Tarhuna	3639931	51.94	3710428	52.95	3888651	55.49

Table 7. The values of the terms in the present value cost equation.

Term	Assumed/Calculated Value
Turbine Life, *t*	20 years
Investment, *I*	1,476,000 USD
Operation, Maintenance and Repair cost, C_{omr}	15,375 USD
Inflation Rate, *i*	0.12
Interest Rate, *r*	0.15
Scrap Value, *S*	147,600 USD

Table 8. Electricity cost of each kWh for each site.

Site	Electricity cost (USD cent/kWh)		
	GM	EM	MLM
Tolmeita	6.13	5.14	4.97
Almqrun	4.56	3.93	3.89
Alazeeziya	2.56	2.54	2.40
Tarhuna	2.23	2.19	2.09

Those calculated electricity costs correspond to the minimum price at which the electricity produced by the wind turbine should be sold such that the turbine will be able to payback itself within the specified turbine life. Table 8 shows that the GM method, gives higher values for the electricity cost for all the site while MLM gives lower results. The average difference in the electricity cost between GM and MLM is around 13% all over the sites. For the low wind speed sites (Tolmeita and Almqrun), the difference in the electricity cost estimation is in the range of 20%. Where, for the high wind speed sites (Alazeeziya and Tarhuna), the difference decreases to around 7.0 %.

According to statista website, the electricity tariff in 2015 is between 6 cent/kWh and 15 cent/kWh with an average of about 11 cent/kWh in Europe and 9.43 cent/kWh in USA. The average price in the world is around 8 cent/kWh. This means that, even using the GM method which gives the highest price, still wind energy projects in the selected sites would be feasible especially in Tarhuna and Alazeeziya. And the outcome of the turbines would cover the turbine cost in fewer years than the assumed turbine life time.

4.6 Greenhouse Gases Emission Reduction

GHG reduction is calculated from Eq. (20). In this study, the base case emission factor for Libya is published by the International Energy Agency [47] as, 0.87 tCO2/MWh. Since the proposed case is the wind turbine which makes use of wind energy for electricity generation, the proposed case GHG emission factor is taken as zero. The T&D losses factor is suggested by RETScreen [44] to be 16% for the developing countries such as Libya. Assuming that there is no credit transfer fee, one may take, e_{cr}, equals to zero. Using the annual GHG reduction formula (Eq. 20) and substituting the above data together with the calculated annual energy production for each site, the annual GHG reduction can be calculated. The annual GHG reduction results are shown in Table 9.

Table 9. Annual GHG reduction for each site.

Site	Annual GHG Reduction (tCO_2/MWh)		
	GM	EM	MLM
Tolmeita	980.4	1167.4	1209.3
Almqrun	1315.6	1529.5	1543.2
Alazeeziya	2346.9	2361.6	2505.6
Tarhuna	2690.6	2742.7	2874.5

Again one notices that the different Weibull methods determine different values for the annual GHG reduction with GM giving the lowest values while MLM gives the highest values.

To see the GHG reduction effect on the cost analysis, a knowledge of the price of tons of CO_2 is needed. According to P. Luckow et al [48], the mid case CO_2 forecast shows that the price of CO_2 will start at \$20 per ton in 2020 and will increase to \$26 per ton in 2030. In this analysis, a lower price of \$8 per tCO_2 will be used to increase the reliability of the results. The new electricity price is calculated form Eq. (21). The results of the updated electricity cost after adding the GHG reduction effects are shown in Table 10. Comparing the results in Table 10 with the ones in Table 8, it is observed that the electricity cost has been reduced by an average of around 18% after adding the GHG reduction effects to the cost calculations.

Table 10. Cost of kWh for each site considering the GHG reduction effect

Site	Electricity cost with GHG effect (USD cent/kWh)		
	GM	EM	MLM
Tolmeita	5.53	4.55	4.37
Almqrun	3.97	3.33	3.30
Alazeeziya	1.97	1.95	1.81
Tarhuna	1.64	1.60	1.50

5. Conclusion

In this study, wind energy assessment of four different sites close to the Libyan coast was conducted using available measured wind data. The assessment includes technical evaluation of the annual energy production and capacity factor and financial assessment to calculate the electricity cost per kWh. Greenhouse Gas emission effects on the cost analysis was also stated.

The annual energy production was calculated using the Weibull distribution function. Three different methods were implemented to calculate the Weibull parameters (shape and scale factors); graphical method, empirical method and maximum likelihood method to see the effects of implementing different methods on the results.

The annual energy production analysis showed that Tarhuna and Alazeeziya sites have the highest wind energy potential compared to the other sites.

The cost analysis was done by means of present value of cost formula which is used in the calculation of the minimum cost of each kWh electrical energy produced by the wind turbines so that the wind energy project becomes feasible within the turbine lifetime. The results showed that Tarhuna site yields the lowest value of the kWh cost followed by Alazeeziya, then Almqrun and Tolmeita.

Applying different Weibull methods results in different estimations for AEP, C_f, electricity cost and annual GHG reduction values. The GM method gives lower values for AEP, C_f and annual GHG reduction and higher values for the electricity cost. Where the MLM method gives higher values for AEP, C_f and annual GHG reduction and consequently lower values for electricity cost.

The kWh cost in Tolmeita was calculated with the GM method as 6.13 USD cent/kWh and the average price for kWh sold in the world is about 8 USD cent/kWh. This means that even Tolmeita (with the lowest potential among the other cities in this study) would be feasible for wind projects and will be able to return the cost of the project in a period less than the wind turbine lifetime.

Adding the contribution of GHG reduction caused by using the wind turbine in electricity generation reduces the kWh cost of the generated electricity by an average of around 18% for the selected sites. Such reduction in the electricity price makes the wind energy project in any of the selected sites more feasible for investment.

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