Alqalam Journal of Medical and Applied Sciences. 2025;8(4):2478-2484
https://doi.org/10.54361/ajmas.258455

Original article

Statistical Evaluation of Wind Speed Distribution in Derna, Libya, Using Two Weibull Methods for Wind Energy Assessment

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Abstract
Following the Hurricane Daniel disaster that struck the city of Derna, interest in reconstruction in the city increased, including renewable energy as a key supporter. This research paper examines wind data in Derna from a meteorological station that has monitored wind data over several years. Windographer software was used to analyze and visualize real wind resource data. Also, this paper It was derived the dimensionless parameters, which are the shape parameter k and the scale parameter C of the Weibull method to provide accurate and efficient estimation of energy output. Two numerical methods, the Maximum Likelihood Method (MLM) and the Least Squares Method (LSM), are examined to estimate the Weibull parameters. To analyze the efficiency of the methods and to ascertain how closely the measured data follow the Weibull methods, goodness of fit tests was performed using the chi-square test (x^2), correlation coefficient (R^2), root mean square error (RMSE), and Relative percentage of error (RPE). The results revealed that the MLM was the most accurate and efficient method for determining the value of Weibull. In addition, the potential for wind energy development in Derna is fitted for generating electricity.
Keywords. Wind Speed Distribution, Derna, Weibull Methods, Wind Energy Assessment.

Introduction

Wind energy has become one of the most promising renewable energy sources due to its sustainability, abundance, and environmental friendliness compared with conventional fossil fuels. Recent research has focused on analyzing wind speed distributions and accurately assessing wind power potential using statistical models such as the Weibull distribution, which plays a fundamental role in evaluating the techno-economic feasibility of wind energy projects [1-3]. Several studies have demonstrated that improved methods for estimating Weibull parameters—including Bayesian, empirical, and optimization-based techniques—can significantly enhance the accuracy of wind resource assessments and facilitate optimal turbine selection for specific sites [4-6]. These developments contribute to better planning and implementation of wind farms worldwide, aligning with global efforts toward sustainable energy transitions.

In Libya, wind energy has attracted increasing attention as part of national efforts to diversify the energy mix and reduce carbon emissions. Comprehensive assessments have been carried out to evaluate wind resources across different regions, such as Green Mountain, Misurata, and Sabha, employing tools like RETScreen Expert and comparative statistical methods to estimate Weibull parameters. These studies consistently highlight the country's strong wind potential, particularly in coastal and elevated areas [7-9], [10]. Moreover, hybrid renewable energy systems that integrate wind, photovoltaic (PV), battery, and fuel-cell technologies have been analyzed for Libyan applications, revealing improved energy reliability, reduced operational costs, and enhanced system efficiency [11-13]. Parallel research has also investigated the carbon footprint and life cycle assessment of the Libyan wind industry, emphasizing its environmental benefits and contribution to sustainable development [14-16].

Overall, recent findings confirm that wind energy development in Libya represents a strategic and feasible pathway toward achieving national energy security, economic diversification, and environmental sustainability. The integration of advanced modeling, hybrid systems, and artificial intelligence tools further strengthens Libya's potential to emerge as a regional leader in renewable energy technologies. Several researchers have previously analyzed and compared various numerical methods—namely, the Empirical Method (EM), Energy Pattern Factor (EPF), Graphical Method (GM), Maximum Likelihood Method (MLM), Method of Moments (MM), and Modified Maximum Likelihood Method (MMLM)—to estimate the parameters of the Weibull distribution [17-19] These methods have been widely applied in wind energy assessment studies to enhance the accuracy of modeling wind speed distributions and to optimize site-specific turbine selection.

Methodology

The analytical workflow illustrated in Figure 1 begins with the data source, where wind speed data are collected. In the next step, the mean wind speed and standard deviation are measured from the recorded data. These statistical parameters are then used to estimate the Weibull distribution parameters (shape factor k and scale factor c), which characterize the wind speed distribution. Two estimation techniques are applied for determining the Weibull parameters: the Maximum Likelihood Method (MLM) and the Least-Square Method (LSM). Once the parameters are estimated, the model performance is investigated through various statistical tests. These include the Root Mean Square Error (RMSE) to assess prediction accuracy,

Received: *25-08-2025* - ***Accepted***: *24-10-2025* - ***Published***: *01-11-2025*

https://doi.org/10.54361/ajmas.258455

the Chi-square test to evaluate the goodness of fit, and the Coefficient of Determination (R^2) to determine the strength of correlation between observed and estimated data. Finally, based on the validated Weibull parameters, calculations are performed to determine both the power density and energy density at multiple heights, providing insight into the wind energy potential of the study site.

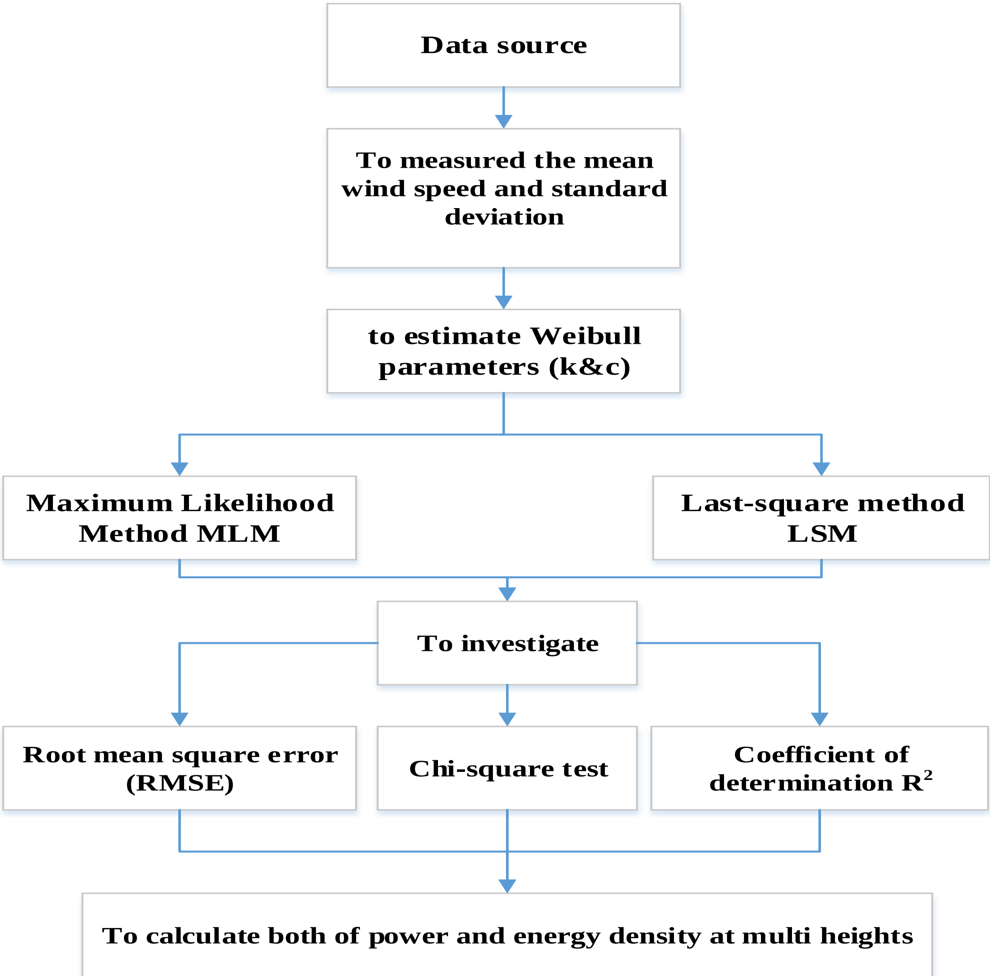

Fig.1. Flowchart showing the work methodology

The following is an explanation of the basic equations for the methods described above:
Measured mean wind speed and standard deviation

$$V_m = \frac{1}{N}\left(\sum_{i=1}^{N} V_i\right)$$

$$\sigma = \left[\frac{1}{N-1}\sum_{i=1}^{N}(V_i - V_m)^2\right]^{1/2}$$

Methods to estimate Weibull parameters (k&c)

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

Maximum Likelihood Method

$$k = \left[\frac{\sum_{i=1}^{n} {v_i}^k . \ln v_i}{\sum_{i=1}^{n} {v_i}^k} - \frac{\sum_{i=1}^{n} \ln v_i}{n}\right]^{-1}$$

$$C = \left(\frac{1}{n}\left[\sum_{i=1}^{n} {v_i}^k\right]\right)^{\frac{1}{K}}$$

Last-square method (LSM) [4]

$$k = \frac{\sum(x_i - \bar{x}) - (y_i - \bar{y})}{\sum(x_i - \bar{x})^2}$$

$$C = \exp - \left(\frac{k \ln C}{k}\right)$$

***Received**: 25-08-2025 - **Accepted**: 24-10-2025 - **Published**: 01-11-2025*

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

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

The root means square error (RMSE)

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

The Chi-square

$$x^2 = \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{x_i}$$

3. The coefficient of determination R^2

$$R^2 = \frac{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2 - \sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}$$

Site-specific wind speeds

$$V_{min} = C.\left(\frac{K-1}{K}\right)^{1/K}$$

$$V_{max} = C.\left(\frac{K+2}{K}\right)^{1/K}$$

Weibull parameters extrapolation

$$C_z = C_{10}(Z/Z_{10})^n$$

$$K_Z = \frac{K_{10}}{\left[1 - 0.0881\ln\left(\frac{Z}{10}\right)\right]}$$

$$V_Z = C_Z\Gamma\left(1 + \frac{1}{K_Z}\right)$$

$$n = 0.37 - 0.0881\ln(C_{10})$$

Wind power density estimation

$$P_w = \frac{p}{A} = \frac{1}{2}.\rho.C^3.\Gamma\left[1 + \frac{3}{k}\right]$$

$$\rho = \rho_0 - 1.194X10^{-4}X\ H_m$$

Wind energy density estimation

$$E_D = p_w.T = \frac{1}{2}.\rho.C^3.\Gamma\left[1 + \frac{3}{k}\right].T$$

Significance of the Derna Location

The geographical and meteorological data presented for Derna, Libya, indicate that the city has favorable conditions for wind energy generation. According to Table 1, the meteorological station in Derna is located at latitude 32°47′ N and longitude 22°35′ E, with an anemometer height of 10 meters and an elevation of 26 meters above sea level. These parameters provide a baseline for assessing the region's wind profile and potential for renewable energy applications.

Table 1. Geographical coordinates of the Meteorological station in Derna

Location	Variable	Value
Derna	Latitude	32^0 47 N
	Longitude	22^0 35 E
	Anemometer height	10 m
	Elevation	26 meters above sea level

As shown in Figure 2, derived from the Global Wind Atlas, the wind availability map highlights Derna's coastal position along the Mediterranean Sea, where wind speeds are relatively high compared to inland areas. The orange and red color zones on the map indicate regions with stronger and more consistent wind flows, suggesting that Derna experiences moderate to high wind energy potential throughout the year. This is primarily due to its coastal exposure, which allows for steady sea breezes and minimal surface roughness, enhancing wind speed uniformity.

The significance of these findings for site selection is substantial. Derna's combination of favorable topography, elevation, and strong coastal winds makes it an ideal location for wind turbine installation. The high wind availability translates into greater energy yield, improved turbine efficiency, and shorter payback periods for wind projects. Consequently, Derna stands out as a strategic site for wind farm development in Libya's renewable energy expansion, supporting both local energy needs and national sustainability goals.

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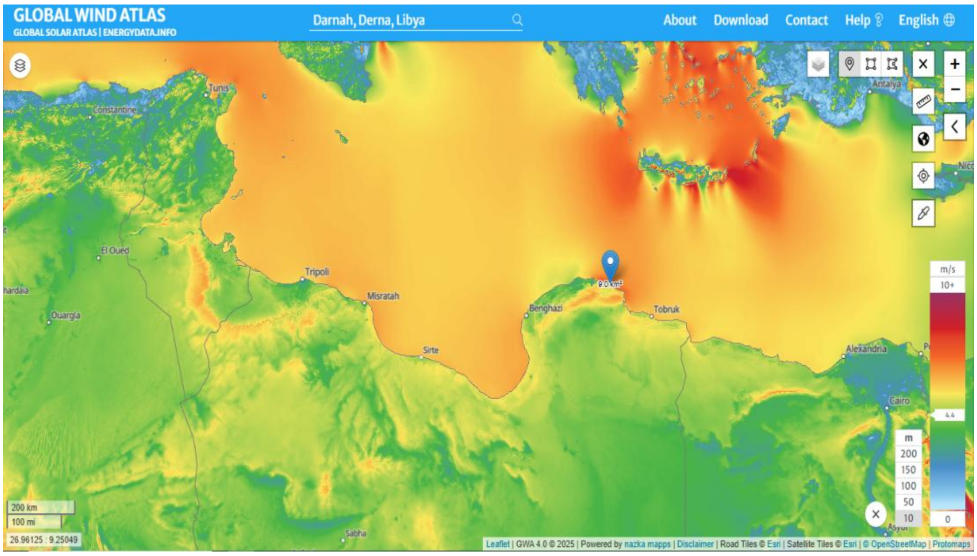

Fig. 2. Geographical location and wind availability of the city of Derna [Global Wind Atlas]

Results and Discussion

In this work, the prediction accuracy of the Weibull EDF methods in the estimation of the wind speeds with respect to the actual values was evaluated based on the chi-square test (x2), correlation coefficient (R^2), and root mean square error (RMSE). Based on the results, it can be noted that the statistical tools used offered enough information for the accuracy of individual forecast errors and for ranking the quality of fit of the six competing Weibull distributions. Successful forecasts correspond to low values of RMSE, while higher values indicate deviations. Since RMSE should be as close to zero as possible, it can be seen that for the available data, the results reveal that the best fitting Weibull distribution methods are ranked as follows: the best estimation method is MLM, and the LSM ranked second. The method generating the best results is established by considering a low value for the chi-square indicator in each case. Since the chi-square value should be as close to zero as possible, it can be seen that for the available data, the results reveal that the best fitting Weibull distribution methods are ranked as follows: the best estimation method is MLM, and the LSM ranked second. The best parameter estimation shall disclose the highest value of R2. The highest value of R2 is one, while the lowest is zero. The results reveal that the MLM is the best-fitting Weibull distribution method. The LSM ranked second. (Figure 3) shows, for each month, the Weibull Frequency plotted against the frequency distribution of measured wind speed. These curves illustrate the Weibull methods that fit best to the measured wind speed data.

The comparative analysis between MLM and LSM demonstrates that the Maximum Likelihood Method provides a superior fit to the actual wind speed distribution. The MLM curve closely follows the empirical data, especially around the modal wind speed, suggesting that this method minimizes estimation errors in both shape and scale parameters of the Weibull function. In contrast, the Least Squares Method tends to deviate near the distribution peak and in the low-speed region. These findings align with the conclusions reported by Khan (2023) [20], who found that MLM performs better in modeling wind speed frequency distributions due to its statistical robustness and lower bias in parameter estimation.

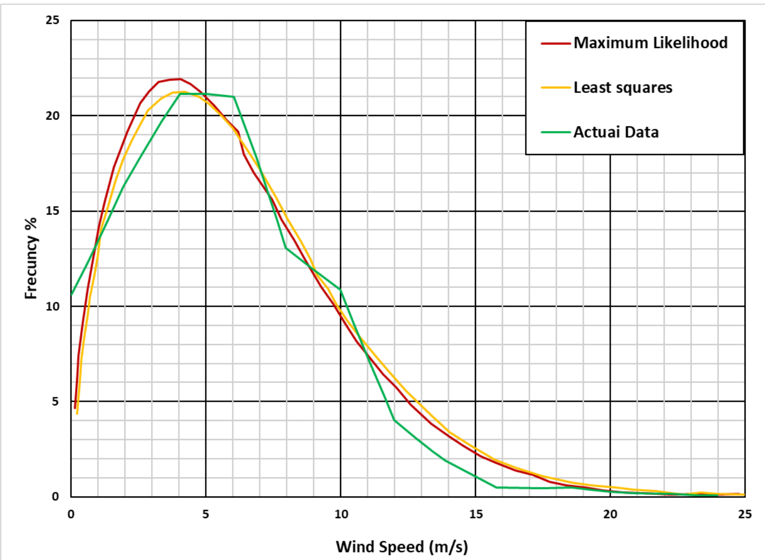

Fig.3. MLM and LSM in comparison with actual data

***Received**: 25-08-2025 - **Accepted**: 24-10-2025 - **Published**: 01-11-2025*

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(Table 2) presents the prediction accuracy of the Weibull probability density function (PDF) parameters estimated using the Maximum Likelihood Method (MLM) and Least Squares Method (LSM) for different seasons and for the yearly mean. The parameters shown include the scale factor (C), shape factor (K), Root Mean Square Error (RMSE), coefficient of determination (R^2), and chi-square (x^2) statistic.
The scale parameter (C) represents the characteristic wind speed, while the shape parameter (K) indicates the distribution's form. A higher K suggests a narrower distribution and less variability in wind speed. The RMSE, R^2, and x^2 values are used to evaluate how accurately the Weibull distribution fits the actual wind speed data. The scale parameter (C) varies seasonally, with the highest values observed in summer (7.47 m/s for MLM and 7.78 m/s for LSM), indicating stronger average winds in that season. The lowest C occurs in autumn, reflecting weaker wind speeds. The shape parameter (K) ranges between approximately 1.4 and 2.1, showing moderate variability in wind regimes across seasons.
RMSE values remain relatively small for both methods (0.05–0.08), demonstrating a good fit overall. R^2 values for both methods are moderate (0.37–0.48), implying that while the Weibull model captures the general trend of the wind distribution, some deviations from measured data exist.
The x^2 statistic indicates the goodness of fit — lower values imply better fitting performance. Here, the MLM method yields a smaller yearly mean x^2 (0.51) compared to LSM (0.61), signifying that MLM provides a more accurate overall fit to the measured data. Every year, both methods yield similar K values (1.67), but MLM shows slightly lower RMSE and x^2, confirming its superior fitting accuracy.

Table 2. Prediction accuracy of the Weibull PDF methods

MLM					
Session	**Scale C**	**Scale K**	**RMSE**	**R^2**	**X^2**
Winter	7.28	1.59	0.052	0.46	0.56
Spring	6.60	1.44	0.050	0.37	0.43
Summer	7.47	2.10	0.080	0.42	0.52
Autumn	6.24	1.55	0.054	0.44	0.53
Yearly mean	**6.90**	**1.67**	**0.059**	**0.42**	**0.51**
LSM					
	Scale C	Scale K	RMSE	R^2	X^2
Winter	7.49	1.64	0.053	0.48	0.61
Spring	6.89	1.48	0.052	0.41	0.50
Summer	7.78	1.95	0.069	0.42	0.73
Autumn	6.46	1.61	0.058	0.46	0.58
Yearly mean	**7.15**	**1.67**	**0.058**	**0.44**	**0.61**

Since the scale and shape parameters have been determined using the MLM as the best fitting Weibull distribution method, the most probable (V_{mp}) and maximum energy carrying (V_{max}) wind speeds have been calculated based on the 10-meter height. Consequently, the wind power density (P_w) and the wind energy density (E_D) have been evaluated, respectively, to assess the wind resource available in the district of Derna. Furthermore, (Table 3) shows that the average wind speed for the site was 4.24 m/s, with an average wind power density of 362.63 W/m² and a daily mean energy density of approximately 8.70 kWh/m²/day. The corresponding annual wind energy density reached 3171.10 kWh/m²/year, indicating a moderate potential for small- to medium-scale wind energy applications. The months of February, March, and December exhibited the highest monthly energy densities, making them the most favorable periods for wind power generation. Researchers such as Sanad MSA, El-Taher A [21]. conducted studies on the wind energy potential in the city of Derna, and the results were positive and encouraging for moving forward with energy projects in Derna.

Table 3. Wind power density and wind energy density at different heights above ground level

Period	**V_{mp}**	**V_{max}**	**V_m**	**P_w (w/m²)**	**Daily E_w (kWh/m²/d)**	**Monthly E_w (kWh/m²/m)**
January	4.2	12.8	6.63	395.8	9.50	294.48
February	4.4	13.6	6.69	471.2	11.31	316.65
March	4.1	13.2	6.42	427.3	10.26	317.91
April	3.5	13.1	6.11	401	9.62	288.72
May	2.6	12.6	5.46	324.4	7.79	241.35
Jun	3.4	12.4	5.77	332.4	7.98	239.33

***Received**: 25-08-2025 - **Accepted**: 24-10-2025 - **Published**: 01-11-2025*

July	6.8	10.9	7.23	371.8	8.92	276.62
Augustus	6.5	10.6	6.98	338.5	8.12	251.84
September	4.1	10.6	5.59	246.1	5.91	177.19
October	3.1	11.0	5.2	240.4	5.77	178.86
November	3.7	12.7	6.05	374.2	8.98	269.42
December	4.5	13.0	6.57	428.4	10.28	318.73
Average	**4.24**	**12.21**	**6.23**	**362.63**	**8.70**	**264.26**
whole year						**3171.10km/m²/y**

Conclusion
This study analyzed wind speed characteristics and wind energy potential using the Weibull probability distribution, applying both the Maximum Likelihood Method (MLM) and the Least Squares Method (LSM) for parameter estimation. The results clearly demonstrate that the Maximum Likelihood Method provides a more accurate and reliable fit to the measured wind speed data compared with LSM. The MLM method yielded lower RMSE and x^2 values and a slightly higher coefficient of determination (R^2) than LSM, confirming its superior predictive performance. The yearly mean x^2 for MLM (0.51) was significantly lower than for LSM (0.61), indicating better statistical agreement with the actual wind speed distribution.
The seasonal analysis showed that summer has the highest scale factor (C) and consequently the highest average wind speeds, while autumn recorded the lowest. This variability directly influences the wind energy potential throughout the year.

Conflict of interest. Nil

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Received*: 25-08-2025 -* ***Accepted****: 24-10-2025 -* ***Published****: 01-11-2025*