



Nanotechnology and statistical analysis of wind speed and wind power density in Baghdad governorate

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Wind speed data obtained at a height of 10 m in Baghdad (Iraq) during the study period 2022-2023 are evaluated and statistically analyzed using different distribution functions (Weibull, Rayleigh, Gamma). The study objectives included determining the best distribution function for the wind speed data, calculating wind energy and the wind density, confirming the wind energy potential of the study area, and the profitability of installing the anemometers. The coefficients of the distribution functions are determined using the Maximum Likelihood Method (MLM). These distributions are also evaluated using the root mean square error method. The results showed that the Weibull distribution function is the most suitable for analyzing the wind speed data compared to the Rayleigh and Gamma distribution functions. The study also found that while the highest wind energy rates are found in June, July, and August, the lowest wind energy rates and wind density rates are found in October, November, and September.

Keywords: Weibull distribution; Wind speed; Wind power; Nanotechnology.

1. INTRODUCTION

Population and industrial growth have created an urgent need for energy [1]. Factories consume a lot of fossil fuel products, including coal and petroleum derivatives [2]. The overuse of energy-producing products derived from combustible fossil fuels raises the greenhouse gas concentrations in the atmosphere, raising the surface temperatures and ultimately causing environmental changes [3]. The use of renewable, non-depleting energy is thought to be the most suitable method of limiting environmental changes, such as air pollution and rising temperatures, and lowering the rates of greenhouse gas emissions [4]. Wind, solar, and geothermal energy are the best, most economical, sustainable, and

ecologically friendly sources [5]. Hydroelectricity, biomass, and marine energy [6]. An eco-friendly, sustainable, and non-polluting energy source is wind power [7]. The increasing interest in energy in Iraq (Baghdad governorate) calls for the necessity of finding alternative sources of fossil fuel energy [8].

Depending on the country's climate, wind energy is one of the renewable energy sources appropriate for energy generation in Iraq [9]. Wind statistics for the Baghdad Governorate are gathered to perform a statistical analysis of wind speed and the possibility of installing wind power plants there [10, 11]. Weibull parameters are estimated using a various technique [12, 13]. Standard deviation, shape factor, scale factor, most likely wind speed, maximum wind speed, wind power density, and wind energy density are all estimated using six Weibull distribution methods: the probability-weighted method of moments, graphical method, empirical method, moments method, maximum likelihood method, and energy mode factor method [14]. The Weibull distribution function's coefficients are estimated using the Empirical method (EM) [15]. The aim of this study analysis of wind speed and wind power density in Baghdad [16].

Use nanotechnology to improve the solar energy conversion efficiency and potentially reduce costs. This involves incorporating nanomaterials, such as nanorods or quantum dots, into the solar cells, which improves the light absorption and charge separation. Although current nano solar cells are still less efficient than conventional cells, their lower manufacturing costs represent a promising path toward affordable solar energy production [17,18].

2. METHODOLOGY

2.1 Data and study area

To evaluate the wind energy potential of the study area, Baghdad Governorate is selected. Data from European stations for 2022-2023 (wind speed and direction at 10 m height) are used to statistically analyze these data and estimate the wind energy density [19]. Use Eq. (1) to calculate the monthly average wind speed as one of the input parameters [20,21]:

$$\bar{V} = \frac{1}{N} \sum_{i=1}^N V_i \quad (1)$$

where \bar{V} is average wind speed, N is amount of wind data, and V_i is wind speed observation.

2.2 Statistical distribution functions

Weibull, Rayleigh, and Gamma distribution functions are examples of statistical distribution functions [19]. These are widely used models in wind energy applications and are typically employed to describe how wind speed varies at a particular place [22].

2.2.1 Weibull distribution function (WDF)

Data on wind speed are frequently evaluated and described using the Weibull distribution function [23,24]. In addition, it is used to statistically evaluate wind direction and speed data and to illustrate wind speed in wind energy research. It is therefore thought to be the most important approach for solving the problem of wind speed [25].

$$f_w = \frac{k}{c} \left(\frac{u}{c}\right)^{k-1} \exp\left(-\left(\frac{u}{c}\right)^k\right) \quad (2)$$

where f_w is Weibull probability density function (PDF), k is shape parameter dimensionless that shows how peaked the wind distribution and c is scale parameter that shows the extent of wind at a location [26].

2.2.2 Empirical approach

The empirical method (EM) is used to estimate the coefficients of the Weibull distribution function, which is dependent on the mean wind speed data and can be computed from Eq. (1) [27].

The wind speed data's standard deviation, which is provided by Eq. (3) [28]. The coefficients of the Weibull distribution function (k, c) can be estimated using a variety of techniques, such as the energy mode factor method, the maximum likelihood method, the graphical method, the moment method, and the probability-weighted moment method [29,30].

$$\sigma_v = \sqrt{\frac{(V_i - \bar{V})^2}{N-1}} \tag{3}$$

$$K = \left(\frac{\sigma_v}{\bar{V}}\right)^{-1.086} \tag{4}$$

$$C = \frac{\bar{V}}{(0.568 + 0.433/K)^{1/K}} \tag{5}$$

2.2.3 Rayleigh distribution function (RDF)

The Rayleigh Distribution Function (RDF) is a specific example of the WDF distribution function. Only uses one coefficient (C) where (K=2); it is regarded as the most popular and straightforward distribution function. It can be computed using Eq. (6) [31,32]:

$$f_R = \left(\frac{2v}{c^2}\right) \exp\left(-\left(\frac{v}{c}\right)^2\right) \tag{6}$$

$$c = \frac{2}{\sqrt{\pi}} \times \bar{V} \tag{7}$$

2.2.4 Gamma distribution function (GDF)

The two-parameter gamma distribution, specified by Eq. (8), is used in the wind speed configuration [33]:

$$f_g = \frac{v^{k-1}}{c^k \Gamma(k)} \exp\left(-\left(\frac{v}{c}\right)\right) \tag{8}$$

$$k = \frac{\bar{V}^2}{\sigma_v^2} \tag{9}$$

$$c = \frac{\sigma_v^2}{\bar{V}} \tag{10}$$

2.3 Statistical error analysis/goodness of fit

Statistical criteria are used to establish the optimum method for wind speed analysis as well as the efficacy of the different distribution functions. The root mean square error test is one of the criteria used for this [34].

2.3.1 Root mean square error (RMSE)

The actual variance between the anticipated and real measured values is compared using the RMSE. The value of RMSE is defined by Eq. (11), where yi is the ith measured data, xi is the anticipated distribution of winds based on the WDF, RDF, and GDF, and n is the number of the binary wind speed data sets. The ideal wind distribution with the lowest value RMSE is the most accurate function to employ when modeling wind speed [35].

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (y_i - x_i)^2}{N}} \quad (11)$$

2.3.2 Wind power density

The Weibull, Rayleigh and Gamma distribution function analysis, the wind power density can be expressed as follows [36]:

$$WPD_{wb} = \frac{1}{2} \rho c^3 \Gamma(1 + 3/k) \quad (12)$$

$$WPD_{RY} = \frac{3}{\pi} \rho c^3 \sqrt{\frac{\pi}{4}} \quad (13)$$

$$WPD_{GA} = \frac{1}{2} \rho c^3 [k(k+1)(k+2)] \quad (14)$$

where (ρ) is air density ($\frac{kg}{m^3}$), which is mostly considered a constant ($1.225 \frac{kg}{m^3}$).

The formula for energy can be expressed as follows: energy is the just the product of power and time:

$$E_d = p_d \times T_i \quad (15)$$

where T_i is period a duration and the wind potential energy based on Weibull probability function is estimated by [37-45]:

$$E_w = \left[\frac{1}{2} \rho c^3 \Gamma(1 + 3/k) \right] \times T_i \quad (16)$$

3. RESULT AND DISCUSSION

3.1 Analyzing monthly wind speed data patterns for 2022 and 2023

The European station (ECMWF) compiled monthly wind speed data for the preceding years 2022- 2023. According to the wind speed statistics, August 2022 had the highest value 4.718 m/s, while November 2022 had the lowest 2.403 m/s. According to Figure 1, the wind speed data indicated that the highest, 4.452 m/s, occurred in July 2023, while the smallest value, 2.387 m/s, occurred in October 2023.

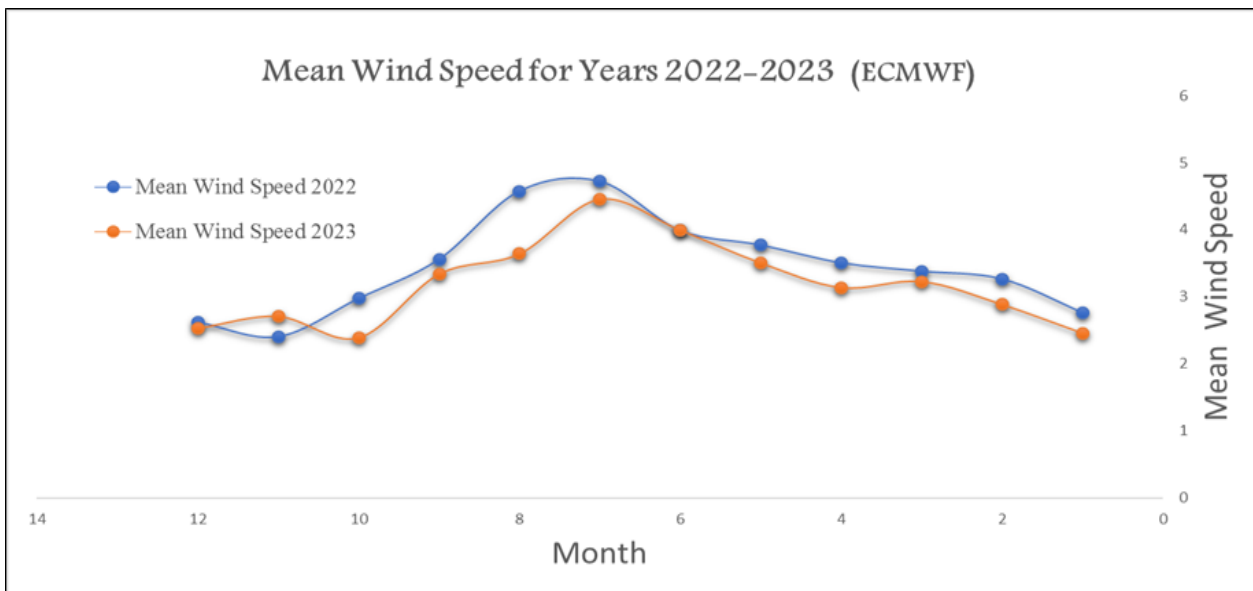


Figure 1 Analyzing monthly wind speed data patterns for 2022 and 2023.

3.2 Estimates of the WDF, RDF, and GDF monthly parameters

The WDF, RDF, and GDF form and scale parameters are displayed in Table 1. Eqs. (4) and (5) are utilized in the computation of these parameters. Eq. (7) is used to determine the RDF scale parameter. Determine the monthly form and scale parameters of the GDF for 2022–2023 using Eqs. (9) and (10).

Table 1 Estimates of the WDF, RDF, and GDF monthly parameters.

Distribution Functions	Weibull Parameters				Rayleigh Parameter		Gamma Parameters			
	2022		2023		2022	2023	2022		2023	
Year	k	c	k	c	c	c	k	c	k	c
January	1.949	3.121	1.911	2.771	3.122	2.773	3.417	0.809	3.295	0.745
February	2.027	3.686	2.535	3.250	3.684	3.255	3.674	0.888	5.544	0.520
March	2.100	3.817	1.888	3.637	3.814	3.641	3.922	0.861	3.224	1
April	1.882	3.951	2.158	3.543	3.956	3.540	3.204	1.093	4.122	0.760
May	2.303	4.256	2.486	3.951	4.254	3.955	4.648	0.810	5.350	0.655
June	2.667	4.485	3.091	4.464	4.500	4.506	6.090	0.654	7.988	0.499
July	3.489	5.244	3.197	4.971	5.326	5.026	9.984	0.472	8.502	0.523
August	2.971	5.124	2.583	4.098	5.163	4.107	7.430	0.615	5.740	0.633
September	3.003	3.983	2.958	3.738	4.015	3.766	7.577	0.469	7.366	0.452
October	2.709	3.343	2.217	2.696	3.355	2.694	6.269	0.474	4.331	0.551
November	2.315	2.714	2.002	3.056	2.713	3.055	4.691	0.512	3.589	0.754
December	2.338	2.959	2.469	2.851	2.958	2.853	4.777	0.548	5.283	0.478

3.3 Mean Wind speed statistical distribution using the Weibull, Rayleigh, and Gamma models

Calculating monthly wind energy tariffs in the Baghdad Governorate and determining if wind turbines can be erected to absorb wind energy and convert it into electricity are the targets to lower the emissions of greenhouse gases that cause global warming. The probability distribution of recorded wind speeds based on the variance of various wind speed distributions is shown in Figure 2. The probability density distribution of monthly wind speeds for data gathered in 2022 and 2023 using WDF, RDF and GDF.

The gray bars show the average monthly wind speeds, while the colored lines show the theoretical probability distributions.

1. The WDF is shown by the red line.
2. The RDF is shown by the green line.
3. The GDF is shown by the blue line.
4. The RMSE is used to evaluate each distribution's accuracy.

The results show the WDF is best at predicting monthly wind speeds, making it the optimal for wind energy modeling and forecasting. Environmental and applied interpretations indicate that monthly wind speeds in the Baghdad Governorate are within moderate to good levels, especially during the summer months (June to August), supporting the feasibility of installing small to medium-sized wind turbines during these periods. The output power from the wind speed can be accurately estimated using the Weibull distribution, depending on its precision. Using wind energy in Baghdad could help with the following:

1. Reducing dependence on fossil fuels.
2. Decreasing greenhouse gas emissions to lessen the region's exposure to the effects of climate change and warming temperatures.

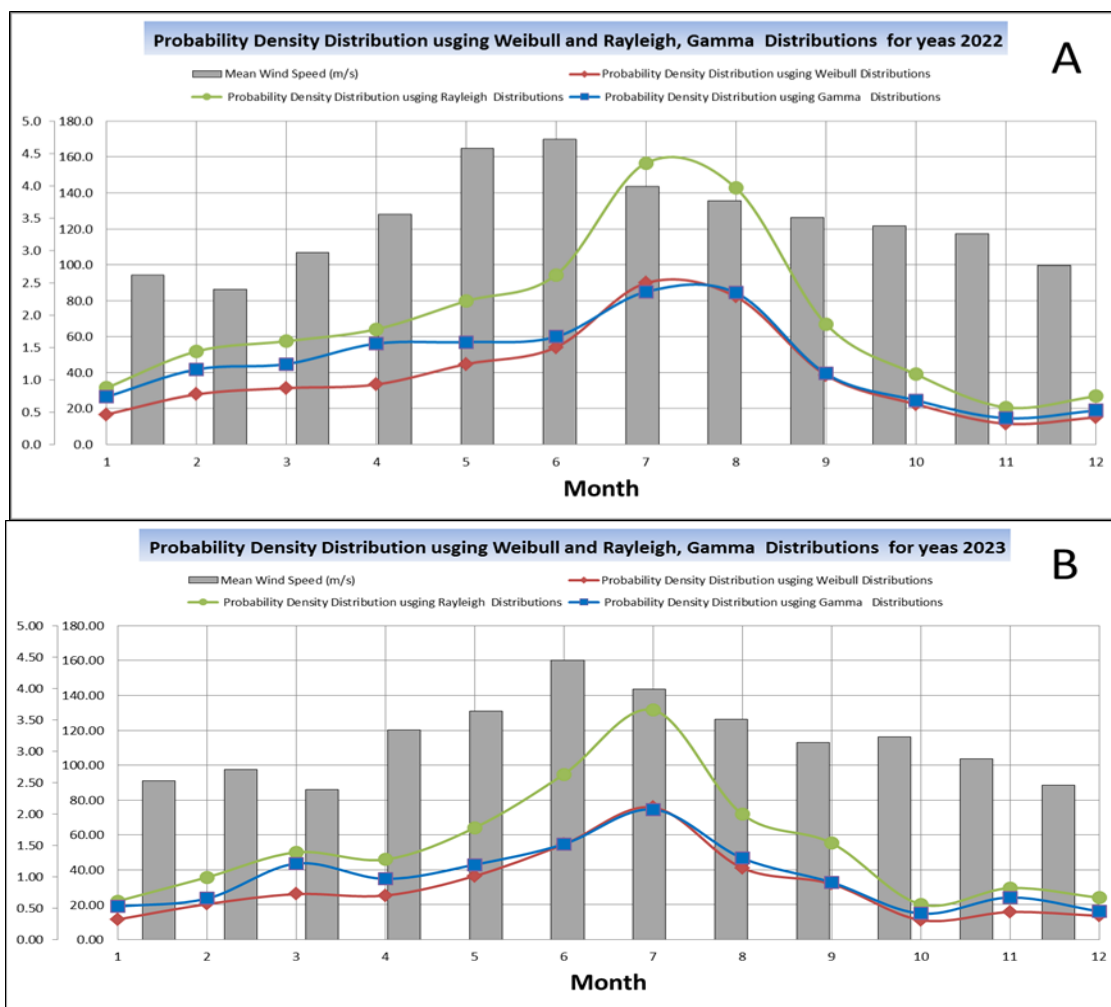


Figure 2 Mean wind speed statistical distribution using the WDF, RDF and GDF.

Table 2 Analyzing probability distribution functions statistically.

Probability distribution functions	RMSE	
	2022	2023
Weibull	7	33
Gamma	77	36
Rayleigh	78	59

3.4 Determine WPD and energy per month for 2022–2023

Table 3 displays the average monthly values for WPD and wind energy, calculated using Eqs. (12) and (16), respectively. The table displays the variations in the wind energy density and wind power values, which correlate to the variations in the Weibull parameters' monthly mean values, shape (k), and scale (c). The months of July/August 2022 and June/July 2023 show the highest values of WPD and wind energy, while November/January 2022 and October/January 2023 show the lowest values. Wind energy density and wind power fall between the lowest and greatest levels throughout the next months. These huge performance differences are due to seasonal fluctuations in the wind speed. In summer, wind speeds are higher due to the increased temperature gradient, which results in a larger pressure difference and therefore higher wind speeds, while the opposite is true in winter. As can be observed, summer wind

speeds are higher than those of other seasons, which leads to higher power output. We can conclude that as average wind speed increases, so do the wind energy and power density.

Table 3 Average monthly energy densities and wind power in 2022–2023.

Months	Power density (w/m ²)		Energy (kw/h)	
	2022	2023	2022	2023
Jan	16.71	11.60	12032.82	8355.45
Feb	27.92	20.40	20105.84	14685.54
Mar	31.41	26.13	22613.64	18810.63
Apr	33.43	25.32	24072.63	18232.34
May	44.75	36.49	32219.57	26269.89
Jun	54.17	54.68	39001.16	39367.63
Jul	89.89	75.84	64723.49	54605.63
Aug	82.27	41.05	59236.62	29559.50
Sep	38.68	31.92	27851.80	22983.20
Oct	22.49	11.26	16189.62	8104.37
Nov	11.61	15.84	8361.78	11408.04
Dec	15.10	13.68	10869.60	9851.51

4. CONCLUSIONS

The best statistical distribution for calculating the wind energy and WPD was WDF. The highest WPD was in summer (July) for years 2022-2023 (75.84 w/m² and 89.89 w/m²), and the lowest was in winter (October and November) for years 2022-2023 (11.26 w/m² and 11.61 w/m²). The highest energy density occurs in summer (July) for years 2022-2023 (64723.49 kw/h and 54605.63 kw/h), and in winter (8104.37 kw/h and 8361.78 kw/h). The huge energy difference between July and November was due to the seasonal fluctuations in the wind speed. The average wind speed rises, so do the wind power and energy density.

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