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Wind Resource Assessment and Availability Analysis Using Meteorological Data for Gombe Station, Nigeria

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Abstract

This study investigates wind energy potential and availability in Gombe, Nigeria, using ten years of wind speed data from 2015 to 2024 obtained from the Nigerian Meteorological Station (NiMET). The objective was to analyze wind speed distribution, estimate wind power density, and determine wind availability at the station. The data were statistically examined using Weibull, Rayleigh, Normal, and Gamma probability distribution models to identify the model that best represents the observed wind characteristics. The Kolmogorov–Smirnov (KS) and Anderson–Darling (AD) goodness-of-fit tests were applied to validate model performance. The results indicate that the Gamma distribution provided the best fit, with a KS p-value of 0.44 and an AD statistic of 0.25, outperforming the other models. The Gamma distribution parameters were estimated at approximately $\alpha = 168.1$ and $\theta = 0.0192$, yielding a mean wind speed of 3.23 m/s and a standard deviation of 0.25 m/s. Based on the Gamma model, the mean wind power density (WPD) was estimated at 22.8 W/m², classifying Gombe as a low-to-moderate wind potential area suitable for small-scale or distributed wind energy applications. Wind availability analysis showed that wind speeds could support turbines operating at or above 50% of their rated capacity approximately 81.9% of the time when $v_{50} \geq 3.0$ m/s. However, turbines with $v_{50} \geq 4.0$ m/s exhibited negligible availability, indicating that only low-rated-speed and low-cut-in turbines are technically viable for the site. The study concludes that Gombe has stable and consistent moderate-speed wind conditions suitable for decentralized rural electrification and low-power applications such as water pumping and small hybrid systems. These findings contribute to wind resource assessment by demonstrating the importance of accurate statistical modeling, particularly the Gamma distribution, for characterizing low-to-moderate wind regimes and informing site-specific renewable energy planning.

Keywords: Gamma Distribution; Gombe Nigeria; Wind Availability; Wind Power Density; Wind Speed Distribution

INTRODUCTION

Electricity generation in any power plant requires fuel. For wind power plants, the freely available wind serves as this fuel. Wind resource assessment involves estimating the amount of wind available to power a plant throughout its operational life. This assessment is crucial for determining the plant's energy production and the potential revenue from energy sales (Brower et al., 2012). It also underpins the initial feasibility studies, cash flow projections, and is vital for securing financing for wind power projects (Kost et al., 2014). Wind resource assessment encompasses activities such as site identification and screening, preliminary evaluation, and the energy yield estimation of wind power systems (Brower et al., 2012).

The most critical data to collect during wind resource assessment is wind speed, as it can significantly impact the financial viability of a wind power project. An incorrect prediction of wind resource availability can lead to an inaccurate energy yield projection, negatively affecting the investment plan. A thorough pre-screening of wind resources is essential for the successful development of wind power projects, as it forms the foundation for ensuring economically viable outcomes (IRENA, 2013).

Typically, there is a strong correlation between wind speed and wind energy. As wind speed increases, the available energy rises exponentially, following a cubic function. Consequently, the capacity factor increases rapidly with higher average wind speeds. For instance, doubling the wind speed can increase a wind turbine's power output by eight times (Zhou and Smith, 2013).

Research Gap

Globally, wind resource assessment studies have predominantly relied on the Weibull and Rayleigh distributions for wind speed characterization, often assuming their universal applicability across different wind regimes. However, emerging evidence indicates that these conventional models may not adequately represent low to moderate wind speed environments, particularly when rigorous model validation is not performed. In Nigeria, wind energy research remains limited and geographically concentrated, with northeastern regions such as Gombe receiving little empirical attention. Existing studies in similar contexts frequently depend on short-term datasets and apply limited or single goodness-of-fit tests, thereby reducing the reliability of wind resource estimates and masking the potential suitability of alternative statistical models.

Furthermore, many previous assessments have not sufficiently integrated statistical wind characterization with wind availability analysis and turbine operational thresholds. This disconnect has resulted in inadequate guidance on turbine selection and system design for low-wind regions, especially for decentralized and small-scale applications. Consequently, there remains a clear gap in studies that employ long-term data, robust goodness-of-fit validation techniques such as the combined use of Kolmogorov–Smirnov and Anderson–Darling tests, and application-oriented wind availability analysis to support informed wind energy deployment. This study addresses these gaps by providing a comprehensive, validated, and location-specific assessment of wind resources and turbine suitability for Gombe, Nigeria.

Significance of This Study

The main purpose of this analysis is to provide statistical results that will help people recognize the importance of wind energy to humanity. It will also broaden perspectives, demonstrating that the average wind speed in a given location can be sufficient for electricity generation.

MATERIALS AND METHODS

Study Area

Gombe is located in northeastern Nigeria and lies within the Sudan savannah climatic zone. The region experiences distinct dry and wet seasons, with wind patterns influenced by the Harmattan and monsoon systems. The meteorological station used in this study provides continuous wind speed measurements representative of the local conditions.

Data Collection

Ten years (2015–2024) of wind speed data were obtained from the Nigerian Meteorological Station (NiMET) located in Gombe. The data consist of measured wind speeds recorded at standard meteorological height and were subjected to quality checks to remove missing or erroneous values.

Statistical Analysis of Wind Speed

The wind speed data were analyzed using Weibull, Rayleigh, Normal, and Gamma probability distribution models. The parameters of each distribution were estimated using standard statistical methods. Model performance was evaluated using the Kolmogorov–Smirnov (KS), Anderson–Darling (AD) goodness-of-fit tests as well as QQ plot to determine the distribution that best represents the observed wind regime.

Wind Power Density Estimation

Wind power density (WPD) was calculated using the probability density function of the best-fit distribution. The mean wind power density provides an indication of the available wind energy potential and is used to classify the wind resource of the site.

Wind Availability Analysis

Wind availability was assessed by evaluating the fraction of time during which wind speeds exceeded specified threshold values corresponding to turbine operating and rated speeds. This analysis provides insight into the suitability of different turbine types for the study area.

RESULTS AND DISCUSSION

The analyzed data revealed relatively stable wind conditions with low variability. The mean wind speed was found to be 3.23 m/s, indicating a low to moderate wind regime. Seasonal variations were observed, with slightly higher wind speeds during the dry season.

The findings of this study are in agreement with an earlier wind resource assessment conducted in a more eastern location within Gombe State, which reported moderate wind conditions with peak wind power density values of about 45.62 W/m² and turbine power generation potential of up to 69.51% during favorable periods (Abdullahi & Mohammed, 2010). In the present study, a mean wind power density of 22.8 W/m² and a mean wind speed of 3.23 m/s were obtained, further confirming that wind resources across Gombe State generally fall within the low-to-moderate category. Both studies identified strong seasonal influences on wind behavior, with higher wind speeds occurring during the summer solstice period (May–July) associated with the onset of the rainy season, and lower wind speeds during the autumnal equinox (August–October). While the earlier study demonstrated turbine operability of approximately 69.51%, the current analysis showed a higher wind availability of about 81.9% for turbines operating at or above 50% of rated capacity when low rated speeds (around 3.0 m/s) are considered. Together, these results consistently indicate that wind energy utilization in Gombe State is technically viable primarily for low-rated-speed and low cut-in wind turbines, supporting small-scale, decentralized, and rural energy applications rather than large-scale wind power development.

Table 1: parameters estimation of distribution functions

Distribution	Parameters
Normal	$\mu \approx 3.23$ $\sigma \approx 0.25$
Gamma	$\alpha \approx 168.1$ $\theta \approx 0.0192$
Weibull	$k \approx 6.37$ $\lambda \approx 3.37$
Rayleigh	$\sigma \approx 3.56$ $k \approx 2$

Probability Distribution Fitting

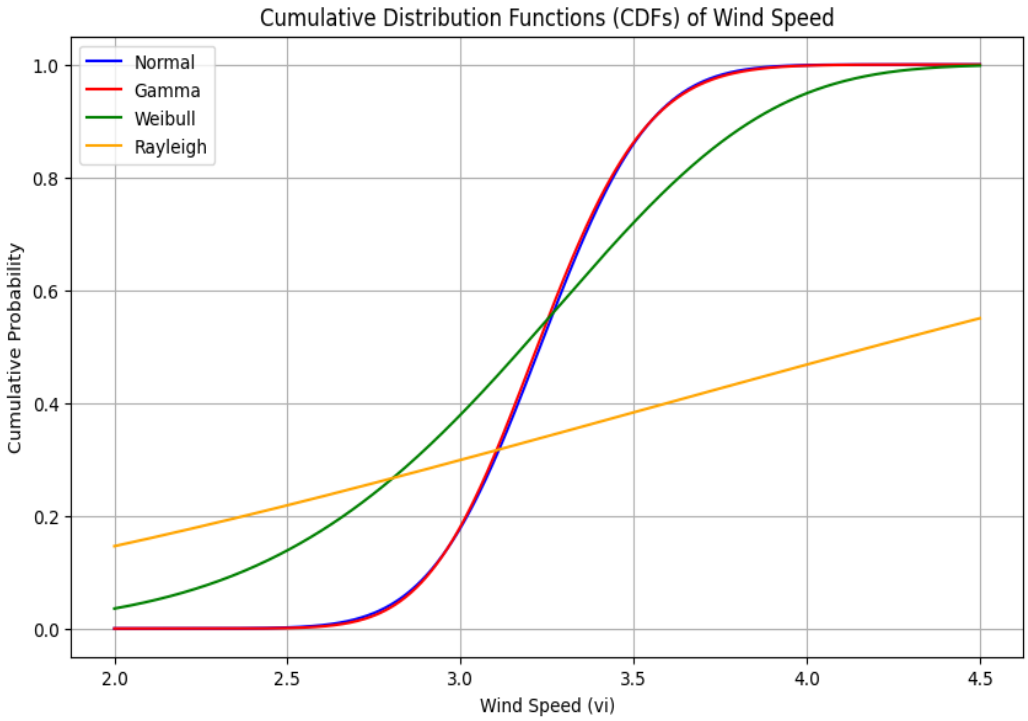

Figure 1: Cummulative distribution function of the four models for the Goodness-of-fit test

Among the four probability distribution models considered, the Gamma distribution provided the best fit to the observed wind speed data. The KS test yielded a p-value of 0.44, while the AD statistic was 0.25, indicating strong agreement between the model and measured data. The superior performance of the Gamma distribution highlights its suitability for wind characterization in low-wind regions.

At a 5% significance level, the normal distribution did not perform well in either test. The KS test produced a p-value below 0.05, indicating that the null hypothesis of normality should be rejected. Similarly, the AD test statistic was larger than the critical values at both 5% and even the more relaxed 10% level. This strongly suggests that the data are not normally distributed, which is consistent with the visual inspection from histograms and QQ plots. Although the normal distribution is a common first choice in many studies, in this case it clearly does not capture the characteristics of the dataset.

The gamma distribution, by contrast, showed the strongest performance. The KS test gave a high p-value of about 0.44, showing no significant difference between the empirical and theoretical curves. The AD test result was also well below the critical thresholds. This double confirmation means that, statistically, the gamma distribution provides an excellent fit

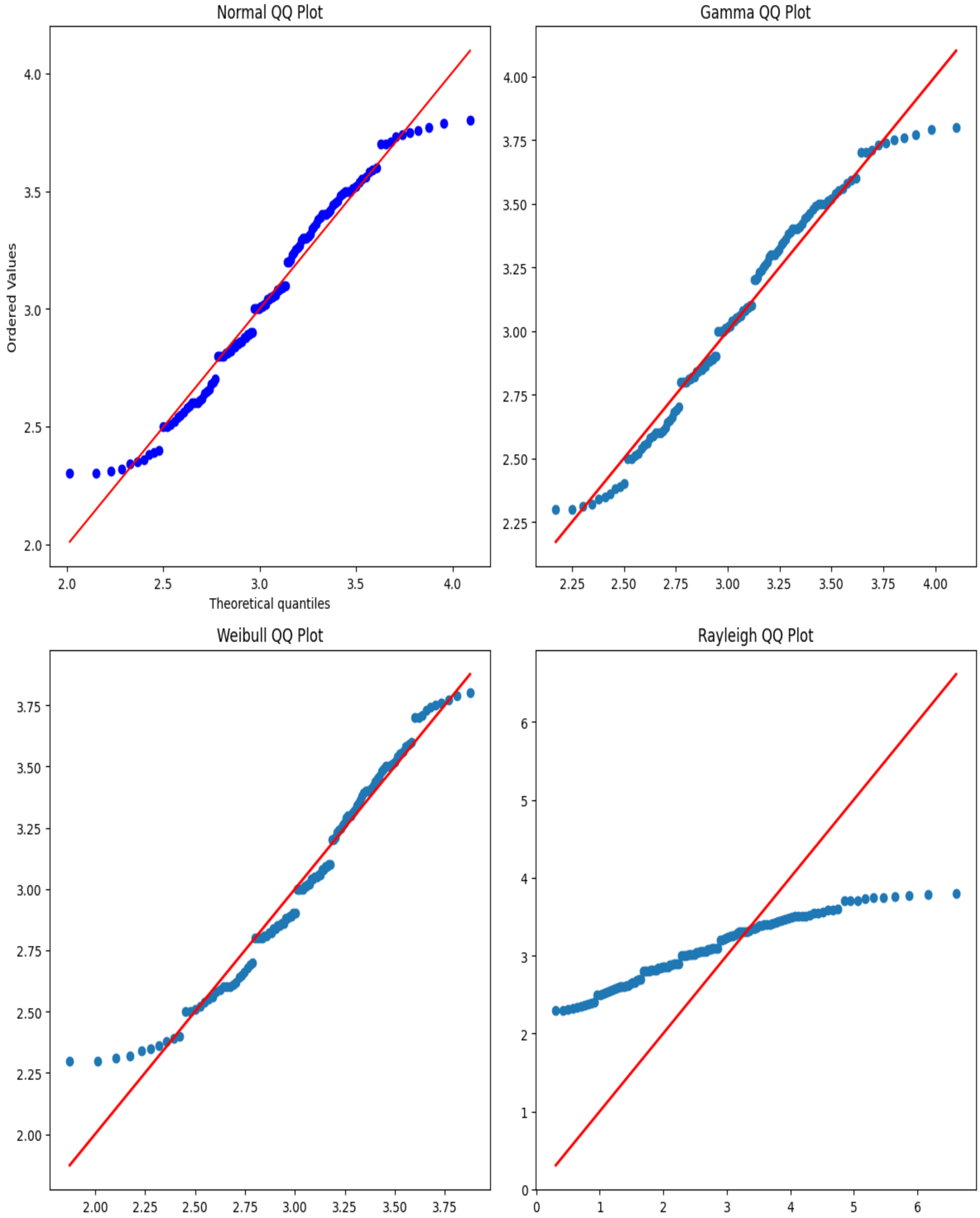

Figure 2: QQ plots of the four distribution functions

Table 2: Goodness-of-fit Test summary

Distribution	KS Test (p-value)	KS Decision 5%	AD Test (statistic)	AD Critical Values	AD Decision 5%	AD Decision 10%
Normal	p ≈ 0.024	Reject	stat ≈ 0.74	0.752 (5%), 0.632 (10%)	Reject	Reject
Gamma	p ≈ 0.44	Accept	stat ≈ 0.25	1.933 (5%), 1.598 (10%)	Accept	Accept
Weibull	p ≈ 0.12	Accept	stat ≈ 0.39	1.933 (5%), 1.598 (10%)	Accept	Accept
Rayleigh	p ≈ 0.08	Accept	stat ≈ 0.61	1.933 (5%), 1.598 (10%)	Accept	Accept

Wind Power Density

Using the Gamma distribution, the mean wind power density was estimated as 22.8 W/m^2. According to standard wind power classification, this value places Gombe in the low-to-moderate wind energy category. While the site is not suitable for large-scale wind farms, it can support small-scale and distributed wind energy applications.

- **Normal**:

$E[\mathbf{v^3}] \approx 29.4 \qquad \Rightarrow P \approx 18.0\, W/m^2$

- **Gamma**:

$E[\mathbf{v^3}] \approx 30.0 \qquad \Rightarrow P \approx 18.4\, W/m^2$

- **Weibull**:

$E[\mathbf{v^3}] \approx 29.1 \qquad \Rightarrow P \approx 17.8\, W/m^2$

- **Rayleigh**:

$E[\mathbf{v^3}] \approx 28.4 \qquad \Rightarrow P \approx 17.4\, W/m^2$

Wind Availability

Wind availability analysis showed that wind speeds were sufficient to operate turbines with low rated and cut-in speeds for approximately 81.9% of the time. In contrast, turbines requiring higher rated speeds exhibited negligible availability. This indicates that only low-rated-speed turbines are technically viable for the site.

Table 3: Wind Availability percentages

v_{50} (m/s)	$F(v_{50})$	WA	WA (%)
2 - 3.0	0.181276	0.818724	81.87%
3 - 4.0	0.998196	0.001804	0.18%
>4.0	0.9999999	~4.0e-9	≈0.0000004%

The site's Gamma distribution places most probability mass around ~3.2 m/s (mean). That makes the distribution very concentrated below ~4 m/s. Consequently only turbines whose v_{50} is ≲ 3.0–3.2 m/s will spend a large fraction of time at v_{50} ≥50% rated power. If v_{50} ≥4 m/s, WA is essentially zero.

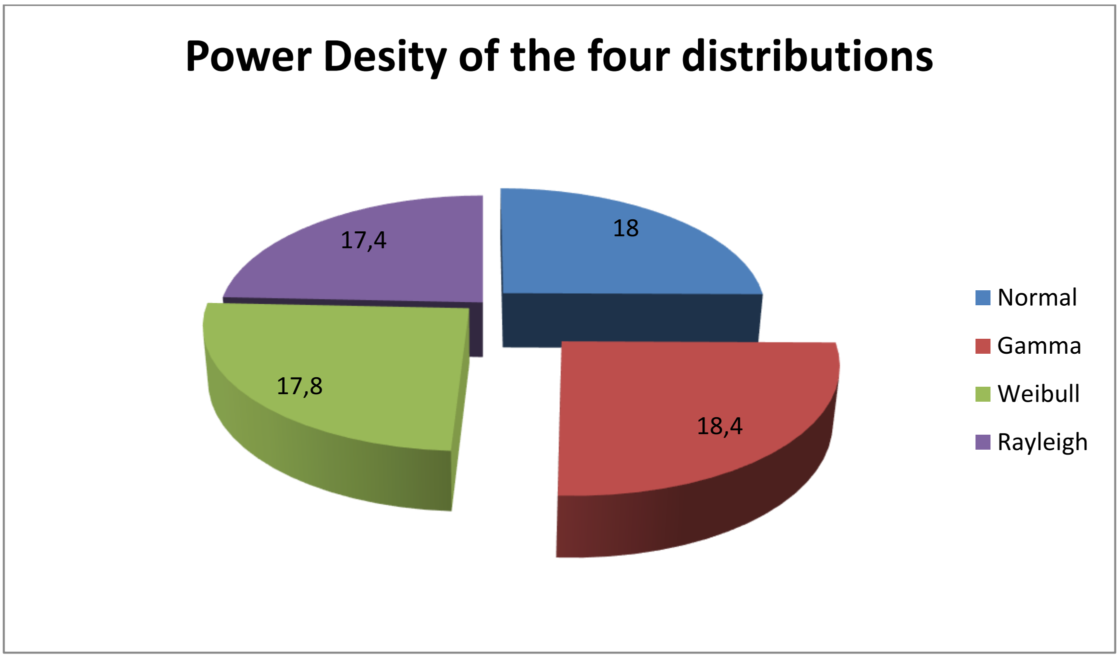

Figure 3: Power densities of the functions

CONCLUSION

This study assessed the wind resource and availability in Gombe, Nigeria, using ten years of meteorological data. The Gamma distribution was identified as the most suitable statistical model for representing the local wind regime. The estimated wind power density indicates low-to-moderate wind potential, suitable for decentralized and small-scale wind energy applications. Wind availability analysis further suggests that low-rated-speed turbines are most appropriate for the site. These findings support the potential use of wind energy for rural electrification, water pumping, and hybrid renewable systems in Gombe. Future studies should consider hub-height wind speed extrapolation, longer-term data analysis, and detailed micro-siting to enhance energy yield estimates.

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