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Wind Profile Analysis and Wind Turbine Selection for a Low-Wind Site: A Case Study of Lokoja, Nigeria

***Nafiu Adam and Mary Samuel**

Department of Mechanical Engineering, Nigerian Defence Academy, Kaduna State, Nigeria

*Corresponding Author's email: narphdon@gmail.com

ABSTRACT

This study presents a comprehensive assessment of wind energy potential and turbine performance in Lokoja, Nigeria, a region characterized by low to moderate wind speeds. Wind speed data at 10 m height, obtained from the Nigeria Meteorological Agency (NiMet) were statistically analyzed using Weibull distribution to model the site's wind profile, forming the basis for simulating the performance of ten wind turbine models ranging from 10 kW to 6 MW. Evaluation criteria included cut-in speed, annual energy production (AEP), capacity factor, and levelized cost of energy (LCOE).Results showed that turbines with low cut-in speeds (≤2.5 m/s) are more suitable for Lokoja's wind regime. Among all models, the Enercon E-115/3.000 demonstrated the highest cost-efficiency, with a capacity factor of 0.124 and an estimated LCOE of $0.085/kWh (₦136.61). Mid-sized turbines like the Polaris P62-1000 and Envision EN-82/1500 also showed balanced performance for decentralized applications. In contrast, smaller turbines such as the Bergey Excel 10 and Aircon 10S were found to be economically unviable due to low energy yield and high unit cost. This study provides a critical, data-driven framework for turbine selection in Nigeria's underexplored inland low-wind regions, supporting the country's goals for renewable energy diversification and rural electrification. It is recommended that small to medium sized turbine with ultra- low cut-in-speed be prioritized for deployment in Lokoja.

Keywords: Wind Energy, Weibull Distribution, Turbine Performance, Low Wind-Site

1.0 INTRODUCTION

The pressing needs of energy security, sustainable development, and climate change mitigation are causing a significant shift in the global energy landscape. Renewable energy sources have risen from alternative options to become essential components of the future energy mix as a result of this paradigm shift. One of the most developed, scalable, and financially feasible of these is wind energy, which has the potential to drastically reduce carbon emissions in the power industry (Global Wind Energy Council [GWEC], 2023). However, a thorough and site-specific understanding of the wind resource is a prerequisite for the effective use of wind power. Any wind energy project's technical and financial viability depend on a careful examination of the local wind profile and the careful selection of turbine technology that best suits it (Manwell, McGowan, & Rogers, 2009).

Unquestionably, one of humanity's most fundamental needs is a sufficient supply of power at a fair price. Giving the people enough and the right kind of power is a global problem. Although developed and developing nations may have different levels of concern, supplying steady power is a significant problem worldwide. Therefore, every effort must be made to find ways to meet the world's growing energy demand. The formation process takes a long time, and these energy sources are found naturally. These resources are limited and non-renewable due to this one factor. Moreover, social and economic poverty are caused by a country's or government's inability to supply its citizens with sufficient and dependable energy or electricity (Ohunakin, 2010; Oyedepo, 2015).

In the developing world, and especially in sub-Saharan Africa, which is marked by a paradoxical combination of enormous renewable energy potential and persistent energy poverty, this need is especially pressing. Nigeria, the most populous country and largest economy in Africa, is a prime example of this problem. The nation has a severe and ongoing electricity crisis despite its enormous oil and gas reserves, with a large portion of the population lacking access to the national grid, which is characterized by irregular, inadequate, and insufficient supply (Adewuyi, 2020). This energy deficit exacerbates poverty, hinders socioeconomic development and industrial growth. As a result, there is a pressing need to use Nigeria's abundant renewable resources such as wind, solar, hydro, and biomass to diversify the country's energy mix (Ohunakin, Adaramola, & Oyewola, 2014).

In Nigeria, while solar energy has received more attention, wind energy research has been gradually increasing due to its potential contribution to sustainable electricity supply (Ajayi, 2010; Ohunakin et al., 2014). Most existing wind energy projects and feasibility studies in Nigeria have focused on coastal or northern regions such as Sokoto, Katsina, and Maiduguri, where wind speeds are relatively higher (Ojosu & Salawu, 1990; Ngala et al., 2007). However, inland areas such as Lokoja remain underexplored, creating a research gap in site-specific wind profile characterization and the performance evaluation of modern turbines designed for low-wind conditions.

This study focuses on Lokoja, the capital of Kogi State and its potential for wind energy. Due to its topography and geographic location, Lokoja presents a particularly intriguing case study for the investigation of wind energy. The city is located inside a geographical trough that directs the dominant winds, at the meeting point of the Niger and Benue, Nigeria's two main rivers. This confluence zone produces a distinct microclimate that may increase wind speeds (Akinbode, Eludoyin, & Fashae, 2008). Additionally, its distance from the coastal belt, which has been the main focus of the majority of Nigerian wind resource assessments, offers a chance to look into the feasibility of inland wind power, which could broaden the country's wind energy map. Furthermore, Lokoja's energy challenges, including grid instability and reliance on diesel generators, underscore the practical relevance of exploring localized renewable energy solutions.

Wind profile analysis is critical for turbine selection because turbine performance strongly depends on local wind regimes (Carta et al., 2009). The Weibull distribution is commonly applied for wind resource characterization, providing shape (k) and scale (c) parameters that describe wind speed variability and consistency (Seguro & Lambert, 2000). In areas with low average wind speeds, such as Lokoja, turbine models with ultra-low cut-in speeds and optimized power curves must be prioritized (Rehman et al., 2012). Globally, studies in similar low-wind regions, such as inland Brazil and parts of India, have demonstrated the economic viability of wind energy through careful turbine matching (Kumar et al., 2019).

Several studies have assessed Nigeria’s wind profile. For instance, Fadare (2008) conducted a Weibull-based analysis of wind speeds in Ibadan, revealing average speeds of 2.9 m/s, which aligns with the classification of Nigeria as a low-wind-speed region. Similarly, Okundamiya and Nzeako (2011) estimated the wind energy potential of Benin-City and emphasized the importance of selecting turbines designed for Class III wind zones. Ajayi et al. (2014) compared wind regimes across different Nigerian locations and confirmed the seasonal variability of wind, with peaks typically between March and May.

Internationally, studies from similar low-wind regions have adopted Weibull modeling to characterize wind regimes and assess energy potential. Carta et al. (2009) in the Canary Islands and Shahadah et al. (2017) in Malaysia both confirmed that accurate estimation of Weibull parameters is essential for realistic turbine performance simulation. These works underscore the need for site-specific analysis, which is the focus of the present study for Lokoja.

This study therefore aims to analyze the ten-year wind profile of Lokoja using Weibull distribution, simulate the performance of selected wind turbines based on key metrics (capacity factor, AEP, and LCOE), and identify the most suitable turbine technology for the region's low-wind regime.

2.0. MATERIALS AND METHOD

2.1 Material

2.1.1 Data Collection

Hourly wind speed data for Lokoja at a height of 10 m were collected from the Nigeria Meteorological Agency (NiMet) for a period of ten (10) years (2015-2024) and processed into daily averages. Microsoft Excel 2019 software was used for the evaluation of the data.

2.2 Method

2.2.1 Wind profile analysis

The wind profile of the study site was evaluated by Microsoft Excel version 2019, utilizing Equations (1) to (7) (Samuel et al, 2024). The Weibull distribution was selected for its robustness in characterizing wind speed variability in low-wind regimes, as established in prior literature (Seguro & Lambert, 2000).

i. The mean speed is given by Equation (1).

$$V_{m=}\frac{1}{n}\sum_{i=1}^{n} V_I \qquad (1)$$

Where v_m the average wind speed (m/s), V is the daily wind speed (m/s) and n is the number of wind speed data

ii. The standard deviation was evaluated by Equation (2).

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(V_{i-}V_m)^2} \qquad (2)$$

Where σ is the standard deviation, v_m is the average wind speed (m/s).

iii. The Weibull shape factor (k):

$$k = \left[\frac{\sigma}{V_m}\right]^{-1.086} \qquad (3)$$

iv. Weibull scale factor (c);

$$c = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \qquad (4)$$

Where σ is the standard deviation, v_m is the average wind speed (m/s), $\Gamma(x)$ is the gamma function of (x).

v. The Wind Power Density

$$p(v) = v = {}^{1}/_{2}\,\rho C^{3}\left(1 + ({}^{3}/_{k})\right) \qquad (5)$$

Where *p(v)* is the wind power density (W/m^2) and ρ is the air density (kg/m^3) at the sites [26].

vi. Potential of Wind Energy

The available energy per unit area perpendicular to the wind stream during a particular period of time t is expressed by kinetic energy as:

$$Ea=0.5\rho V^3 \qquad (6)$$

Where ρ is the air density in kilograms per cubic meter, and Ea denotes the theoretical total energy available to operate the turbine. Only a small portion of the total energy would be retrieved, though. A coefficient of performance known as the Beltz limit (16/27 = 0.593) limits the maximum extractable energy from a system operating at its greatest efficiency gives

$$E_M = 0.2965\rho V^3 \qquad (7)$$

As the capacity factor, which makes the extractable energy approximately 59.3% of the theoretical energy.

2.2.2 Wind Speed Simulation Using Weibull Distribution

The probability distribution of wind speeds was modeled using the two-parameter Weibull distribution. The scale (c) and shape (k) parameters were estimated using the empirical method based on the mean and standard deviation of the measured wind speed data. The probability density function (PDF) and Cumulative density function (CDF) for each wind speed bin were computed using

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{8}$$

$$F_W = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{9}$$

Where, $f(v)$ = Weibull distribution function, F_W = Weibull cumulative distribution function, v= wind speed, k= the Weibull shape parameter (dimensionless), c= the Weibull scale parameter (in meter per second) (Samuel et al, 2024).

2.2.3 Wind Turbine Performance Simulation

Ten commercial wind turbine models were selected for evaluation based on explicit criteria: a cut-in speed of ≤ 2.5 m/s, suitability for IEC Class III/IV wind sites, and commercial availability in power ratings from 10 kW to 6 MW to cover various application scales.Each selected wind turbine's performance was simulated using its power curve, defined by:

i. Cut-in speed
ii. Rated speed
iii. Rated power
iv. Cut-out speed

A piecewise linear model was developed in Microsoft Excel to relate wind speed to power output:

i. Below cut-in speed: 0 kW output
ii. Between cut-in and rated speed: linear ramp-up from 0 to rated power
iii. Between rated and cut-out speed: constant rated power
iv. Above cut-out speed: 0 kW output

For each wind speed bin, the turbine's expected power output was multiplied by the probability of that wind speed (from the Weibull PDF). The mean expected power was integrated across all wind speeds to determine the capacity factor and AEP using:

$$AEP\ (kWh/year) = Mean\ Power\ (kWh) \times 8760 \tag{10}$$

$$Capacity\ Factor = \frac{AEP}{Rated\ Power \times 8760} \tag{11}$$

The cost per unit energy generated by each turbine was estimated using the assumed capital cost and the simulated AEP using:

$$Cost\ per\ kWh\ (USD) = \frac{Estimated\ Cost\ (USD)}{AEP\ (kW/year)} \tag{12}$$

2.2.4 Selection of Suitable Turbine

Based on the simulation results, turbines were evaluated according to:

i. Compatibility with low wind speeds (low cut-in speed)
ii. High capacity factor and AEP in Lokoja's wind conditions
iii. Low cost per kWh

2.2.4 Sensitivity Consideration

To account for data variability and uncertainty, a basic sensitivity analysis was performed by considering a ±5% variation in the mean wind speed and observing its impact on the Annual Energy Production (AEP) of the top-performing turbine models. This provides a range of expected energy yields.

3.0 RESULT AND DISCUSSION

3.1 Wind Profile Analysis

3.1.1 Wind Speed Characteristics

The daily mean wind speed data (2015 – 2024) for the site considered in this work as presented in Appendix (A) were averaged into monthly and yearly mean values and the results presented in the Figures1 and 2 respectively.

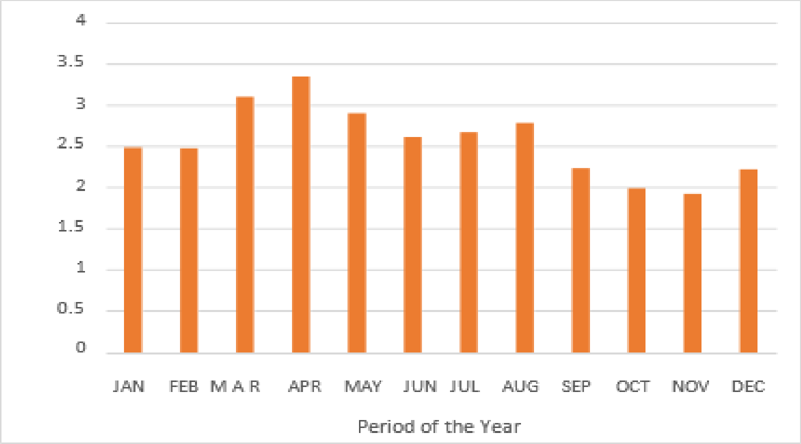

Figure 1: Monthly Average Wind Speed Data

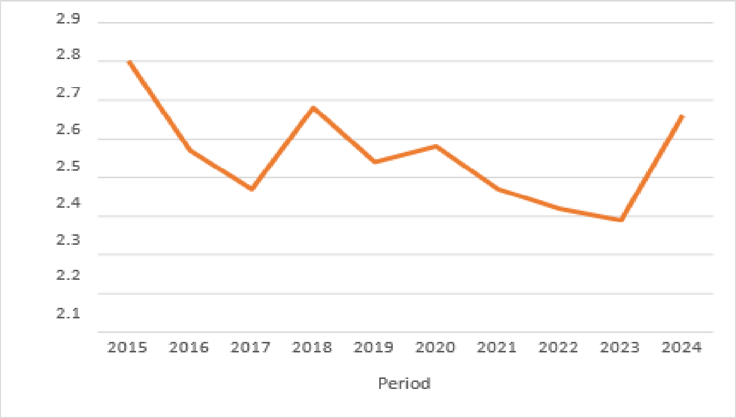

Figure 2: Annual Average Wind Speed Data

From Figure 1 it could be deduced that the monthly maximum and minimum wind speeds of 3.34m/s and 1.92m/s for the location, for the range of period from 2015 to 2024, occurred in the months of April and November respectively. Whereas, the annual mean values as shown in Figure 2 revealed that the minimum value of 2.39m/s and maximum value of 2.8m/s occurred in year 2023 and 2015 respectively. This result is broadly consistent with prior inland and central Nigerian studies. For example, Ohunakin et al. reported mean speeds between 2.0–3.0 m/s for parts of the North-Central region, including Lokoja. This low mean speed of 2.55 m/s implies that only turbines designed for ultra-low-speed startup (typically with a cut-in speed ≤ 2.5 m/s) would operate consistently at this site, directly influencing the turbine selection criteria.

Peak wind speeds were recorded from March to May, with the highest average in April (3.34 m/s) while lowest wind speeds occur in October (1.99 m/s) and November (1.92 m/s). This suggests a seasonal pattern: higher wind potential in late dry and early rainy season, and lower potential during the wet season peak and harmattan months. The fluctuation of ±0.8 m/s from the annual mean across seasons suggests that energy yield may drop significantly during the low-wind months, highlighting the need for hybrid energy systems or storage. These could be linked to the fact that during the dry season and harmattan period wind speed tends to be higher as a result of strong winds covering the country especially in the northern parts where the main wind direction is from the North-east.

Also, from Figure 2, over the ten years covered by this studies, the average wind speed ranged from 2.4 to 2.8 m/s indicating moderate to low wind potential. However, some months exceed 3.0 m/s, which is promising for small-scale or low cut-in speed wind turbines. Lokoja's mean wind speed aligns closely with reported values for other low-wind tropical inland cities like

Nairobi (3.1 m/s), suggesting broader relevance for small-turbine adoption in similar climatic zones.

3.1.2 Weibull Distribution Parameters

The results of the weibull distribution parameters k and c for the site considered in the analysis were evaluated using equations 1 to 3. The results were shown in Figures 3 and 4.

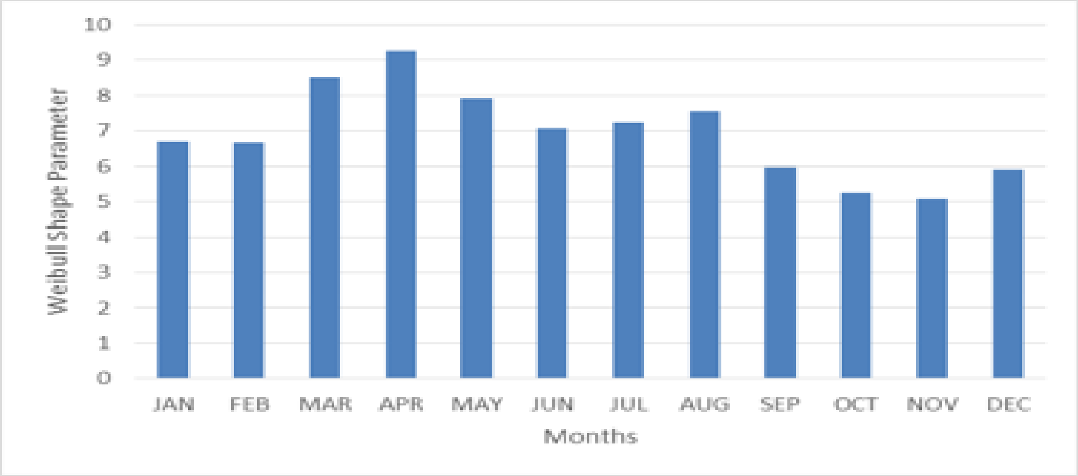

Figure 3: Monthly Average Weibull Shape Factor (k)

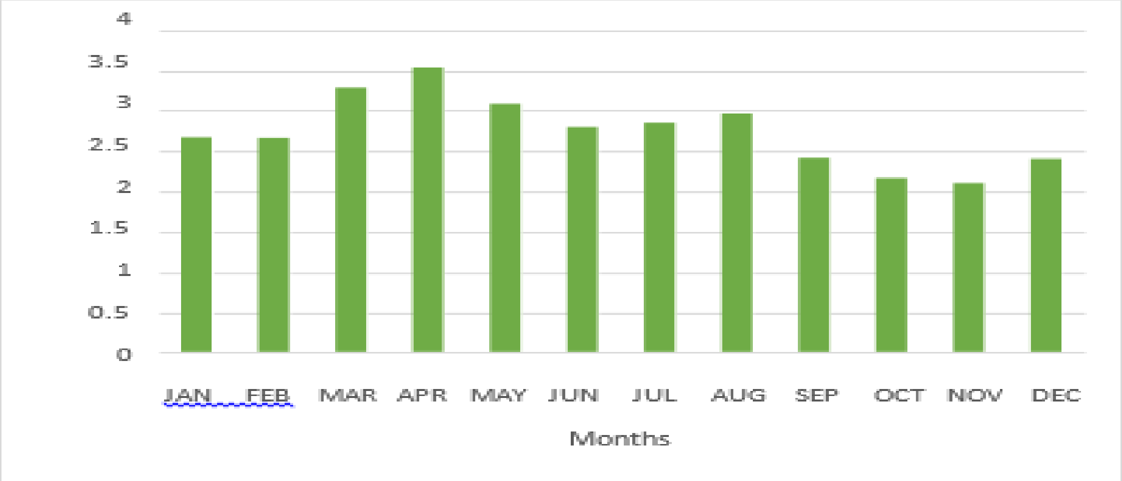

Figure 4: Monthly Average Weibull Scale Factor (c)

From Figure 3, the Weibull shape parameter (k) values, ranging from 5.07 to 9.25, suggest a moderately narrow wind speed distribution, indicating that wind speeds in Lokoja are relatively stable across each month. Higher k-values observed in March and April reflect more predictable wind conditions which is a positive indicator for turbine performance. As shown in Figure 3, the Weibull k-value of 5.65 indicates a relatively stable and predictable wind regime, which is favorable for energy forecasting.

From Figure 4 the minimum monthly average c value was 2.09m/s while the maximum monthly average c value was 3.52m/s. The Weibull scale factor c indicate the potentiality of the wind power of the site, it is directly proportional to the wind speed. As observed from Figure 4, the c parameter increased with respect to increase in wind speed for the range of period considered. The scale parameter (c), peaking at 3.52 m/s (April), aligns well with the mean wind speed trends, affirming the suitability of the Weibull distribution for wind data modeling in this region.

3.1.3 Wind Power Density

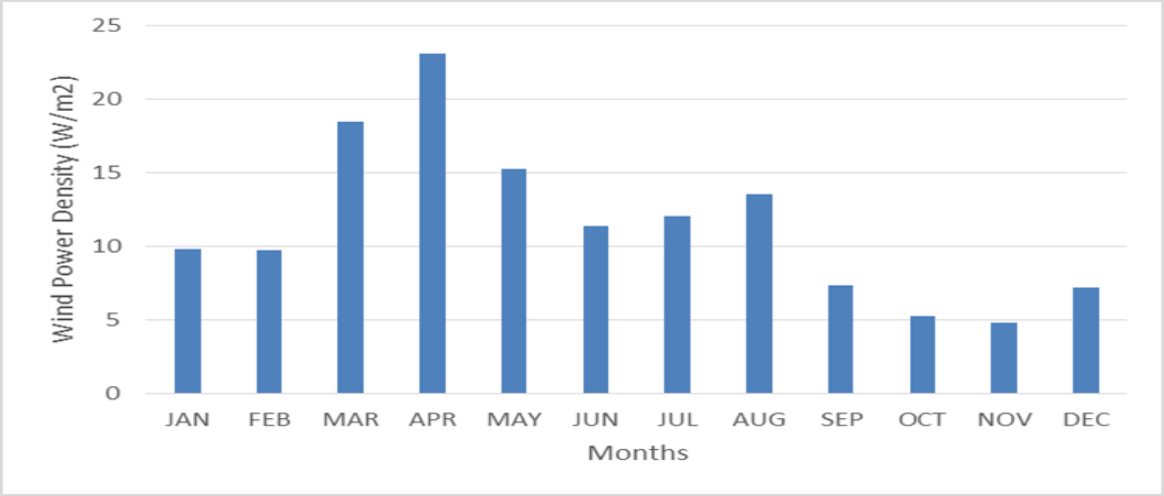

Figure 5: Wind Power Density

As observed from Figure 5, it could be deduced that The Wind Power Density (WPD) values throughout the year are uniformly low, with a maximum of 23.14 W/m² in April and a minimum of 4.83 W/m² in November. The power density for the range of period considered were evaluated using Equation 7. Manwell et al revealed that when wind power density is less than 100 W/m², the region falls under the zone of low wind speed region. The observed values are very low and cannot be recommended for large-scale wind energy investments. This firmly classifies Lokoja as a marginal (Class 1 based on NREL wind classification) wind site, necessitating specialized turbine technology.

3.1.4 Theoretical Wind Energy and Maximum Extractable Energy

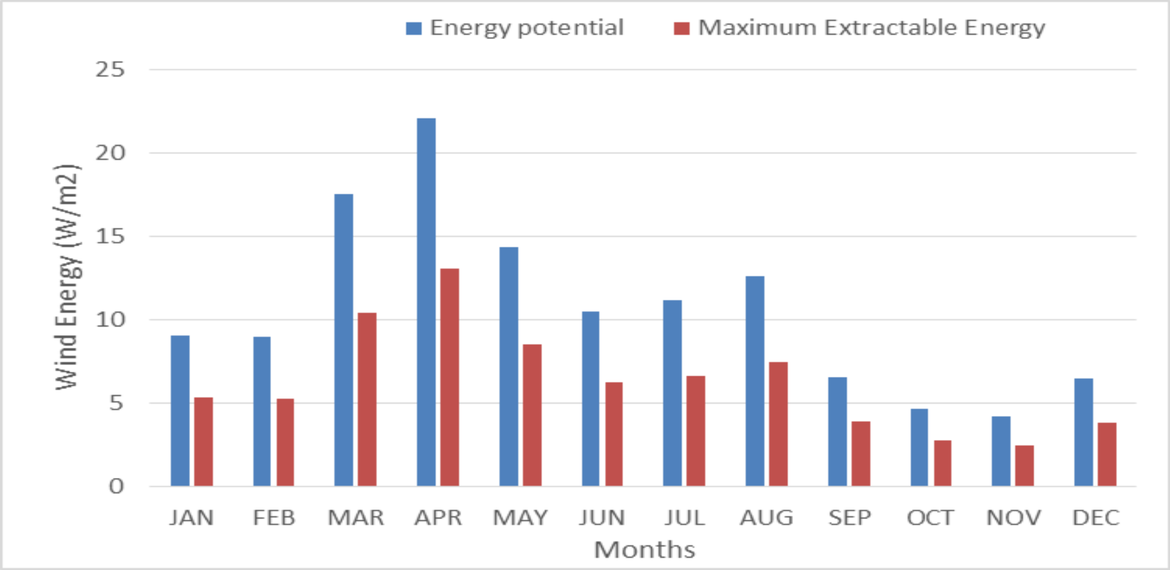

Figure 6: Monthly Average of Theoretical and Extractable Wind Energy

From Figure 6, the maximum monthly average wind energy potential was 22.06W/m² in April, while the minimum monthly average wind energy potential was 4.20W/m² in November which was the theoretical total energy available for doing work on the wind turbine of the site. However, only a fraction of the total energy was extracted. The maximum extractable energy from a system working at its optimum efficiency is limited by a coefficient of performance called Beltz limit (16/27 = 0.593). This capacity factor makes the extractable energy approximately

59.3% of the theoretical energy. Equations 9 and 10 were used to evaluate the theoretical and extractable energy of the site. As observed from Figure 6 the minimum average monthly extractable energy was 2.49W/m² in November and the maximum was 13.08W/m² in April. The presence of these seasonal peaks in wind energy potential indicates that wind can play a supportive role in hybrid configurations, especially when paired with solar PV during low-radiation periods. Given the limited local capacity for servicing complex machinery, turbines selected for such applications should ideally have robust designs with fewer moving parts to reduce maintenance demands and downtime.

3.2 Weibull Distribution

Weibull parameters for Lokoja were estimated as k = 5.65 and c = 2.76 m/s. The distribution curve confirms that most wind speeds fall within 2–3.5 m/s, supporting the case for turbines with low cut-in speeds.

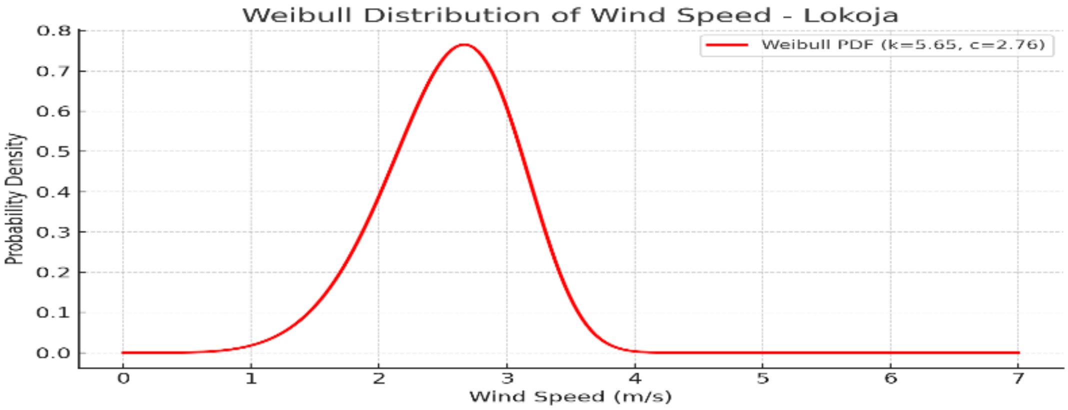

Figure 7: Weibull Distribution

3.3 Wind Turbine Performance Evaluation

Ten turbine models were selected for performance evaluation based on their compatibility with Lokoja's wind profile. Each of the turbines was evaluaed in terms Capacity factor, Annual energy production and Cost per kWh.

Table 1: Selected Wind Turbine Models

S/No	Model	Rated Power (kW)	Cut-in Speed (m/s)	Rated Speed (m/s)	Cut- out Speed (m/s)
1	Enercon E-166/18.70	1800	2.5	12.8	30
2	Enercon E-115/3.000	3000	2	11.5	25
3	Enercon E-175Ep5	6000	2	12.5	25
4	Nordex N60	1300	2.5	15	25
5	Polaris P62-1000	1000	2.5	12	25
6	Xzeres 442SR	10	2	10	22
7	Bergey Excel 10	10	2.5	11.5	20
8	Aircon 10S	10	2.5	12	18
9	Envision EN-82/1500	1500	2.5	12	25
10	Eocycle EO25	25	2	10.5	20

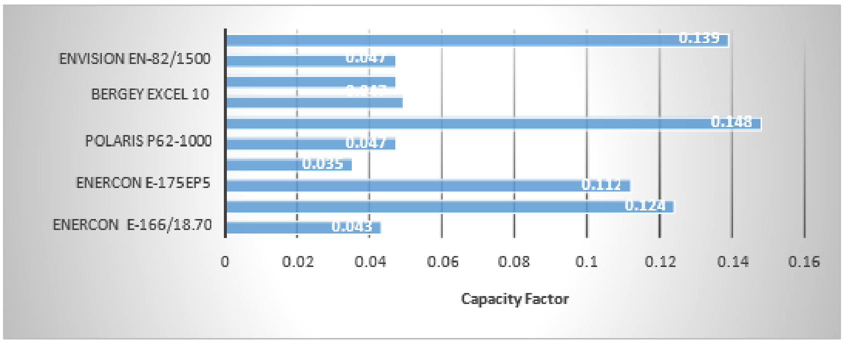

Figure 8: Capacity Factor Estimation

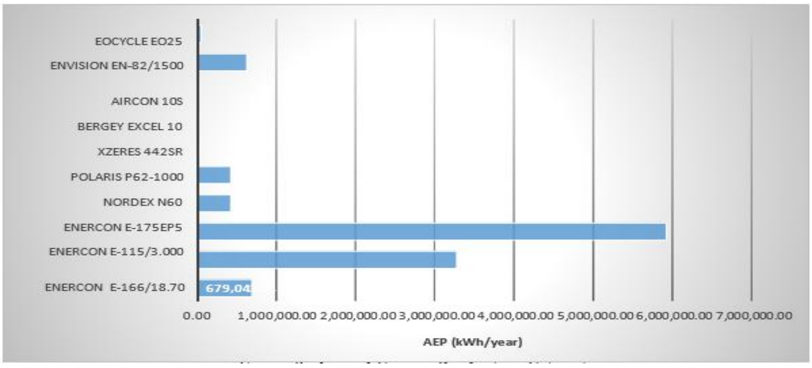

Figure 9: Annual Energy Production Estimation

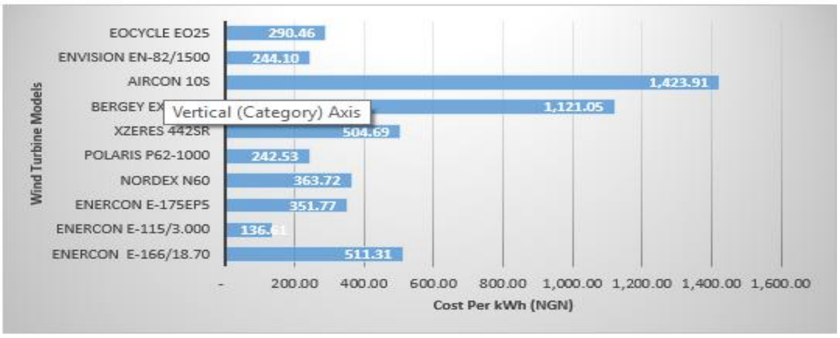

Figure 10: Cost Estimation

From Figures 8 to 10, it can be observed among the ten turbine models evaluated, The Enercon E-175 EP5 delivered the highest AEP (5,912,964.65 kWh/year) and rated output (52,560,000 kWh/year), a reflection of its large 6 MW capacity. However, its capacity factor stood at 0.112, indicating moderate efficiency. The Enercon E-115/3.000, though smaller (3 MW), achieved a slightly higher capacity factor of 0.124 and an AEP of 3,267,690.99 kWh/year, making it more efficient under Lokoja's moderate wind regime. Notably, its cut-in speed of 2 m/s makes it well-suited for the prevailing wind profile.

Smaller turbines like the Xzeres 442SR and Eocycle EO25 outperformed expectations with capacity factors of 0.148 and 0.139, respectively. Despite their low rated capacities, their performance suggests adaptability to low wind speed regions, likely due to their design optimization for distributed or off-grid systems. However, they remain limited in total output capacity, producing only 12,934.61 kWh/year and 30,434.38 kWh/year, respectively.

From a cost perspective, the Enercon E-115/3.000 proved the most economically viable with a cost per kWh of $0.085 (₦136.61), the lowest among all models. This is due to its relatively high energy yield, optimal capacity factor, and reasonable estimated cost ($5.58 million). The

Enercon E-175 EP5, while producing the highest absolute energy, had a cost per kWh of $0.220 (₦351.77) due to its high capital cost of $32.5 million, reducing its overall cost-efficiency.

On the opposite end of the spectrum, turbines such as the Aircon 10S and Bergey Excel 10 showed poor technical and economic performance, with extremely low AEPs (around 4,000 kWh/year) and costs per kWh of $0.890 (₦1423.91) and $0.701 (₦1121.05), respectively. Their high costs and low productivity make them unsuitable for deployment in Lokoja. Similarly, the Nordex N60, while moderately sized (1.3 MW), had the lowest capacity factor (0.035) and a relatively high cost per kWh of $0.227 (₦363.72), highlighting its inefficiency in low-wind environments.

Mid-tier options like the Polaris P62-1000 and Envision EN-82/1500 demonstrated balanced performance, with cost per kWh values of $0.152 (₦242.53) and $0.153 (₦244.10) respectively. Their capacity factors were modest (0.047) but acceptable, and their moderate capital costs make them appropriate for medium-scale applications such as rural electrification or hybrid grid integration.

3.4 Sensitivity Analysis

A sensitivity analysis on the top three turbines (Enercon E-115/3.000, Enercon E-175 EP5, and Polaris P62-1000) revealed that a ±5% variation in mean wind speed leads to a corresponding ±15-18% change in AEP. This underscores the significant impact of inter-annual wind speed variability on project economics and reinforces the need for robust feasibility studies that account for this uncertainty.

4.0 CONCLUSION

A 10-year study (2015-2024) of wind data in Lokoja revealed an average wind speed of 2.55 m/s, with seasonal trends showing higher speeds from March to May and lower speeds in November and December. The analysis concluded that Lokoja falls within a marginal wind zone and classified as Class 1 according to NREL scale, making it suitable only for specialized turbines designed for low wind regimes. Through modelling of the wind profile using Weibull distribution parameters (shape parameter (k) of 5.65 and a scale parameter (c) of 2.76 m/s), the study quantified the energy generation potential across different months. The simulation results confirmed that approximately 70% of the annual energy production occurs during the dry season, highlighting a significant generation gap during the rainy season. This finding underscored the need for either energy storage solutions or hybrid systems to ensure consistent power supply throughout the year. The combined technical and economic evaluation shows that the Enercon E-115/3.000 demonstrates strong performance, with relatively high annual energy output (3,267,691 kWh/year), the highest capacity factor among the models studied, and the lowest cost per kilowatt-hour ($0.085/kWh), suggesting good adaptability to Lokoja's low wind speeds. The Enercon E-175 EP5 offers the highest energy output but at a significantly higher cost, making it less economically efficient. Smaller turbines such as the Xzeres 442SR and Eocycle EO25 showed favorable capacity factors but limited total energy generation, while models like the Aircon 10S and Bergey Excel 10 performed poorly both technically and economically. Mid-sized turbines like the Polaris P62-1000 and Envision EN- 82/1500 showed balanced performance and cost, indicating potential for medium-scale or rural applications. The Enercon E-115/3.000 offers the best all-round performance under Lokoja's wind conditions, balancing capacity factor, energy yield, and affordability. Turbines such as the Enercon E-175 EP5 and Polaris P62-1000 are viable alternatives depending on project scale and budget. The selection was guided by matching turbine characteristics with local wind behavior, capacity factor, and cost per kWh to ensure feasibility and sustainability. A key limitation of this study is the use of 10 m data without extrapolation to hub heights, and the reliance on a single statistical method for wind characterization. Future work should incorporate hub-height measurements, explore other distribution models, and include detailed feasibility studies for hybrid wind-solar-storage systems tailored to Lokoja's specific energy demand profiles.

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