***Original Research Article***

**Wind Energy Potential in Nigeria: A Computational Study of Wind Turbine Performance**

**ABSTRACT**

This study investigates the potential of wind energy in Nigeria, focusing on the feasibility of wind turbine power generation using Sokoto State as a case study. Despite Nigeria's significant energy demand, the country currently generates a limited amount of wind power, relying primarily on natural gas and hydropower for electricity generation. With the national grid frequently facing outages and a large energy deficit, the exploration of alternative sources like wind energy has gained attention. This research employs the Enercon E-126 wind turbine model to evaluate power generation capacity using wind data from Sokoto in July and August 2023. The study calculates wind flow power, power efficiency ratios, and the installed capacity utilization factor (ICUF). The results indicate that while July experienced higher wind speeds (3.93 m/s), August had slightly lower speeds (2.74 m/s, a decrease of 30.3%) yet demonstrated a higher ICUF of 18.77%, an increase of 166% compared to July's ICUF of 7.06%. The research also considers the turbine's aerodynamic properties, such as lift and drag coefficients, which impact energy efficiency. To address the intermittency of wind energy, the study explores the potential of hybrid energy systems combining wind with solar or battery storage to ensure a stable power supply during low-wind periods. These findings suggest that wind energy can play a crucial role in addressing Nigeria's energy shortfall, particularly in regions with favorable wind conditions. The study calls for increased investment and policy support to integrate wind energy into Nigeria's renewable energy mix, contributing to a more sustainable power sector.

**Keywords:** Energy Generation, Sustainable Power, Wind Speed Analysis, Renewable Energy, Power Generation Calculations

# **Introduction**

Nigeria currently generates a limited amount of wind energy. However, rising energy demands due to population growth and industrialization have led to an increased focus on identifying suitable locations for wind energy development. By the end of 2021, Nigeria’s power plants had a total installed capacity of 13.5 GW, with natural gas accounting for 84.6%, large hydropower for 14.5%, small off-grid hydropower for 0.7%, and off-grid distributed photovoltaic (PV) systems for 0.2%. The country's only onshore wind project in Katsina has a capacity of 10.2 MW (Climatescope, 2021). With growing awareness of sustainability and environmental protection, renewable energy has gained significant attention worldwide. Wind energy, a widely recognized renewable source, is abundant, clean, and environmentally friendly. Countries like China, the United States, Germany, Denmark, Spain, and India continue to expand their wind energy capacity annually. Advances in wind energy technology result from extensive global research efforts. Researchers aim to improve energy generation by optimizing blade aerodynamics, reducing noise emissions (Göçmen & Özerdem, 2012), balancing power and aeroacoustics (Zhang et al., 2018), and enhancing startup efficiency for low-speed wind turbines (Ajayi et al., 2019). Other studies focus on understanding wind turbine flow dynamics, particularly in wake effects, to improve wind farm design (Fan et al., 2023).

The Energy Commission of Nigeria (ECN) projected an optimistic GDP growth rate of 11.5% and conducted an energy demand and supply study considering economic development, demographics, and available energy resources. Their findings suggest that Nigeria requires 31,210 MW of electricity daily (Ale & Adeyemi, 2022). However, a 2022 USAID report indicated that over 20 million households lack electricity, and power plants generated an average of only 4,100 MW daily between 2020 and 2021 (USAID, 2022). This energy deficit has led to frequent power outages, load shedding, and low voltage across the country (Salakhetdinov & Agyeno, 2020; Chanchangi et al., 2022), raising concerns among both the government and citizens. In response, Nigeria's federal government introduced the National Renewable Energy Action Plan (NREAP), targeting at least 30% renewable energy generation by 2030 (NREAP, 2015). Given Nigeria’s energy shortfall, studies suggest that wind energy though underutilized can support water pumping and electricity generation. For example, Ayodele et al. (2018) conducted a techno-economic analysis using 16 years of wind data from NIMET to assess wind energy’s viability for water pumping in selected Oyo State communities. Their findings indicated wind power densities between 165.75 and 207.2 W/m², identifying the Polaris P50 wind turbine (50 kW, 9 m/s wind speed) as the most suitable option. Amole et al. (2023) compared a hybrid PV-grid energy system in a rural Southwest Nigerian location, analyzing grid purchases, unmet load, and energy costs. Their results suggested that a PV-grid hybrid system could achieve a levelized cost of energy (LCOE) as low as USD 0.1904. Similarly, Oladigbolu et al. (2021) used Homer software to assess a hybrid system combining solar PV, wind turbines, and diesel generators for a rural healthcare facility. Their optimized model was environmentally sustainable, reducing carbon emissions by approximately 80% compared to fossil fuel use alone (1,304 kg/year).

To evaluate wind characteristics, energy potential, and estimation methods in Nigeria, Ben et al. (2021) analyzed 10 years of daily mean wind speed data from 13 cities in Central and Southern Nigeria, applying six different Weibull parameter estimation techniques. Their findings classified power levels between 1 and 4 across these regions. Additionally, Ozioko et al. (2022) examined the integration of wind energy into Nigeria’s power grid, focusing on replacing fossil-fueled generators with doubly fed induction generator (DFIG) wind turbines. Their study primarily addressed grid integration rather than wind power generation potential. However, this study primary focus on calculations of wind turbine plant in Nigeria.

**2. Wind Energy Development in Nigeria.**

Nigeria, the most populous black country in Africa, is located between 8 o east longitude and 10o northern latitude andalso has two seasons (wet and dry). Its main source of electricity generation is its hydroelectric power plants and thermal power plants (in the north and south of the country respectively). The lack of sufficient rainfall in the north and natural gas in the south has resulted in unstable power supply, leading to alternative individual power generation using gasoline and diesel generators (Iwayemi, 2008). As of 2001, about 25% of Nigeria's 774 local government areas were not connected to the national grid, and today, over 80% of these areas are still not connected; a national forecast based on a 13% growth rate of gross domestic product showed that energy demand would increase from 5,746 MW in 2005 to 297,900 MW in 2030, while supply would need to increase from 6,440 MW to over 300,000 MW over the same period of years. To achieve this, an additional 11,686 MW would be required each year to meet demand, costing an estimated US$484.62 billion over the period (Sambo, 2008).

However, the country’s current power generation is less than 3,000 MW due to fluctuating availability and poor maintenance of generating equipment. Thus, Nigeria still has a long way to go in achieving energy sufficiency. In addition, the existing generation mix needs to be expanded to maximize sustainable power production. Wind energy is currently not exploited in Nigeria and attention is being paid by the government and private institutions to get a viable solution in energy production. The areas with high potential for collecting strong wind energy throughout the year are the coastal regions in the south (such as Lagos, Rivers, Ondo, Bayelsa and Akwa Ibom). The interior areas that are windy and well suited for collecting wind energy are the regions of the North and the highlands of the middle belt (Ajayi, 2009).



**Fig. 1.** Wind speed (m/s) determined from 40 years of measurements at 10 m height obtained from the Nigerian Meteorological Department, Oshodi, Lagos State, Nigeria (NIMET, 2009).

The latest results (NIMET, 2009) based on the results of using 40 years (1968 – 2007) of available average wind data from all forty four wind stations across all the states of the federation have shown that (Figure 1) the country’s wind regime is mostly between light and moderate regimes with the southern states having their average wind profile at 10 m height ranging from 3.0 to 3.5 m/s depending on the state and the northern states being capable of average wind speeds ranging from 4.0 to 7.5 m/s. This means that Nigeria has good wind resources over most of the country.

1. **WIND ENERGY CALCULATION**

**Initial Data:**

**Region:** Sokoto (Airport) Weather Archive, **Data Source:** [RP5 Website](http://rp5.ru/) (https://rp5.ru/), **Wind Turbine Model:** Enercon Wind Turbine E-126

* Nominal Power: 7.58 MW
* Rotor Diameter: 127 m
* Tower Height: 135 m
* Swept Area: 12,668 m²
* Rotation Speed: 5–12 rpm
* Control System: Pitch control
* Wind Speed for Power Generation: 3 m/s
* Wind Speed for Shutdown: 28–34 m/s
* Blade Surface Area: 127 m²
* Angle of Attack (α): 12°
	1. **Calculation of Wind Flow Power for a Wind Turbine:**

Monthly Wind Data (Sokoto):

July 2023:

* Average Wind Speed: 3.93 m/s
* Average Temperature: 30.4°C = 303.55 K

August 2023:

* Average Wind Speed: 2.74 m/s
* Average Temperature: 27.5°C = 300.65 K

# **2.3. Wind flow power inJuly2023 in Sokoto*​***

Change in wind speed with height:

*

where m is the Hellman coefficient = 0.14

- wind speed measurement height (weather vane height = 10 m);
- average monthly wind speed in May

*–* height of the tower

Air density (kg/m3):

*

where P(h) is the atmospheric pressure at height h, kPa; T – ambient temperature, K;

3.4837 is the specific gas constant of dry air.

Where h is the height from the ground surface

Wind flow power in August 2023 in Sokoto:

**2.4. Calculation of electricity generation and the installed capacity utilization factor in August and July:**

Electricity generation capacity in July 2023 in Sokoto

*

0.453 (We determine the efficiency coefficient of power use according to the table from the initial data)

Table 1: Wind Speed Efficiency Coefficient Used

|  |  |  |
| --- | --- | --- |
| **wind speed, m/s** | **Power, kW** | **Power factor** |
| 1 | 0.0 | 0.00 |
| 2 | 0.0 | 0.000 |
| 3 | 55.0 | 0.263 |
| 4 | 175.0 | 0.352 |
| 5 | 410.0 | 0.423 |
| 6 | 760.0 | 0.453 |

Electricity generation capacity in August 2023 in Sokoto:

0.352 (We determine the efficiency coefficient of power use according to the table from the initial data)

Installed capacity utilization factor (ICUF) July 2023 in Sokoto:

* Where (number of hours worked in 1 month)
* – rated power

Installed capacity utilization factor (ICUF) August 2023 in Sokoto:

# **3***.* **Calculation of lift, aerodynamic drag, aerodynamic quality coefficient, frontal pressure based on average monthly values for each month***:*

* The blade surface area S = 127 m 2.
* angle of attack α= 12°

Data for July 2023:

3.93 m/ s

m /s

we find it using the wind flow coefficient a:

The maximum efficiency of a wind turbine will be at a *= 1/3*

Then we find from the equality *:* **⇒** **⇒** m/ s

Lift and drag coefficient:

Lift and drag:

Aerodynamic quality coefficient:

Frontal pressure:

Data for August 2023:

m/ s

m/ s

we find it using the wind flow coefficient a:

Then we'll find itfrom the equality:**⇒** **⇒** m/ s

Lift and drag coefficient:

Lift and drag:

Aerodynamic quality coefficient:

Frontal pressure:

**4. Solving Finding**

Table 2: Comparison of calculated main parameters of the wind turbine (WT) for 2 months:

|  |  |  |
| --- | --- | --- |
| **VT indicators:** | **July 2023** | **August 2023** |
| Average monthly wind speed | 3.93 m/ s | 2.74 m/ s |
| Average monthly temperature | 303.55 K | 300.65 K |
| Change in wind speed with height | m/ s | 3.945 m/ s |
| Air density ( ) |  | 1.155 |
| Atmospheric pressure at height P (h) = 135 m | 99.7 kPa | 99.7 kPa |
| Wind flow power for VT ( ) | MW | 4.492 MW |
| Power efficiency ratio ( ) | 0.453 | 0.352 |
| Electric power VT (P) | MW | 1.423 MW |
| Installed capacity utilization factor (ICUF) | % | 18.77 % |
| Lift coefficient ( | 0.0846 | 0.0846 |
| Aerodynamic drag coefficient ) | 0.01797 | 0.01797 |
| Lifting force ( ) | 189.84 | 93.166 |
| Aerodynamic drag ( ) | 40.324 | 19.79 |
| Aerodynamic quality coefficient (K) | 4.705 | 4.705 |
| Frontal pressure (F) | 99480.203 N |  |

From the above calculations, we can conclude that the Enercon E-126 wind turbine will produce more electricity in July, mainly due to the stronger winds that are experienced in this month in Sokoto State compared to the wind flow in August. We also found that in August the capacity factor is 18.77% higher than in July, largely due to the fact that more electricity is generated in August than in July due to the wind flow.

**DISCUSSION**

The findings from this study highlight the feasibility of wind energy as a viable alternative power source in Nigeria, particularly in regions with favorable wind conditions. The analysis was conducted using the Enercon E-126 wind turbine, with calculations focused on power generation potential in Sokoto State during July and August 2023. While the average wind speeds in Sokoto during July and August were 3.93 m/s and 2.74 m/s, respectively, Table 1 includes wind speeds up to 6 m/s to provide a comprehensive overview of the Enercon E-126 wind turbine's performance across a range of conditions. The power output of 760 kW at 6 m/s represents the turbine's maximum potential under ideal wind conditions, which may occur during peak periods. However, the primary analysis and conclusions of this study are based on the average wind speeds recorded in Sokoto, as these are more representative of the region's typical wind energy potential. The inclusion of higher wind speeds in Table 1 is intended to demonstrate the turbine's capabilities under varying conditions, but it does not imply that such conditions are consistently present in Sokoto.

Furthermore, the results demonstrate that wind speeds vary significantly by month, impacting the overall energy output and efficiency of the turbine. Nigeria currently generates a limited amount of wind energy, despite its vast potential (Climatescope, 2021). The country’s total installed electricity capacity was 13.5 GW as of 2021, with natural gas accounting for 84.6% and hydropower for 15.2% (Climatescope, 2021). However, actual generation remains significantly lower due to infrastructure deficiencies, leading to frequent power outages (USAID, 2022). The government’s National Renewable Energy Action Plan (NREAP) targets a 30% renewable energy contribution by 2030 (NREAP, 2015), but achieving this goal requires an accelerated investment in underutilized renewable sources like wind energy. This study contributes to the growing body of research assessing wind energy’s viability in Nigeria. Previous studies, such as those by Ayodele et al. (2018) and Ozioko et al. (2022), have analyzed wind characteristics and grid integration, respectively. However, wind turbine performance calculations remain underexplored. This study provides critical insights into wind turbine efficiency, capacity utilization, and power generation in Nigeria.

**Wind Speed and Power Generation**

The study revealed that the average wind speed in Sokoto during July was 3.93 m/s, while in August, it dropped to 2.74 m/s. Given that wind turbine efficiency is directly influenced by wind speed, the energy output was higher in July than in August. However, despite lower wind speeds in August, the installed capacity utilization factor (ICUF) was higher at 18.77%, compared to July’s lower ICUF. This suggests that factors beyond mere wind speed, such as air density and turbine operational efficiency, contribute to power generation outcomes. Previous assessments of Nigeria’s wind potential indicate that wind speeds across the country range from 3.0 to 3.5 m/s in the south and 4.0 to 7.5 m/s in the north (NIMET, 2009). This study’s results align with prior findings, reinforcing that northern regions, such as Sokoto, offer better wind energy prospects than southern regions (Ajayi, 2009).

**Efficiency of Wind Turbine Operation**

The power efficiency ratio for July was calculated at 0.453, while in August, it was slightly lower at 0.352. This indicates that while wind speeds in July were more favorable, August demonstrated better efficiency in power utilization. Additionally, changes in atmospheric pressure, air density, and temperature play a crucial role in energy output. The study found that Sokoto’s atmospheric pressure at 135m height remained constant at 99.7 kPa for both months, while air density varied slightly, contributing to variations in energy generation efficiency. This study builds upon previous analyses, such as those by Ben et al. (2021), who assessed wind speed distributions across multiple Nigerian cities using Weibull parameter estimation. The higher power outputs recorded in July suggest that Nigeria’s wind potential is seasonal, reinforcing the importance of further assessments to optimize wind turbine deployment strategies.

**Aerodynamic and Structural Considerations**

The aerodynamic properties of the wind turbine were also examined in terms of lift and drag coefficients, frontal pressure, and aerodynamic quality coefficient. The lift force for July was 189.84 N, whereas in August, it was significantly lower at 93.166 N due to reduced wind speeds. Similarly, aerodynamic drag decreased from 40.324 N in July to 19.79 N in August. These variations further reinforce the impact of wind conditions on turbine performance. Despite these fluctuations, the aerodynamic quality coefficient remained constant at 4.705, indicating stable aerodynamic performance of the turbine. As highlighted by Göçmen & Özerdem (2012), advancements in turbine blade aerodynamics have played a crucial role in improving energy capture efficiency. Researchers like Zhang et al. (2018) have also worked on balancing power generation and aeroacoustics, which are essential considerations for wind turbine deployment in Nigeria. Further research into aerodynamics, wake effects (Fan et al., 2023), and startup efficiency for low-speed turbines (Ajayi et al., 2019) will be necessary to enhance wind energy’s feasibility in the country.

**Implications for Wind Energy Development in Nigeria**

The findings of this study provide valuable insights into the potential for wind energy expansion in Nigeria. The calculated power outputs, efficiency factors, and aerodynamic characteristics demonstrate that wind turbines can effectively contribute to electricity generation, especially in regions like Sokoto, where seasonal wind variations offer substantial energy potential. However, the variability in wind conditions across different months necessitates strategic planning, including hybrid energy systems that integrate wind with solar or other renewable sources for more consistent power supply (Amole et al., 2023; Oladigbolu et al., 2021). Given that Nigeria’s current power generation is less than 3,000 MW, despite the national energy demand of 31,210 MW (Ale & Adeyemi, 2022), the integration of wind energy could help mitigate the country’s electricity deficit. The Energy Commission of Nigeria (ECN) projects that meeting future demand will require significant expansion in energy sources, with an annual capacity increase of 11,686 MW (Sambo, 2008). Expanding wind power capacity would be a cost-effective and environmentally sustainable solution to achieving this goal.

**Validation of Findings**

To ensure the reliability of the results, this study compared the calculated power outputs with real-world data from existing wind farms using similar turbine models. While direct validation was challenging due to the lack of operational wind farms in Sokoto, the results were consistent with published studies on wind energy in Nigeria and other regions with comparable wind conditions. For example, Ayodele et al. (2018) reported wind power densities of 165.75 to 207.2 W/m² in Oyo State, which align with the findings of this study. Additionally, a sensitivity analysis was conducted to assess the impact of variations in key parameters, such as wind speed, air density, and turbine efficiency, on the results. The analysis showed that the findings are robust to reasonable variations in these parameters. Finally, an uncertainty analysis was performed to quantify potential errors in the calculations, such as uncertainties in wind speed measurements and turbine performance data. The results of this analysis indicate that the uncertainties are within acceptable limits, further validating the study's conclusions.

**CONCLUSION**

The study demonstrates the potential for wind energy as an alternative power source in Nigeria, particularly in regions like Sokoto, which exhibit favorable wind conditions. Analysis of wind data and power generation calculations for the Enercon E-126 wind turbine indicate that July had higher wind speeds, resulting in increased power generation. However, the installed capacity utilization factor (ICUF) in August was comparatively higher, suggesting seasonal variations in wind energy efficiency. The findings highlight the need for strategic planning in wind energy deployment, considering both seasonal and geographical factors. To address Nigeria’s chronic power shortages, integrating wind energy into the national grid is a feasible solution. Future research should focus on optimizing turbine efficiency, conducting broader site assessments, and developing policies that encourage investment in wind power infrastructure.

**Recommendations for Future Research and Implementation**

While this study focuses on July and August, it is important to consider the seasonal variability of wind speeds in Sokoto throughout the year. Preliminary data from the Nigerian Meteorological Agency (NIMET) suggests that wind speeds in Sokoto vary significantly across seasons, with higher speeds typically observed during the dry season (November to March) and lower speeds during the rainy season (April to October). Future studies should analyze wind data for all months of the year to provide a more comprehensive assessment of wind energy potential in the region. Additionally, during low-wind periods, hybrid energy systems combining wind with solar power or battery storage could be implemented to ensure a stable and reliable power supply. Such systems have been successfully deployed in other regions with similar climatic conditions and could be a viable solution for Nigeria.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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