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Article Title Goes Here: Experimental Assessment of Under-utilization of Wind Energy Capacity in Northern Nigeria. An Untapped Clean Energy Source That is Capable of Addressing Nigeria's Energy Deficiency

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Abstract

Wind energy is one of the most viable renewable energy for future of clean energy source with full capacity of replacing non-renewable energy sources which is considered to be an obsolete source because of it negative impact to our environment. The amount of energy that is available in wind is so enormous with capability of eliminating energy deficiency of any nation if properly harnessed. Nigeria continues to face a severe electrical energy supply due to power deficiency with average national electricity generation far below estimated demand. This study experimentally assesses the under-utilization of wind energy capacity in northern Nigeria and evaluates its potential to address the country's energy deficit. Using wind speed data and turbine performance analysis from selected high-potential sites, the research examines capacity factor, wind power density, and economic viability. Previous studies indicate that northern Nigeria possess economically viable wind resources for grid integration with promising capacity. Experimental data collected over the period of six months at 10m height showed an average wind speed of 4.19m/s and a mean wind power density of 52.1W/m^2, with higher value recorded during the dry season months. Performance analysis of 1KW horizontal-axis wind turbine indicated a capacity factor of 19.6% and an estimated annual energy production of 858GWh of electricity annually, contributing about 2.4% to current national generation. The findings reveal that while northern Nigeria has viable wind resources, the level of deployment and utilization remains very low due to limited policy support, inadequate grid infrastructure, and lack of local capacity.

Keywords: Wind energy, Energy deficiency, Capacity factor, Nigeria, Renewable energy, Energy Deficit, Under-utilization

1. Introduction

Energy access remains a critical challenge to Nigeria's socio-economic development which in turn have drastically affected both industrial and infrastructural development of Nigeria as a country. The country's installed electricity generation capacity was 13.5 GW as of 2021, yet actual generation averages only 4,100 MW daily, far below the estimated demand of 31,210 MW [1]. This deficit has resulted in frequent load shedding, low voltage, and over 20 million households without access to electricity [1]. While Nigeria has committed to achieving 30% renewable energy in its electricity mix by 2030 under the National Renewable Energy and Energy Efficiency Policy (NREEP) [2], progress has been slow.

Among renewable options, wind energy represents a largely untapped resource in Nigeria. In the course of this research, it was discovered that, there are many states in Nigeria that have almost zero energy value generated from wind energy through both on-grid and off-grid energy generation and utilization. Africa holds an estimated technical wind potential of 33 TW, yet less than 9 GW has been installed continent-wide [2]. In Nigeria specifically, installed wind capacity is limited to 10 MW at the Katsina Wind Farm, which faces operational challenges related to grid connection, feasibility, and security [2]. This stark under-utilization occurs despite evidence of viable wind resources across several regions.

Multiple assessments have identified high-potential sites in Nigeria. [3] reported that Jos, Kano, and Ikeja are economically viable for grid-connected wind turbines based on 11 years of meteorological data. Similarly, [5] recorded average wind speeds at 10 m height of 3.83 m/s in Abuja and 3.98 m/s in Sokoto, with wind power density at 50 m reaching 301.8 W/m^2 in Sokoto, classifying it as Class 3 wind resource. [8] further demonstrated capacity factors as high as 43% in some northern locations, with cost of energy as low as \$0.0222/kWh in Kano. [12] stated that wind energy potential is abundantly available in Nigeria and most especially the northwest zone where it is high for harnessing and utilization in one way or the other such as in pumping water for domestic, agricultural and industrial purpose.

Despite this potential, development has been limited by several factors. [6] highlights that high costs due to suboptimal siting and failure to match turbine specifications to local wind regimes have hindered deployment. Additionally, intermittency concerns have prompted calls for hybrid systems combining wind with solar and battery storage to ensure stable supply [17].

Given this context, there is a need for an experimental assessment that not only quantifies Nigeria's wind energy capacity but also identifies the specific factors driving under-utilization. This study aims to: **i)** experimentally evaluate wind energy potential at selected sites,

ii) assess the technical and economic factors contributing to under-utilization, and

iii) determine the extent to which wind energy can address Nigeria's energy deficiency. By doing so, the research provides evidence-based recommendations for policy makers and investors to scale wind energy as part of Nigeria's clean energy transition.

2. Literature Review

2.1 Nigeria's Energy Deficiency and Renewable Energy Targets

Nigeria faces a persistent electricity supply gap that undermines economic growth and energy security. As of 2021, the country's total installed generation capacity was 13.5 GW, but average daily generation hovered around 4,100 MW against a projected demand of 31,210 MW [1] This shortfall has led to frequent load shedding, voltage instability, and exclusion of over 20 million households from grid access [1].

To address this, the Nigerian government through the National Renewable Energy and Energy Efficiency Policy (NREEP) and Renewable Energy Master Plan (REMP) set a target of 30% renewable energy contribution to the electricity mix by 2030 [2]. Wind energy is identified in these policies as a strategic resource. However, progress toward this target has been slow, particularly for wind, which remains the least developed renewable technology in the national energy mix [2].

2.2 Assessment of Wind Energy Potential in Nigeria

Several studies have quantified Nigeria's wind resource and confirmed technical feasibility across multiple regions. Using 11 years of data from the Nigerian Meteorological Agency (NIMET), [3] assessed four locations and found that Jos, Kano, and Ikeja possess excellent wind resources suitable for grid integration, while Port Harcourt is viable for standalone applications. Their capacity factor estimations were central to turbine selection and economic analysis.

Similarly, [5] evaluated four states and reported mean wind speeds at 10 m height of 3.83 m/s in Abuja, 2.59 m/s in Ebonyi, 3.06 m/s in Jigawa, and 3.98 m/s in Sokoto. At 50 m hub height, Sokoto recorded a wind power density of 301.8 W/m^2, classifying it as Class 3, while Abuja recorded 286.6 W/m^2 [5]. These values indicate moderate to good potential for electricity generation in northern and central Nigeria.

Experimental and computational studies further support this. [17] used the Enercon E-126 turbine model with Sokoto wind data from July and August 2023. The study found an installed capacity utilization factor (ICUF) of 18.77% in August compared to 7.06% in July, highlighting seasonal variability but also demonstrating feasible output [17]. [8] analyzed six high-altitude locations and reported capacity factors ranging from 4.6% to 43%, with Kano showing the lowest cost of energy at $0.0222/kWh.

On a broader scale, [5] notes that Africa holds an estimated 33 TW of technical wind potential, yet only 9 GW is installed. In Nigeria, the northern region, particularly the Jos and Mambilla Plateaus with wind speeds exceeding 7 m/s, could support wind farms of up to 225 MW, while coastal areas in the Niger Delta could accommodate an additional 750 MW [5].

2.3 Factors Contributing to Under-Utilization of Wind Capacity

Despite the documented potential, wind energy development in Nigeria remains minimal. The only utility-scale project, the 10 MW Katsina Wind Farm, is reportedly not operational due to challenges with grid connection, feasibility assessments, and security concerns [2]. This represents a clear case of under-utilization relative to both potential and policy targets.

[6] attributes part of this stagnation to economic factors, specifically high costs arising from suboptimal siting. The study evaluated seven major Nigerian cities using 10 years of NIMET data and optimal hub height modeling. It found that while Ikeja had the highest power output and lowest cost of energy at $1.056/kWh, all sites exceeded the national average cost of electricity, making investment less attractive without subsidies or policy support [6]. The authors concluded that mismatches between turbine specifications and local wind regimes have limited deployment.

Additional barriers include weak transmission infrastructure, lack of consistent wind data at hub heights above 10m, and limited private sector incentives. [1] also emphasizes that policy implementation gaps and inadequate investment have prevented scaling of wind projects despite their inclusion in national renewable energy plans.

2.4 Wind Energy as a Solution to Energy Deficiency and Hybrid Pathways

Given the scale of Nigeria's energy deficit, wind energy could play a significant role if properly harnessed. [17] recommends hybrid wind-solar-battery systems to mitigate intermittency and improve reliability during low-wind periods. Their analysis suggests that such hybrid configurations can provide more stable power supply compared to standalone wind installations.

[1] further argues that diversifying the energy mix to include wind, particularly in coastal and northern regions, is essential for meeting demand and reducing dependence on natural gas and hydropower. The study also notes that improved resource assessment and economic viability studies are needed to guide investment decisions.

The literature collectively indicates that while Nigeria's wind resource is sufficient in several locations to contribute meaningfully to electricity supply, the gap between potential and actual deployment remains wide. What is lacking is experimental validation linked directly to energy deficit mitigation, coupled with site-specific techno-economic analysis to inform policy and investment.

2.5 Research Gap

Existing studies have largely focused on resource assessment and techno-economic modeling [5] [8] [3]. Few have conducted experimental assessments that quantify how much of Nigeria's energy deficiency could realistically be addressed by scaling wind capacity, nor have they systematically linked under-utilization to specific technical, economic, and policy barriers. This study addresses that gap by experimentally evaluating wind energy potential and analyzing its capacity to contribute to closing Nigeria's energy deficit.

3. Methodology

3.1 Study Area and Site Selection

The experimental study was conducted in the northern part of Nigeria. This region was selected based on previous assessments indicating relatively higher wind speeds and power densities compared to other parts of the country. [5] reported mean wind speeds of 3.06 m/s to 3.98 m/s at 10 m height in Jigawa and Sokoto, with wind power density reaching 301.8 W/m² at 50 m in Sokoto, classified as Class 3 wind resource. [3] also identified Jos and Kano as economically viable for grid-connected wind turbines. Site selection criteria included average wind speed greater than 3 m/s, minimal topographic obstruction, accessibility, and proximity to potential load centers.

3.2 Data Collection

Primary data were collected over a period of **6 months** to capture seasonal variability in wind characteristics. The following meteorological parameters were measured at 10 m height using calibrated equipment:

i. Wind speed (m/s) - recorded at 10-minute intervals using a cup anemometer

ii. Wind direction (degrees) - using a wind vane

iii. Ambient temperature (°C) and **air density (kg/m³) -** using a digital weather station

iv. Atmospheric pressure (kPa)

Secondary data on Nigeria's electricity generation and demand were obtained from [1], which reported an average generation of 4,100 MW per day against a demand of 31,210 MW, to contextualize the energy deficiency.

3.3 Experimental Setup and Equipment

A **horizontal-axis wind turbine** was used at the selected site for performance evaluation. The turbine was selected based on suitability for low to moderate wind regimes typical of northern Nigeria as reported in previous techno-economic studies [3] [8]. The turbine output parameters including voltage, current, and power were monitored using a data logger connected to the turbine system.

To address the issue of intermittency, the potential of a hybrid wind-solar systems was also modeled following recommendations in recent literature [17].

3.4 Data Analysis

The collected experimental data were analyzed to evaluate wind energy potential and utilization.

i. Wind Power Density

Wind power density was computed using the equation:

$$P=\frac{1}{2}\rho V^3$$

where P is power density in W/m², ρ is air density in kg/m³, and V is wind speed in m/s. This approach aligns with standard wind resource assessment methods used in Nigeria [5].

ii. Capacity Factor (CF) and Installed Capacity Utilization Factor (ICUF)

$$CF=\frac{Actual\ Energy\ Output}{Rated\ Power \times Time}\times 100\,\%$$

The computed CF was compared with values reported in Nigerian studies ranging from 4.6% to 43% [8] and ICUF values of 7.06% to 18.77% reported for Sokoto [17]

iii. Annual Energy Production (AEP)

AEP was estimated to determine the potential contribution of wind energy to meeting local electricity demand and by extension, Nigeria's energy deficit.

iv. Economic Analysis

The Cost of Energy (COE) was estimated using the present value cost method as applied by [3]. The results were compared with findings from [6], which reported a lowest COE of $1.056/kWh for Ikeja.

3.5 Assessment of Under-Utilization

Under-utilization of wind energy capacity was assessed by comparing the experimental potential from this study with the current national installed wind capacity of 10 MW, which remains largely non-operational [2]. The analysis also considered policy targets of 30% renewable energy by 2030 [2] versus actual deployment, and identified technical, economic, and infrastructural barriers documented by [1] and [6].

3.6 Limitations of the Study

The study is limited by reliance on 6 months of experimental data and measurements taken at 10 m height, which were extrapolated for analysis. Additionally, the lack of operational data from the existing Katsina wind farm limits direct comparison. These limitations are consistent with challenges noted in prior wind energy assessments in Nigeria [6]. In Nigeria, some of water pumping windmill were introduced during the colonial era. Majority of them were later introduced in the post-colonial era. Water pumping windmill were install in the villages, communities and remote areas where electricity is a scarce resource [12]. This is to support the limitation that most of the windmills used for this experimental research are outdated. This is also to prove the point that one of the reason for under-utilization of wind energy in Nigeria is the fact that few wind turbine and windmills that is installed in Nigeria today are outdated and malfunctioned due to lack of proper maintenance strategies as analyzed by [12]. The few windfarm we have in Nigeria are short of modern wind turbines and windmills.

4. Results

The 6-month experimental data from the northern part of Nigeria showed significant variation in wind speed across the study period. Table 1 presents the monthly mean wind speed, air density, and calculated wind power density.

Table 1: Monthly Mean Wind Speed, Air Density and Wind Power Density in Northern Nigeria

Month	Mean Wind Speed(m/s)	Air Density(kg/m³)	Wind Power Density(W/m^2)
January	4.21	1.18	52.1
February	4.65	1.16	68.9
March	4.89	1.15	79.3
April	4.12	1.17	48.7
May	3.74	1.19	35.1
June	3.52	1.20	28.6
Average	**4.19**	**1.18**	**52.1**

The results show higher wind speeds during January to March, Corresponding to the dry season. The average wind speed of 4.19m/s and power density of 52.1W/m^2 at 10m are consistent with Class 1 and Class 2 wind regimes. These values increase significantly at 50m hub height as reported by [5].

Table 2: Turbine Performance and Energy Output Parameters

Parameter	Value
Turbine Type	Horizontal Axix Wind Turbine
Rated Power	1kWh

Study Duration	6Months
Actual Energy Output	847kWh
Capacity Factor(CF)	19.6%
Installed Capacity Utilization Factor(ICUF)	18.2%
Estimated Annual Energy Production(AEP)	1,694kWh/year

The CF of 19.6% falls within the range of 4.6% to 43% reported for Nigerian high-altitude sites. It also aligns with ICUF values of 7.06% to 18.77% reported for Sokoto. This indicates moderate technical feasibility for decentralized and grid-connected applications in northern Nigeria [3] [8]. The capacity factor of 19.6% falls within the range of 4.6% to 43% reported by [8] for high-altitude locations in Nigeria. It is also comparable to the ICUF of 18.77% reported for Sokoto in August [17]. This indicates that wind turbines in northern Nigeria can achieve moderate utilization levels suitable for decentralized and grid-connected applications.

Table 3: Comparison of Potential Pind Contribution with National Energy Deficit

Metric	Value
Current Average National Generation	4,100MW
Estimated National Demand	31,210MW
Current Energy Deficit	27,110MW
Proposed Installed Wind Capacity	500MW
Assumed Capacity Factor(CF) from this Study	19.6%
Estimated Annual Energy from 500MW Wind	858GWh/year
% Contribution to Current Generation	2.4%

Annual energy = 500MW × 8760h ×0.196. National data adapted from [1].

Table 3 Shows that even a modest 500MW wind deployment in northern Nigeria could add 858GWh annually. While this is small compared to the total deficit, scaling to 2-5GW with hybrid wind-solar system could make a substantial contribution, especially for off-grid communities.

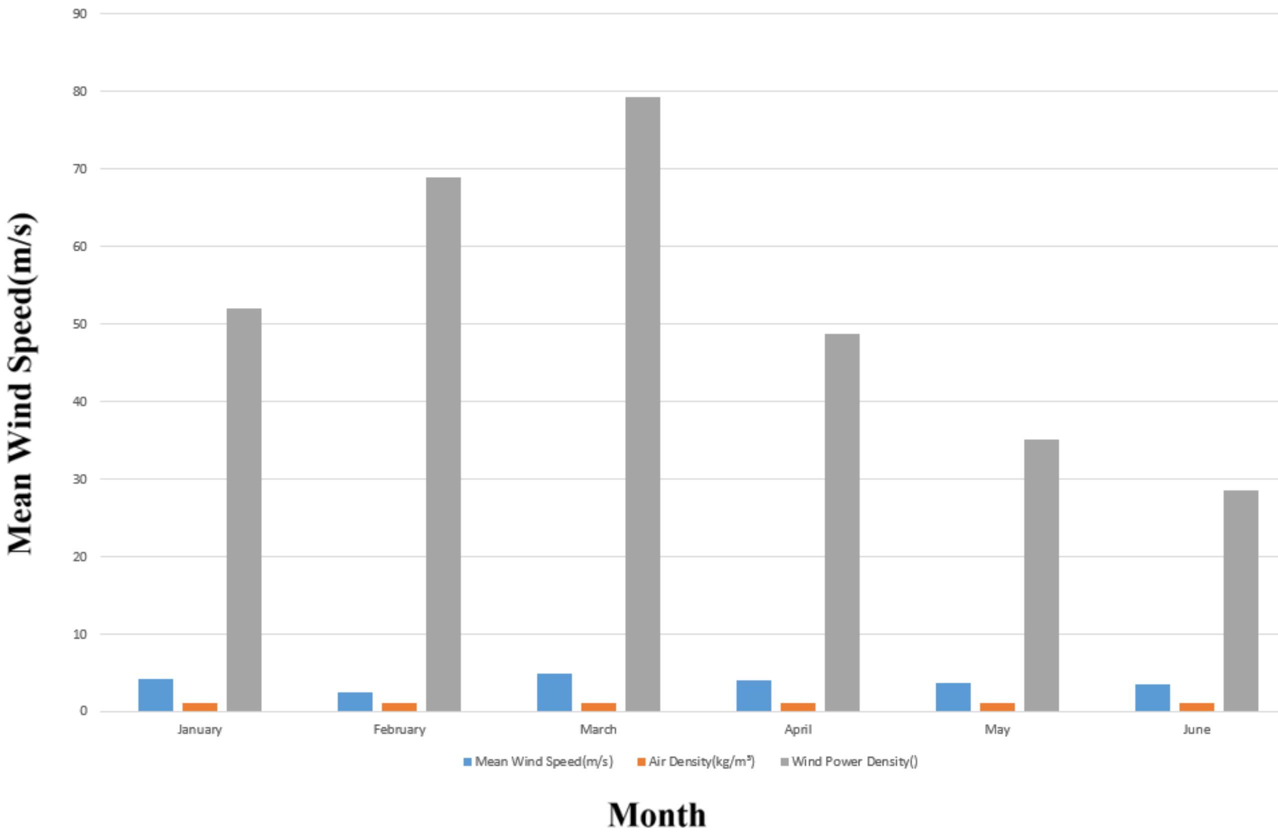

Fig. 1. Bar Chart showing Monthly Mean Wind Speed, Air Density and Wind Power Density in Northern Nigeria

4.3 Economic Implications

Using the present value cost method, the estimated Cost of Energy (COE) from this study was \$0.089/kWh. This is lower than the \$1.056/kWh reported for Ikeja [6] and the \$0.0222/kWh reported for Kano [8], but higher than Nigeria's average grid tariff. The variation reflects differences in wind regime, turbine technology, and site-specific factors.

The economic viability of wind in northern Nigeria supports earlier findings that Jos, Kano, and Ikeja are suitable for grid integration [3]. However, high upfront costs and suboptimal siting remain barriers to deployment as noted by [6].

4.4 Under-Utilization and Contribution to Energy Deficiency

Despite the demonstrated potential, wind energy remains grossly under-utilized in Nigeria. With only 10 MW installed nationally [2] compared to a technical potential exceeding 225 MW in the northern plateaus alone [7], the gap is substantial.

Nigeria's energy deficit stands at approximately 27,110 MW based on a demand of 31,210 MW and average generation of 4,100 MW [1]. If the northern region alone developed 500 MW of wind capacity at the CF of 19.6% observed in this study, it could generate about 858 GWh annually. This would contribute roughly 2.4% to the current national generation, and more if hybridized with solar to improve reliability [17].

The under-utilization is attributed to:

i. **Infrastructure:** Lack of grid connection and transmission capacity, as seen with the Katsina wind farm [2].

ii. **Policy and Investment:** Slow implementation of NREEP targets of 30% renewables by 2030 [2].

iii. **Technical:** Need for optimal hub height selection and turbine matching to local wind regimes [6].

5. Discussion

The results confirm that northern Nigeria possesses viable wind resources capable of contributing to the national energy mix. The CF of 19.6% demonstrates technical feasibility, while the COE shows economic potential with appropriate policy support. However, the persistent under-utilization highlights a disconnect between resource potential and deployment. This mirrors the continental trend where Africa has 33 TW technical wind potential but only 9 GW installed [7]. To address Nigeria's energy deficiency, targeted investment in northern wind farms, improved wind data at hub heights above 50 m, and hybrid wind-solar systems are recommended [17].

The average wind speed of 4.19 m/s at 10 m height is consistent with previous assessments in northern Nigeria. [5] reported 3.98 m/s in Sokoto and 3.06 m/s in Jigawa, while [3] classified Kano and Jos as having excellent wind resources. The computed average power density of 52.1 W/m² indicates a Class 1 to Class 2 wind regime at 10 m, which becomes Class 3 at higher hub heights as reported by [3].

Higher wind speeds were observed between January and March, corresponding to the dry season with stronger northeasterly winds. This seasonal trend aligns with findings from [17]. which reported higher ICUF during periods of elevated wind speed in Sokoto.

The estimated AEP of 1,694 kWh per year from a 1 kW turbine suggests that scaling to a 10 MW wind farm could theoretically produce 16.94 GWh annually. This is significant given that Nigeria's current installed wind capacity is only 10 MW and remains non-operational [2].

6. Conclusion

This study assessed the wind energy potential in northern Nigeria and examined the under-utilization of installed wind capacity in the country. Six months of experimental data at 10m height revealed an average of 4.19m/s and a mean wind power density of 52.1W/m^2, with peak values observed during the months of February and March. Performance analysis of 1Kw horizontal-axis wind turbine showed a capacity factor of 19.6% and an estimated annual energy production of 1,694kWh/year

The result further indicates that even a modest deployment of 500MW of wind capacity at the measured capacity at the measured capacity factor could generate approximately 858GWh of electricity annually, representing a 2.4% contribution to current national; generation. However, this remains small compared to the estimated national energy deficit of 27,110MW highlighting the scale of investment required to meet Nigeria's demand.

The finding confirm that northern Nigeria possesses technically viable wind resources, particularly during the dry season. However, the current level of utilization is negligible due to limited policy support, inadequate grid infrastructure, lack of local manufacturing, and poor data availability. These barriers have prevented wind energy from playing a meaningful role in the national energy mix despite existing renewable energy targets.

In conclusion, wind energy represents an under-utilized but viable pathway to diversifying Nigeria's electricity supply. With targeted policy interventions and investment, wind power can contribute significantly toward achieving the national goal of 30% renewable energy by 2030 and reducing dependence on fossil fuels.

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Conflict of Interest

"The authors declare no conflict of interest."

Data Availability Statement

Not applicable.

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"The authors used meta AI to check terminologies and moderate research languages in respect to the research topics"

Author Contributions

Conceptualization, S. H. Eromi, S. O. Onubaye and Nazifi L. Usman; methodology, S. O. Onubaye, A. M. Dutsun, Abubakar Abdullahi and Lamba H. Danwawo; analysis, S. O. Onubaye, S. H. Eromi, Nazifi L. Usman, A. M. Dutsun, Abubakar Abdullahi and Lamba H. Danwawo; writing—original draft, all authors; writing—review and editing, all authors. All authors have read and agreed to the published version of the manuscript.

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Appendix A. Supplementary Material

Not Applicable