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Comparative Analysis of Wind Resource Potential and Turbulence Intensity for Small-Scale Power Generation in Coastal Nigerian University Communities

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Abstract
This paper evaluates wind-resource potential, monthly wind-speed variability, and small-scale power-generation suitability at the University of Uyo Main Campus in coastal Akwa Ibom State, Nigeria. Ten years of wind-speed records from the Nigerian Meteorological Agency for 2011-2020 were combined with site-level field measurements collected in July 2021 at five campus locations. The NIMET records were used for climatological assessment, annual wind-speed classification, Weibull distribution fitting, and coefficient-of-variation analysis. The campus measurements were used to compare micro-siting effects across locations with different terrain exposure and obstruction levels. A rotor-level CFD interpretation was also used to relate the reported torque result to possible mechanical power. The decadal annual mean wind speed was 2.26 m/s, while the mean of the monthly climatological averages was 2.41 m/s. Site 2 recorded the highest mean speed of 3.1 m/s and wind power density of 20.13 W/m², while Site 5 recorded only 1.6 m/s and 2.60 W/m². The coefficient of variation of the monthly mean wind speed was about 0.18. This value is interpreted as a monthly wind-resource variability indicator, not as measured turbulence intensity, because the available record does not contain short-interval wind-speed fluctuations. The CFD torque value of about 3.2 N·m corresponds to limited mechanical power and must be interpreted together with rotor speed, drivetrain efficiency, generator efficiency, storage losses, and actual load demand. The results do not support utility-scale wind generation at the study location. They indicate, however, that carefully sited low-cut-in-speed micro-wind systems may support limited loads such as LED lighting, small electronics charging, sensor nodes, and hybrid wind-solar battery systems.
Keywords: wind-resource assessment, coastal Nigeria, coefficient of variation, low-wind regime, Weibull distribution, wind power density, CFD; micro-siting,University of Uyo

1. Introduction

Unstable electricity supply remains a practical constraint in many Nigerian university communities. Teaching spaces, hostels, laboratories, administrative offices, security lights, and digital learning facilities all depend on dependable power. Diesel backup can reduce outage effects, but its fuel cost, maintenance burden, noise, and emissions make it unsuitable as the only long-term response. Renewable-energy options are therefore important when they are assessed at realistic scales and matched to local resource conditions [1], [2], [3].

Wind energy can serve distributed loads where the local wind regime, turbine cut-in speed, terrain exposure, and hub height are suitable [4], [5]. A national or regional wind-resource statement is not sufficient for a small turbine decision because the wind available at rotor height depends on terrain, seasonal flow, building obstruction, vegetation, and surface roughness. A location that is attractive for wind power in northern Nigeria may not perform well in the coastal south.

Uyo lies in a coastal Niger Delta setting where low wind speeds are common [6], [7]. Earlier Nigerian wind-resource studies have shown that the southern coastal belt generally has weaker wind regimes than the northern inland belt, although open local sites can still provide usable low-speed winds for micro-generation [6], [7], [8]. For a university campus, this difference matters. The campus contains open fields, road corridors, hostels, workshops, trees, and large buildings; these features can either expose or shield a turbine from the incoming wind. Micro-siting is therefore central to any small-wind decision.

Wind-resource assessment also goes beyond a mean wind speed. The Weibull distribution is widely used to describe wind-speed frequency behaviour, while coefficient of variation helps describe the steadiness of monthly wind-resource availability [9], [10]. Turbulence intensity is a separate quantity derived from short-interval wind-speed fluctuations and used in turbine fatigue, gust response, and structural-loading assessment. This paper retains the title term “turbulence intensity” by treating it as an engineering measurement requirement and by clarifying the limits of the available data.

This study combines long-term NIMET records, July 2021 campus measurements, Weibull analysis, wind-resource variability assessment, and a rotor-level CFD interpretation. The objectives are to: (i) characterize the 2011-2020 wind-speed pattern in Uyo; (ii) compare campus measurement sites using mean wind speed and wind power density; (iii) estimate the Weibull distribution parameters of the low-wind regime; (iv) distinguish monthly wind-resource variability from true turbulence intensity; (v) interpret the CFD rotor torque result as mechanical power rather than direct electrical output; and (vi) recommend siting and deployment conditions for low-cut-in-speed micro-wind systems.

2. Materials and Methods

2.1 Study area

The study was conducted at the University of Uyo Main Campus, also known as the Permanent Site, along Nwaniba Road in Uyo, Akwa Ibom State, Nigeria. The campus is located within the coastal Niger Delta environment and experiences wind patterns influenced by south-westerly maritime flows during the wet season and north-easterly trade winds during the dry season. The selected field points are low-elevation locations, with terrain heights in the range of 47-54 m. Five locations were selected to represent different levels of exposure and obstruction: Administration Block, Multipurpose Hall, Central Library, NDDC Hostel, and Engineering Workshop.

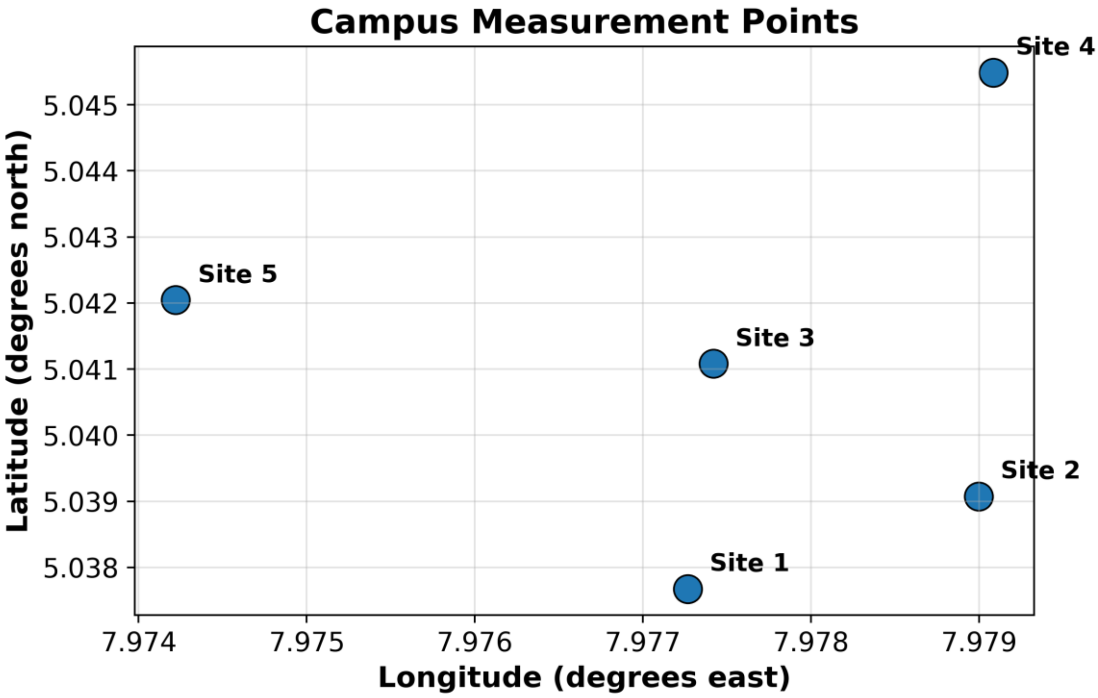

Figure 1: Coordinate-based schematic of the five campus wind-measurement sites.

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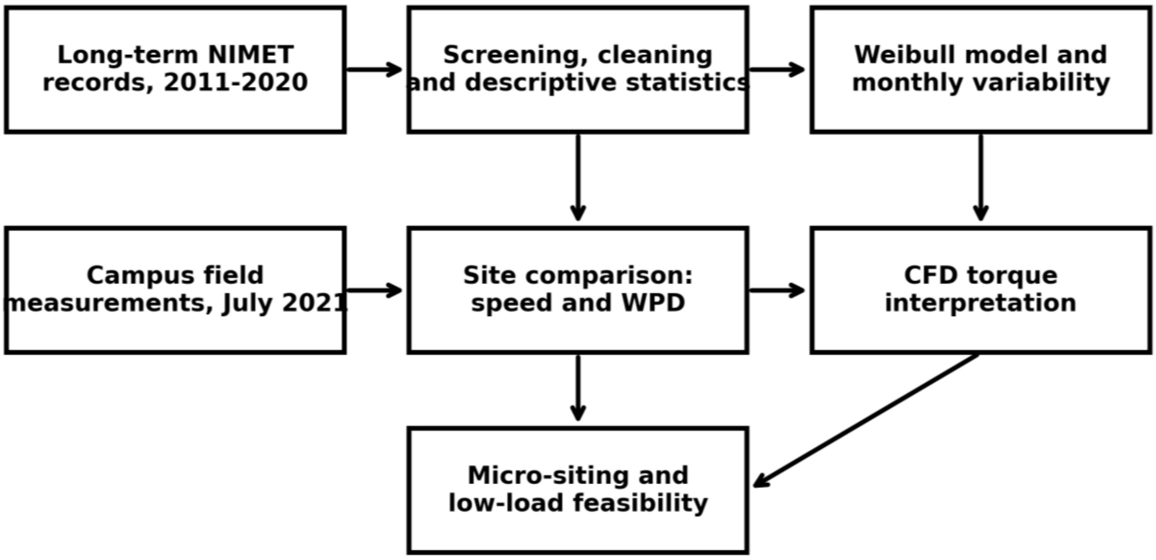

Figure 2: Research process used for the wind-resource, variability, CFD, and feasibility analyses.

2.2 Data sources and field measurement protocol

Two datasets were used. The long-term dataset comprised monthly wind-speed records obtained from NIMET for 2011-2020 at the Uyo weather station. These records were used for monthly and annual climatology, wind-resource classification, Weibull fitting, and coefficient-of-variation analysis. The campus dataset comprised July 2021 field measurements collected at five campus sites. Two measurement points were considered at each site, giving ten field points.

Field readings were taken with a digital anemometer mounted on a steel rod at 7.5 m above ground level. The readings were averaged by site to compare local wind access. The field record does not contain a complete calibration and sampling log. For that reason, the campus measurements are used for site-to-site comparison and micro-siting interpretation rather than investment-grade annual energy-yield prediction. This treatment is consistent with the short duration of the field campaign and the near-ground measurement height.Table 1 gives the field-site details in a compact form. Coordinates from the field notes were used to plot Figure 1.

Table 1: Campus measurement locations and terrain details.

Site	Landmark	Dist. A (m)	Dist. B (m)	Alt. A (m)	Alt. B (m)
Site 1	Admin Block	100	150	54	53
Site 2	Multipurpose Hall	70	120	49	50
Site 3	Central Library	50	100	47	51
Site 4	NDDC Hostel	50	100	54	53
Site 5	Engineering Wksp.	30	80	52	52

2.3 Wind-speed height adjustment

When wind speed measured at a reference height is compared with a proposed turbine hub height, the Hellmann power-law profile can be used:

$$v_z = v_r \left(\frac{z}{z_r}\right)^{\alpha} \quad (1)$$

In Equation (1), v_z is the estimated wind speed at height z, v_r is the measured wind speed at the reference height z_r, and α is the Hellmann exponent. For a built-up campus, the exponent must reflect local surface roughness and obstruction. The present analysis uses the available 7.5 m field measurements for site comparison. Hub-height effects are treated as a deployment-design sensitivity because wind speeds above the obstruction layer may differ from near-ground field measurements.

2.4 Weibull wind-speed model

The two-parameter Weibull model was used to describe the wind-speed distribution. The probability-density function is:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (2)$$

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The cumulative-distribution function is:

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{3}$$

The linearized form used for graphical estimation is:

$$\ln\left[-\ln\left(1 - F(v)\right)\right] = k\ln(v) - k\ln(c) \tag{4}$$

Here, k is the dimensionless shape parameter and c is the scale parameter in m/s. The fitted values used in this paper are $k = 2.8$ and $c = 2.8$ m/s. The fitted curve is used as an indicative distributional description because the available wind-speed record contains summarized values rather than the complete frequency series. It is not used as a procurement-grade model.

2.5 Wind power density and turbine power

Wind power density was used to compare site potential. For a representative wind speed, the available kinetic power per swept area is:

$$\text{WPD} = \frac{P}{A} = \frac{1}{2}\rho v^3 \tag{5}$$

For frequency-distribution analysis, the preferred estimate uses the mean of cubed wind speed or Weibull moments. The Weibull-based estimate is:

$$\text{WPD}_{\text{Weibull}} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{6}$$

The electrical output from a turbine is lower than the kinetic power in the wind because of aerodynamic and electrical losses:

$$P_e = \frac{1}{2}\rho A v^3 C_p \eta_g \eta_c \tag{7}$$

In Equations (5)-(7), ρ is air density, v is wind speed, A is rotor swept area, Γ is the gamma function, C_p is the rotor power coefficient, η_g is generator efficiency, and η_c is controller or conversion efficiency. The site WPD values are reported as comparative micro-siting indicators. The calculations use the standard near-surface air-density assumption $\rho = 1.225$ kg/m³ unless measured temperature and pressure data are available.

2.6 Coefficient of variation and turbulence intensity

The coefficient of variation was used to describe relative monthly wind-speed variability:

$$\text{CoV} = \frac{\sigma}{\mu_v} \tag{8}$$

True turbulence intensity is defined from short-interval velocity fluctuations as:

$$I = \frac{\sigma_u}{\mu_u} \tag{9}$$

In Equations (8) and (9), σ is the standard deviation of monthly mean wind speed, μ_v is the mean of the monthly wind-speed series, σ_u is the standard deviation of short-interval wind-speed fluctuations, and μ_u is the corresponding short-interval mean wind speed. The available NIMET series and July 2021 field measurements do not contain the high-frequency wind-speed record required for direct turbulence-intensity calculation. The paper therefore reports 0.18 as a monthly variability indicator and discusses turbulence intensity as an engineering measurement requirement for turbine design.

2.7 Rotor torque and CFD interpretation

Rotor thrust is represented with an aerodynamic coefficient as:

$$F_T = \frac{1}{2}\rho A v^2 C_T \tag{10}$$

Mechanical power and torque are related by:

$$T = \frac{P}{\omega} \tag{11}$$

The angular speed is:

$$\omega = \frac{2\pi N}{60} \tag{12}$$

In Equations (10)-(12), F_T is thrust force, C_T is thrust coefficient, T is rotor torque, P is mechanical power, ω is angular speed in rad/s, and N is rotor speed in rpm. The CFD model used an inlet speed of 2.74 m/s, a rotating inner domain, and a static outer domain. The reported torque is interpreted as a mechanical indicator,

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not as delivered electrical power. For numerical traceability, the CFD interpretation is limited to the reported torque scale. The result is treated as a rotor-level scale estimate rather than a validated turbine-performance prediction.

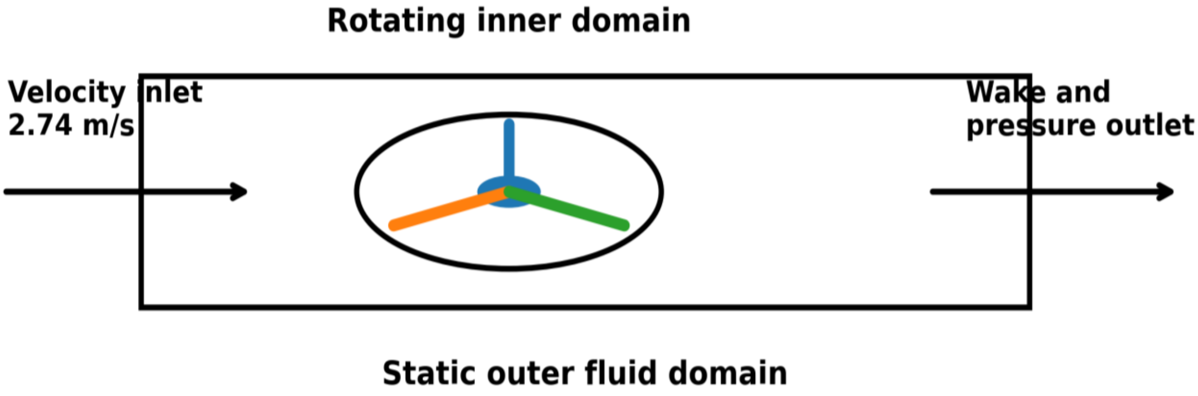

Figure 3: Clean CFD-domain schematic showing inlet, rotating inner domain, outer domain, and wake region.

3. Results and Discussion

3.1 Long-term NIMET wind-speed pattern

The monthly wind-speed climatology shows that the highest mean values occurred from January to April, with April recording 2.69 m/s. October was the calmest month, with a mean speed of 2.07 m/s. The mean of the monthly climatological averages was 2.41 m/s. This statistic differs from the decadal annual mean of 2.26 m/s because the two values are obtained from different aggregations. The decadal annual mean is used for the overall wind-resource classification.

Table 2: Monthly climatological mean wind speed for Uyo, 2011-2020.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean speed (m/s)	2.56	2.56	2.59	2.69	2.50	2.44	2.11	2.44	2.35	2.07	2.30	2.35

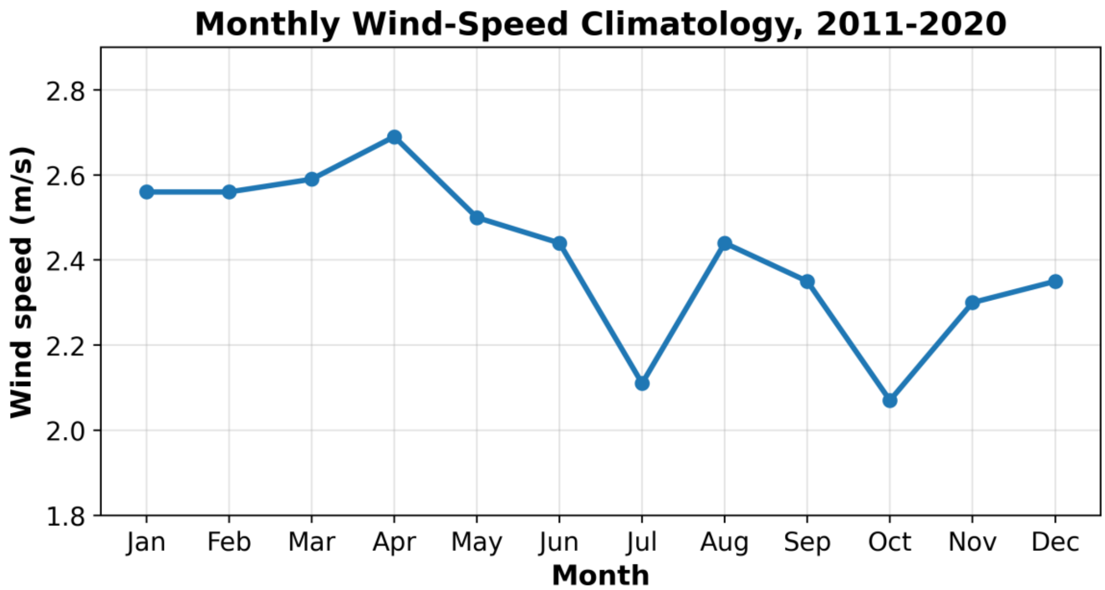

Figure 4: Monthly mean wind-speed pattern derived from the NIMET 2011-2020 dataset.

The annual mean speed varied from 1.87 m/s in 2012 to 2.74 m/s in 2020. The decadal annual mean was 2.26 m/s. These values confirm a low-wind environment and make large-scale wind generation unattractive under

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the assessed conditions. The result does not rule out micro-wind applications, but it narrows them to low-cut-in-speed turbines and small loads. The Class 1 interpretation is based on the low mean wind speed and low wind power density of the assessed record [11].

Table 3: Annual mean wind speed for Uyo, 2011-2020.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Mean speed (m/s)	2.02	1.87	2.23	2.45	2.11	2.45	2.02	2.33	2.36	2.74

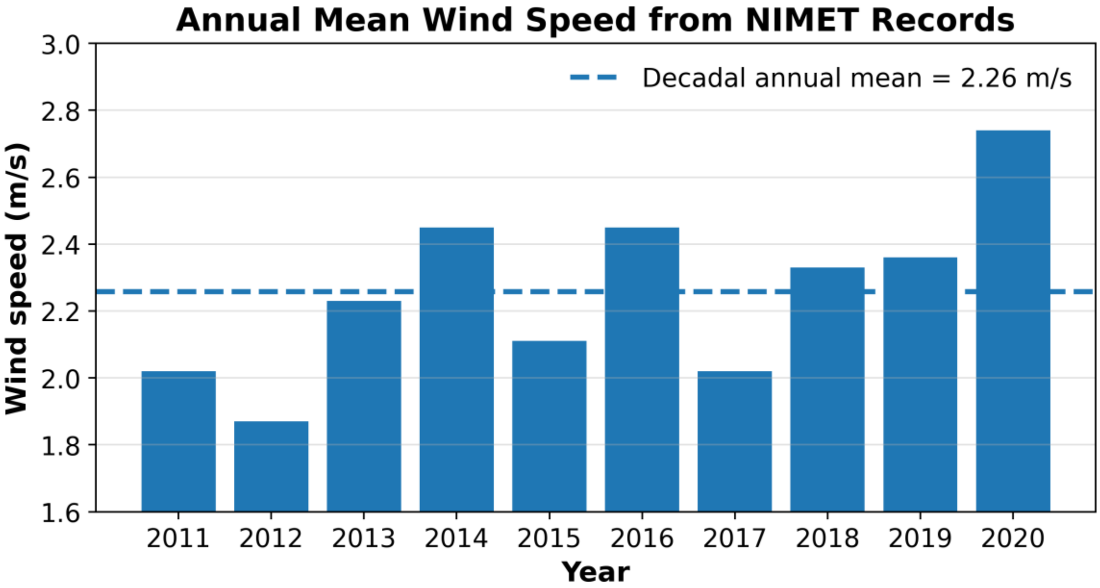

Figure 5: Annual mean wind-speed variation and decadal mean for the Uyo NIMET record.

3.2 Site-specific wind assessment

The July 2021 campus measurements show that wind access changes substantially across short distances. Site 2, near the Multipurpose Hall, produced the highest mean wind speed of 3.1 m/s and the highest wind power density of 20.13 W/m². Sites 1 and 4 also performed relatively well, each with a mean wind speed of 3.0 m/s. Site 5, near the Engineering Workshop, recorded the weakest performance, with 1.6 m/s and 2.60 W/m². The result is consistent with the expected effect of buildings, trees, and ground-level roughness on near-surface wind flow.

Table 4: Site-level mean wind speed and wind power density, July 2021.

Site	Mean wind speed (m/s)	Wind power density (W/m²)	Engineering interpretation
Site 1	3.0	19.62	Relatively open; useful for low-speed micro-wind screening
Site 2	3.1	20.13	Best-performing site in the field measurements
Site 3	2.3	8.80	Moderate speed; affected by nearby structures
Site 4	3.0	19.90	Promising site subject to safety and structural assessment
Site 5	1.6	2.60	Weak site; strong obstruction and poor wind access

Note: WPD values are comparative site indicators computed with the standard air-density assumption $\rho = 1.225$ *kg/m³ and the reported site mean speeds. Final design calculations would use measured temperature, pressure, and a defined averaging method.*

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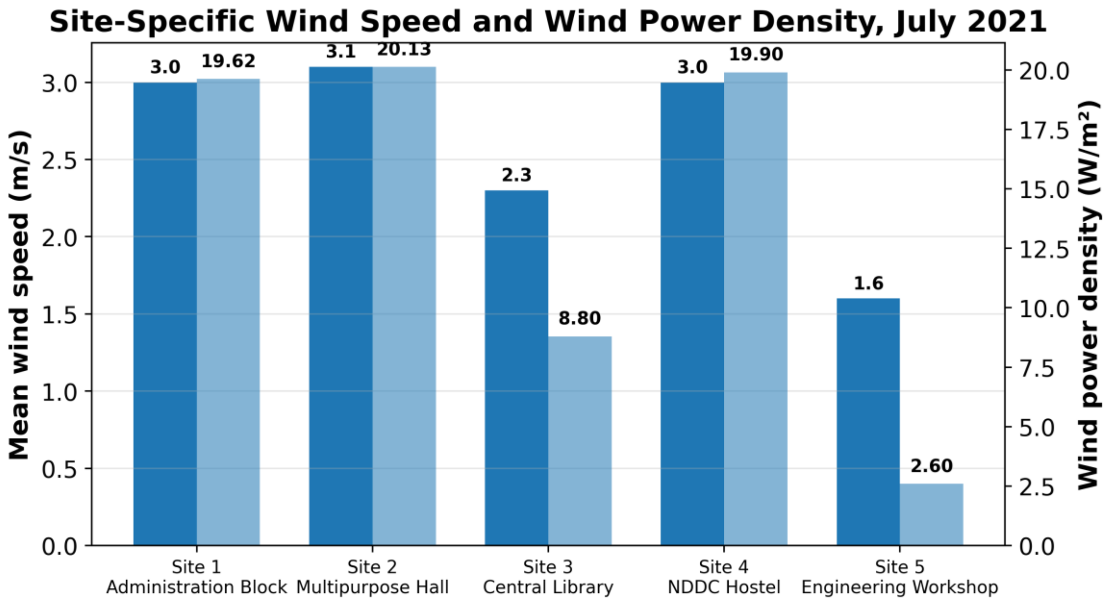

Figure 6: Site-specific comparison of wind speed and wind power density.

The contrast between Site 2 and Site 5 is important. A difference of 1.5 m/s in mean speed has a large effect on WPD because available wind power varies with the cube of wind speed. Small turbines are therefore better suited to open, elevated, and obstruction-free positions than to locations selected only by convenience or proximity to loads.

3.3 Weibull distribution and monthly variability

The Weibull parameters $k = 2.8$ and $c = 2.8$ m/s indicate a concentrated low-speed wind distribution. The practical implication is that the available wind is clustered close to the low-speed range. Turbines with cut-in speeds above about 3.5 m/s would be idle for much of the time. Low-cut-in-speed turbines and hybrid systems are therefore more suitable than conventional small turbines designed for stronger wind regimes [12,13].

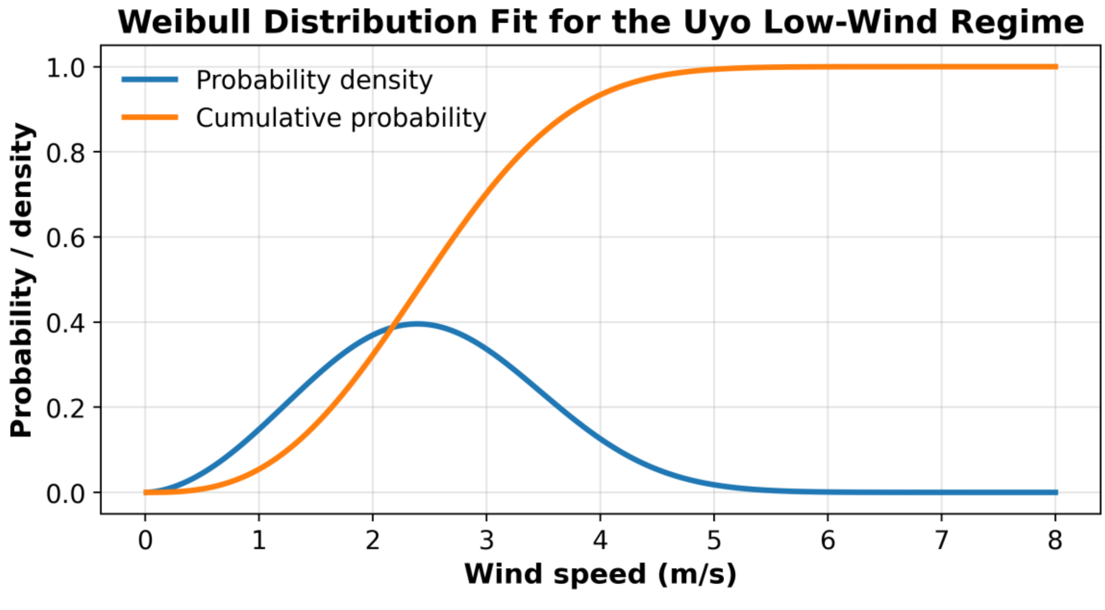

Figure 7: Weibull probability density and cumulative distribution curves for k = 2.8 and c = 2.8 m/s.

The coefficient of variation of monthly mean wind speed was about 0.18. This indicates moderate month-to-month resource variability. It does not measure turbulence intensity because the available data do not contain the short-interval fluctuations required for turbulence calculation. This distinction is central to the paper: monthly CoV can guide energy-variability discussion, while turbine fatigue, gust response, and structural loading depend on higher-resolution measurements.

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3.4 CFD torque result and mechanical-power interpretation

The CFD rotor simulation reported a torque of approximately 3.2 N·m at an inlet wind speed of 2.74 m/s. Torque alone does not establish electrical feasibility. Mechanical power depends on rotor speed. The 150 rpm case represents a conservative low-speed operating condition, while 250 rpm is taken from the nominal rotor speed of the turbine geometry used in the simulation record. At 150 rpm, 3.2 N·m corresponds to about 50.3 W before losses. At 250 rpm, it corresponds to about 83.8 W before drivetrain, generator, controller, battery, and inverter losses. The delivered electrical power would therefore be lower than these mechanical values.

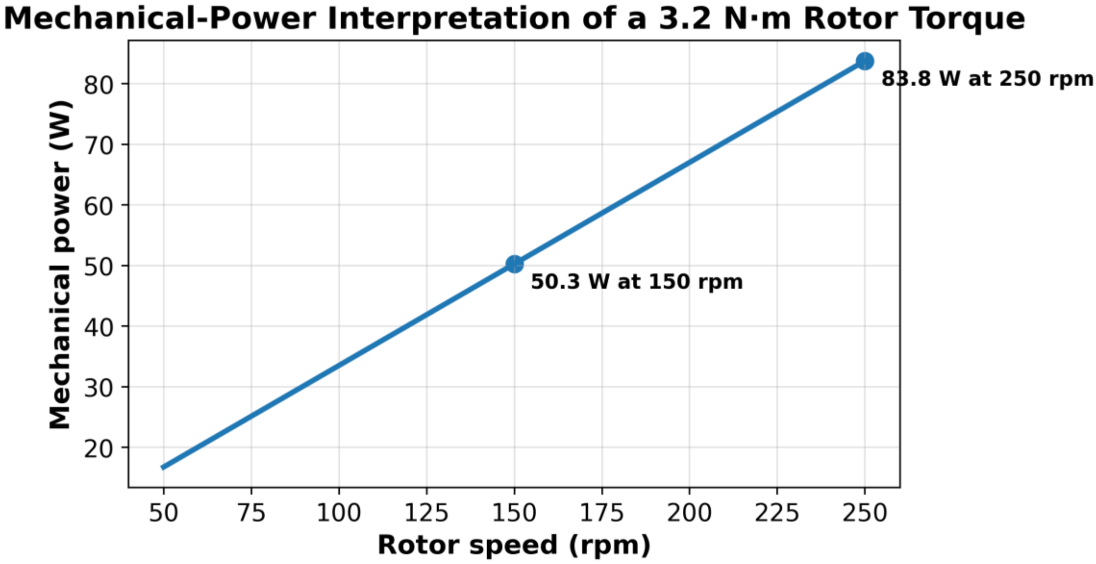

Figure 8: Mechanical-power interpretation of the reported 3.2 N·m CFD torque.

The CFD torque result provides a scale estimate of mechanical output under the selected inlet condition. It is consistent with limited low-load applications rather than general hostel electrification. The wake implication is also practical: a downstream unit would receive slower and more disturbed inflow, so turbine spacing must be checked during layout design.

3.5 Feasibility of small-scale campus wind generation

The combined statistical, field, and CFD evidence does not support utility-scale wind generation at the University of Uyo Main Campus. It does support a more modest option: carefully sited micro-wind generation for specific low-load uses. The most suitable pilot locations are Sites 2 and 4, with Site 1 as a secondary option. Site 5 is not suitable under the observed near-ground condition.

A low-wind campus turbine is best matched with a cut-in speed close to or below 2.0 m/s, a rotor suited for low-speed operation, safe tower design, lightning protection, charge control, and battery storage. Pilot deployment is best limited to small measurable loads such as LED security lighting, phone charging, IoT sensor nodes, or a hybrid wind-solar battery unit.

Table 5: Screening-level load-matching guide for pilot micro-wind use.

Load type	Indicative demand	Example use	Approx. daily energy	Wind-system implication
LED security light	10-20 W per lamp	8-10 h nightly	80-200 Wh/day	Suitable for pilot testing with battery storage
Phone or small-device charging	5-30 W per charging point	Intermittent charging	30-150 Wh/day	Suitable where use is controlled and intermittent
Sensor node or data logger	2-10 W	Continuous or duty-cycled	20-120 Wh/day	Good match for hybrid wind-solar charging
Hostel fan or larger appliance	40-100 W per unit	4-8 h use	160-800 Wh/day	Use only after AEP and battery sizing
General hostel electrification	Hundreds of watts to kW scale	Mixed loads	>1 kWh/day	Not supported by the present evidence

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4. Conclusion and Recommendations

4.1 Conclusion

This study assessed wind-resource potential and small-scale power-generation suitability at the University of Uyo Main Campus using NIMET records, July 2021 field measurements, Weibull analysis, monthly variability assessment, and CFD torque interpretation. The decadal annual mean wind speed was 2.26 m/s, while the mean of the monthly climatological averages was 2.41 m/s. These values confirm a low-wind, Class 1 wind-resource environment under the assessed conditions.

The campus measurements showed meaningful micro-siting differences. Site 2 recorded the highest mean wind speed and WPD, followed closely by Sites 1 and 4. Site 5 recorded the weakest performance and is unsuitable for near-ground turbine deployment unless a higher hub height or a less obstructed position is used. The coefficient of variation result is best interpreted as monthly wind-resource variability, not direct turbulence intensity. True turbulence assessment requires short-interval wind-speed measurements. In this study, the turbulence-intensity component is addressed as a measurement requirement and not as a direct turbulence result.

The CFD torque result of about 3.2 N·m indicates limited mechanical output under the selected low-wind inlet condition. It may support low-load applications when matched with low-cut-in-speed turbines, efficient conversion, battery storage, and proper micro-siting. The evidence does not support large-scale wind generation or broad hostel electrification from wind alone.

4.2 Recommendations

Subsequent field campaigns should use logged short-interval wind-speed data at relevant hub heights so that turbulence intensity, gust behaviour, uncertainty, and annual energy production can be computed directly. A monitored pilot system at Site 2 or Site 4 would provide the most useful campus evidence. The pilot record should include wind speed, rotor speed, voltage, current, battery state of charge, downtime, and delivered energy. Turbine selection is best based on a verified power curve, cut-in speed, tower height, safety requirements, expected annual energy yield, and local maintenance capacity. A hybrid wind-solar battery system is preferable for campus low-load applications because solar generation can complement the weak wind regime and improve reliability.

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