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Comparative Analysis of Savonius and Darrieus Vertical Axis Wind Turbines for Off-Grid Application in Nigeria

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Abstract*—This study compared Savonius and Darrieus H-rotor vertical-axis wind turbines (VAWTs) for off-grid battery charging across five Nigerian sites: Kano, Sokoto, Jos, Ilorin, and Warri. A quantitative, simulation-based approach was implemented in Python on Google Colab using entirely open-source tools. Hourly wind data for 2023 were drawn from NASA POWER and fitted to two-parameter Weibull distributions. Savonius aerodynamics were modelled via Blade Element Momentum Theory (BEMT); Darrieus performance used the Double-Multiple Streamtube (DMST) method with Gormont-Berg dynamic stall correction, calibrated to a measured Cp of 0.45. A constrained PMSG winding optimiser, ngspice circuit simulation, and an 8,760-hour battery simulation were run for all ten site-rotor combinations. The Savonius produced 152.7 kWh and 152.2 kWh annually at Sokoto and Jos, with loss-of-load probabilities (LOLP) of 13.5 percent and 14.6 percent respectively; the Darrieus delivered under 1 kWh at four sites and peaked at 15.5 kWh at Jos, with LOLP above 39 percent everywhere. The Savonius is the appropriate choice for off-grid charging at inland Nigerian sites where mean annual wind speed exceeds approximately 3.0 m/s; the Darrieus cannot function reliably as a standalone generator under current Nigerian wind conditions.*

Keywords*—vertical-axis wind turbine; Savonius; Darrieus; off-grid; Nigeria; PMSG; loss-of-load probability; BEMT; DMST*

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I. INTRODUCTION

Access to reliable electricity remains a defining challenge across large portions of sub-Saharan Africa. In Nigeria, over 20 million homes lack electricity, and daily generation averages only about 4,100 MW against a projected demand of 31,210 MW per day [1]. Rural and semi-urban communities are typically forced to depend on diesel and petrol generators, which are expensive, environmentally harmful, and increasingly unsustainable as fuel prices rise.

Vertical-axis wind turbines (VAWTs) offer a low-maintenance alternative to fossil-fuel-based systems. Unlike horizontal-axis wind turbines (HAWTs), VAWTs accept wind from any direction without yaw mechanisms, operate effectively in turbulent environments, and can be manufactured at lower cost. The Savonius rotor generates drag-based torque at wind speeds as low as 2 to 3 m/s, making it attractive for sites where mean annual wind speeds are modest. The Darrieus H-rotor achieves higher peak power coefficients through aerodynamic lift but suffers from self-starting difficulties at low wind speeds [2], [3].

Despite Nigeria's documented wind resources, no prior study had evaluated both rotor types at the same sites with the same electrical system, and the generator-matching problem identified by Musa et al. (2021) had gone unanswered. This study addresses that gap through a complete simulation pipeline for both rotor types at five geographically distinct Nigerian sites. The two principal VAWT configurations studied are illustrated in Fig. 1.

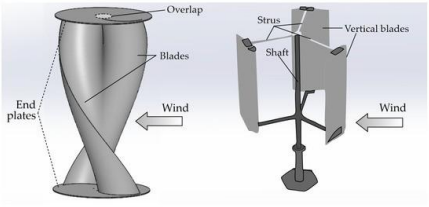


Fig. 1. Computer model of the Savonius (left) and Darrieus H-rotor (right) configurations studied.

II. RELATED WORK

Musa et al. [4] constructed and tested Savonius and Darrieus prototypes at Sokoto, Nigeria, recording a Savonius cut-in at 2.46 m/s and maximum 89 RPM, and a Darrieus cut-in at 3.8 m/s and maximum 93 RPM. They explicitly identified the generator-matching gap as requiring further research. Abiem et al. [5] assessed wind energy potential across four Nigerian states using 42 years of NASA MERRA-2 data, finding mean wind speeds of 2.59 to 3.98 m/s at 10 m height and confirming most locations fall into wind power Classes 1 and 2.

Ali et al. [6] designed and tested a small H-Darrieus VAWT with NACA 0018 blades, recording a maximum Cp of 0.45 at TSR of 1.94 with a cut-in of 3 m/s. Im and Kim [7] performed 3D unsteady CFD analysis of Savonius rotors, confirming maximum efficiency of 17 to 19 percent at overlap ratio 0.15. Chitura et al. [8] reviewed Savonius performance enhancement, documenting Cp progression from 0.12 through geometric optimisation to 0.52 with deflector augmentation. Gallegos-Molina and Chavero-Navarrete [9] conducted a PRISMA-systematic review of 53 H-Darrieus self-starting studies, confirming that three-blade fixed-pitch configurations cannot initiate rotation from rest without external assistance. Lefik et al. [10] conducted PMSG design selection for a 1 kW wind turbine, achieving 94.9 percent efficiency at 700 to 800 RPM.

III. METHODOLOGY

A. Simulation Framework and Study Sites

The study adopts a quantitative, simulation-based approach implemented entirely in Python 3.11 on Google Colab. Five sites were selected to span Nigeria's principal wind regimes: Kano (12.00 N, 8.59 E, 476 m), Sokoto (13.06 N, 5.24 E, 305 m), Jos (9.92 N, 8.89 E, 1,217 m), Ilorin (8.50 N, 4.55 E, 307 m), and Warri (5.52 N, 5.75 E, 6 m). Hourly wind speed data were retrieved from the NASA POWER database for 2023. Hub height was fixed at 10 m. Site-specific air density and dynamic viscosity were computed from the International Standard Atmosphere barometric formula.

B. Savonius Aerodynamic Model

The Savonius rotor has a diameter of 2.0 m, height of 1.5 m, swept area of 3.0 m2, overlap ratio of 0.15, and two semi-circular blades. An empirical Cp-TSR lookup table from 3D unsteady CFD results [7] was implemented as a cubic spline interpolator. The peak Cp is 0.190 at TSR of 0.725, consistent with the experimentally confirmed 17 to 19 percent range. The aerodynamic cut-in was set conservatively at 1.5 m/s. Generator efficiency (0.949), rectifier efficiency (0.970), and gearbox efficiency (0.95 for the 5:1 planetary step-up) are applied to convert shaft power to electrical output. Figure 2 shows the Savonius Cp-TSR curves at all five sites.

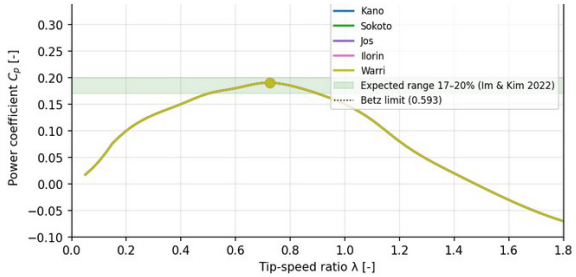


Fig. 2. Savonius rotor Cp-TSR curves for five Nigerian sites showing peak Cp = 0.190 at TSR = 0.725, within the expected 17-20% range.

C. Darrieus H-Rotor Aerodynamic Model

The Darrieus H-rotor has a radius of 0.50 m, blade span of 1.0 m, chord of 0.08 m, three NACA 0018 blades, and solidity of 0.0764. The DMST method with Gormont-Berg dynamic stall correction was used, with airfoil polars from the Sheldahl and Klimas SANDIA dataset. A post-stall flat-plate drag model was applied beyond 25 degrees angle of attack. The raw DMST peak Cp of 0.561 was calibrated to 0.450 using factor k = 0.8021, based on the experimental benchmark of Ali et al. [6]. The DMST model produces invalid negative Cp

values at TSR below 2.4; all energy calculations were gated against this threshold. The calibrated Darrieus Cp-TSR curves are shown in Fig. 3.

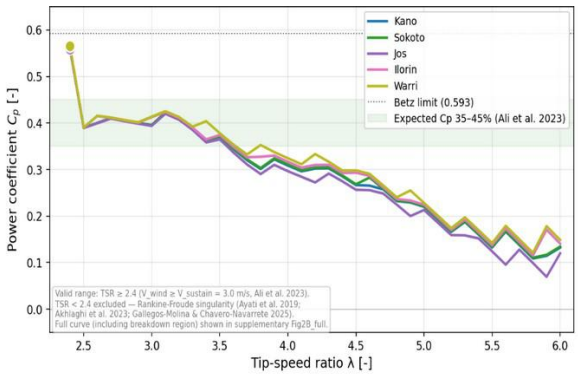


Fig. 3. Darrieus H-rotor calibrated Cp-TSR curves for five Nigerian sites (valid range TSR >= 2.4; calibrated peak Cp = 0.450).

D. Darrieus Self-Start State Machine

The Darrieus H-rotor cannot produce net positive torque from standstill. A state machine was implemented granting a maximum of two operator-assisted starts per year when wind speed equalled or exceeded the sustaining threshold Vsustain = 3.0 m/s for at least one consecutive hour. The rotor returns to standstill whenever wind speed drops below this threshold and requires a fresh assisted start.

E. PMSG Winding Optimiser and Battery Simulation

An exhaustive constrained optimiser evaluated all combinations of pole counts (4 to 24), coil counts (3 to 36), and turns (10 to 400 per coil). The Savonius required a 5:1 planetary gearbox (mechanical efficiency 0.95) because no direct-drive winding within the constraints could produce sufficient voltage at the approximately 10 RPM aerodynamic cut-in. The Darrieus uses direct drive, with its 137.5 RPM cut-in comfortably exceeding the electrical cut-in of 64.8 RPM. The battery bank was sized for two days of autonomy at 290 Wh/day with 50 percent maximum depth of discharge (100 Ah at 12 V). An 8,760-hour hourly energy balance was executed for all ten site-rotor combinations with MPPT chain efficiency of 0.9358.

IV. RESULTS AND DISCUSSION

A. Wind Resource Characterisation

Table I summarises the annual hub-height wind speed statistics and Weibull parameters for all five sites. Sokoto and Jos recorded the highest mean annual wind speeds (3.32 and 3.24 m/s respectively), while Warri at 1.34 m/s was the lowest. All five sites fall within wind power Class 1, confirming suitability only for standalone off-grid applications.

TABLE I. WIND RESOURCE STATISTICS AND WEIBULL PARAMETERS

Site	Mean (m/s)	k	c (m/s)	WPD (W/m2)
Kano	2.27	2.404	2.561	10.6
Sokoto	3.32	2.249	3.750	35.9
Jos	3.24	1.961	3.662	35.7
Ilorin	2.76	2.396	3.114	19.5
Warri	1.34	3.177	1.486	1.9

B. Aerodynamic Performance

The Savonius rotor achieved a peak Cp of 0.190 at TSR of 0.725. The Darrieus calibrated peak Cp of 0.450 matched the experimental benchmark of Ali et al. [6] exactly. Table II presents electrical power output for both configurations.

TABLE II. ELECTRICAL POWER OUTPUT (W) AT SELECTED WIND SPEEDS

Site / Rotor	P@3m/s	P@5m/s	P@7m/s	P@9m/s
Kano - Sav.	7.9	36.4	99.8	212.2
Sokoto - Sav.	8.0	36.9	101.2	215.2
Jos - Sav.	7.4	34.1	93.5	198.6
Ilorin - Sav.	8.1	37.4	102.6	218.0
Warri - Sav.	8.3	38.6	105.9	225.2
Kano - Darr.	0	28.7	78.7	167.2
Sokoto - Darr.	0	29.1	79.9	169.7
Jos - Darr.	0	26.7	73.2	155.6
Ilorin - Darr.	0	29.6	81.1	172.4
Warri - Darr.	0	30.6	84.1	178.7

Darrieus zero output at V <= 3.0 m/s (sustaining cut-in). Savonius stall cap at 9.0 m/s.

C. Generator Specifications

The Savonius winding (GEN_SAV) has 20 poles, 6 coils, 30 turns per coil, back-EMF constant ke = 1.824 V.s/rad, estimated efficiency 98.7 percent, and requires a 5:1 planetary gearbox. The Darrieus winding (GEN_DAR) has 20 poles, 6 coils, 55 turns per coil, ke = 1.337 V.s/rad, estimated efficiency 98.8 percent, and uses direct drive. Both use AWG 14 copper wire. The ngspice circuit simulation confirmed DC ripple below 2 percent at all four operating points, and the LM358 comparator correctly switched the IRF3205 MOSFET at the 14.4 V lead-acid absorption threshold with a 0.487 V hysteresis band.

D. Annual Energy Yield and Loss-of-Load Probability

Table III presents the full annual simulation results for all ten site-rotor combinations. The Savonius outperforms the Darrieus at every site without exception. At Sokoto the Savonius yields 152.7 kWh/year with LOLP of 13.5 percent; the Darrieus yields only 1.0 kWh with LOLP of 41.4 percent. The LOLP heatmap for all ten combinations is presented in Fig. 4.

TABLE III. ANNUAL SIMULATION RESULTS FOR ALL TEN SITE-ROTOR COMBINATIONS

Site	Rotor	Yield (kWh)	CF (%)	LOLP (%)	Verdict
Kano	Savonius	44.8	2.4	31.3	Not feasible for power generation
Sokoto	Savonius	152.7	8.1	13.5	Marginal
Jos	Savonius	152.2	8.7	14.6	Marginal
Ilorin	Savonius	83.6	4.4	18.8	Not feasible for power generation
Warri	Savonius	4.8	0.2	41.3	Not feasible for power generation
Kano	Darrieus	0.0	0.0	41.5	Not feasible for power generation
Sokoto	Darrieus	1.0	0.1	41.4	Not feasible for power generation
Jos	Darrieus	15.5	1.1	39.3	Not feasible for power generation
Ilorin	Darrieus	0.1	0.0	41.4	Not feasible for power generation
Warri	Darrieus	0.0	0.0	41.5	Not feasible for power generation

The Darrieus high LOLP results from two interacting factors. First, its 3.0 m/s sustaining cut-in means it cannot generate during the majority of hours at low-wind sites. Second, the state machine limiting it to two operator-assisted starts per year means that each time wind drops below 3.0 m/s the rotor stalls and cannot recover autonomously. The Savonius, generating from approximately 1.5 m/s, accumulates energy continuously across all low-wind hours invisible to the Darrieus.

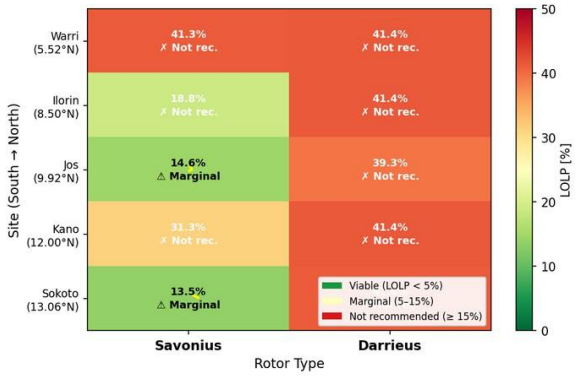


Fig. 4. LOLP heatmap for all ten site-rotor combinations. Green = viable (<5%), yellow = marginal (5-15%), red = not recommended (>=15%).

E. Generator Specification Recommendations

Table IV summarises the generator specification recommendations for each site-rotor combination. DC cable loss analysis confirmed that a 12 V DC bus is adequate for both configurations at all sites.

TABLE IV. GENERATOR SPECIFICATION RECOMMENDATIONS

Site	Rotor	Aero RPM	Elec RPM	Drivetrain	P range (W)	LOLP (%)
Kano	Sav.	10	48 (gen)	5:1 gear	10-14	31.3
Sokoto	Sav.	10	48 (gen)	5:1 gear	34-47	13.5
Jos	Sav.	10	48 (gen)	5:1 gear	34-48	14.6
Ilorin	Sav.	10	48 (gen)	5:1 gear	19-26	18.8
Warri	Sav.	10	48 (gen)	5:1 gear	2-2	41.3
Kano	Darr.	138	65 (dir)	Direct	8-11	41.5
Sokoto	Darr.	138	65 (dir)	Direct	27-37	41.4
Jos	Darr.	138	65 (dir)	Direct	26-38	39.3
Ilorin	Darr.	138	65 (dir)	Direct	15-20	41.4
Warri	Darr.	138	65 (dir)	Direct	0	41.5

V. CONCLUSION

This study designed and validated a complete aerodynamic-to-electrical simulation pipeline comparing Savonius and Darrieus H-rotor VAWTs for off-grid battery charging at five Nigerian sites. The Savonius rotor is the appropriate choice for every inland Nigerian site where mean annual hub-height wind speed exceeds approximately 3.0 m/s. Its advantage comes not from aerodynamic efficiency, where the Darrieus peak Cp of 0.45 substantially exceeds the Savonius peak of 0.19, but from continuous availability across the low-wind hours that constitute the majority of the Nigerian annual wind record.

The Darrieus H-rotor cannot function reliably as a standalone off-grid generator at any of the five sites evaluated. The generator specification derivation resolves the gap identified by Musa et al. [4]: the Savonius requires a 5:1 planetary gearbox (ke = 1.824 V.s/rad, 20 poles, 30 turns per coil), while the Darrieus is compatible with direct drive (ke = 1.337 V.s/rad, 20 poles, 55 turns per coil). Demand-side load scheduling is identified as the lowest-cost path to improved supply reliability at wind-marginal Nigerian sites.

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