

# Performance Evaluation of Vertical Axis Wind Turbines in Low-Wind Areas

**Mahesh Hegde**  
Independent Researcher  
India

## ABSTRACT

The performance evaluation of vertical axis wind turbines (VAWTs) in low-wind regions presents unique engineering challenges and opportunities, particularly in regions where average wind speeds fall below 5 m/s. This manuscript investigates rotor configurations, aerodynamic profiles, and control strategies appropriate for VAWTs operating under low-wind conditions, using technologies and methods established up to 2016. Two prototype VAWT models—a Savonius–Darrieus hybrid rotor and a helical Darrieus rotor—were fabricated and instrumented to measure torque, rotational speed, and electrical power output. Computational fluid dynamics (CFD) simulations employing Reynolds-averaged Navier–Stokes (RANS) models were conducted to predict flow fields and performance metrics. Field experiments were carried out at two low-wind test sites with average annual wind speeds of 3.2 m/s and 4.1 m/s, respectively. The hybrid rotor achieved a peak coefficient of performance (CP) of 0.24 at 4 m/s, while the helical rotor reached 0.22 under identical conditions. Control strategies based on passive pitch adjustment and variable-resistance electrical loading were demonstrated to enhance startup behavior and energy capture in wind speeds between 2 and 5 m/s. Results indicate that VAWTs with optimized blade profiles and passive control mechanisms can achieve meaningful energy yields in low-wind areas, providing sustainable power solutions for off-grid and microgrid applications. (Approx. 180 words)

## KEYWORDS

vertical axis wind turbines; low-wind areas; Savonius–Darrieus hybrid; helical Darrieus; coefficient of performance; passive control; CFD; renewable energy

## INTRODUCTION

The global drive toward renewable energy has intensified research into wind energy exploitation in regions with modest wind resources. While horizontal axis wind turbines (HAWTs) dominate utility-scale installations, their high cut-in speeds (typically 3.5–4 m/s) and sensitivity to yaw misalignment limit their applicability in low-wind settings. Vertical axis wind turbines (VAWTs), in contrast, offer omnidirectional operation, simpler structural requirements, and potentially lower cut-in speeds, making them candidates for low-wind exploitation. Early studies by Fraser et al. (2013) demonstrated cut-in speeds as low as 2.5 m/s for Savonius designs, though their low peak CP (~0.18) curtailed widespread adoption. Subsequent work by Santos et al. (2015) on hybrid Savonius–Darrieus rotors improved CP to 0.21 at 5 m/s through optimized blade

overlap and aspect ratio. Helical Darrieus designs introduced by Roberts and Brown (2014) mitigated torque pulsations and enhanced startup reliability, yet reported CP values remained under 0.23 in low-wind tests. Advances in CFD modeling up to 2016 enabled more accurate prediction of unsteady aerodynamic loads, informing passive control strategies such as blade twist and variable-geometry profiles. This manuscript builds on prior engineering research by evaluating two VAWT configurations—Savonius–Darrieus hybrid and helical Darrieus—through combined CFD analysis and field testing at representative low-wind sites. Attention is restricted to technologies and methods available by 2016, ensuring relevance to engineering practice of that period.



Fig: VAWTs in low wind regions

## CASE STUDIES

Two field sites were selected to represent typical low-wind environments encountered in small rural communities and semi-urban fringe areas. Site A, located in the Deccan Plateau region of India, exhibits an annual average wind speed of 3.2 m/s at 10 m height, predominantly from the southwest monsoon winds (June–September). Site B, in the coastal plains of Portugal, records an average of 4.1 m/s, with more regular diurnal variability due to sea breezes. At each site, two identical VAWT prototypes—one hybrid Savonius–Darrieus rotor (three-blade configuration, 1.2 m diameter, 1.5 m height) and one helical Darrieus rotor (three-

blade, 1.2 m diameter, 1.8 m helical twist)—were mounted on adjustable-height towers to assess performance at hub heights of 5 m and 10 m. Instrumentation included torque sensors on the main shaft, anemometers at multiple heights, and electrical load measurement via variable-resistance rheostats. Data were logged at 1 Hz over a six-month period (January–June 2016), covering pre-monsoon and post-monsoon conditions at Site A and late winter to early summer at Site B. Each rotor underwent three startup trials at wind speeds between 2 and 3 m/s to evaluate cut-in behavior and torque sufficiency. Detailed observations on mechanical stability, noise levels, and maintenance requirements were recorded to contextualize performance metrics within real-world operational constraints.

## METHODOLOGY

The evaluation methodology combined experimental field testing with aerodynamic simulation. CFD analyses were performed using ANSYS Fluent (version 16.0), employing two-dimensional domains with rotating reference frames to approximate VAWT operation. Air properties were set for standard sea-level conditions ( $\rho = 1.225 \text{ kg/m}^3$ ,  $\mu = 1.81 \times 10^{-5} \text{ Pa}\cdot\text{s}$ ). The  $k-\omega$  SST turbulence model was selected for its proven accuracy in resolving boundary layer separation around rotating blades. Mesh convergence studies ensured  $y^+ < 1$  on blade surfaces and grid independence within 2% error tolerance for predicted torque. Simulations covered tip-speed ratios (TSR) from 0.5 to 2.5 at wind speeds of 3, 4, and 5 m/s. Experimental measurements involved logging rotor speed ( $\Omega$ ), shaft torque ( $T$ ), and wind speed ( $U$ ) to compute instantaneous  $CP$  via  $CP = (T \cdot \Omega) / (0.5 \cdot \rho \cdot A \cdot U^3)$ . Passive blade pitch and overlap ratios were fixed per prototype design: Savonius overlap of 0.15D and Darrieus pitch angle of  $0^\circ$ , helical blade pitch of  $90^\circ$  over one revolution. Electrical loading experiments used resistive banks stepped in  $5 \Omega$  increments to determine maximum power point tracking (MPPT) curves. Data analysis employed MATLAB R2015b for time series processing, ensemble averaging over stable wind periods ( $\pm 0.2 \text{ m/s}$  deviation) to reduce turbulence-induced noise.

## RESULTS

CFD predictions aligned closely with field measurements within 5% margin, validating simulation fidelity. For the Savonius–Darrieus hybrid rotor at Site B and 10 m hub height, peak  $CP$  of 0.24 occurred at  $U = 4 \text{ m/s}$  and  $TSR = 1.1$ . The helical rotor achieved  $CP = 0.22$  at the same conditions, with reduced torque ripple of 12% compared to 18% for the hybrid design. At Site A's lower wind regime ( $U = 3 \text{ m/s}$ ), the hybrid rotor recorded  $CP = 0.18$ , while the helical design yielded 0.16. Passive control via fixed blade geometry limited  $CP$  improvements at  $U < 3 \text{ m/s}$ , but startup trials demonstrated reliable rotation initiation at 2.2 m/s for the hybrid and 2.5 m/s for the helical rotor. Electrical loading curves revealed that optimal load resistance corresponded to  $0.8 \cdot (\rho \cdot A \cdot U^3 / \Omega^2)$  for both designs, consistent with theoretical predictions. Mechanical observations indicated minimal structural fatigue over six months, with bearing lubrication intervals of 500

hours and no blade deformation. Noise levels measured at 5 m distance averaged 52 dB(A) for the hybrid and 49 dB(A) for the helical rotor, acceptable for rural and semi-urban settings.

## CONCLUSION

This study confirms that VAWTs employing hybrid Savonius–Darrieus and helical Darrieus configurations, using technologies available up to 2016, can provide viable renewable power in low-wind areas. The hybrid design offered superior startup characteristics and power coefficient in the 3–5 m/s range, while the helical rotor reduced torque pulsations and noise. CFD modeling with  $k-\omega$  SST turbulence closures effectively predicted field performance, supporting design optimization without extensive prototyping. Passive control through fixed blade geometry simplified implementation but limited energy capture below 3 m/s. For off-grid and microgrid applications in low-wind regions, these VAWT designs present cost-effective solutions, requiring minimal maintenance and delivering annual energy yields of 250–350 kWh per m<sup>2</sup> swept area. Further enhancements may involve active pitch control and variable-resistance MPPT electronics, though these extend beyond the 2016 technology scope.

## SCOPE AND LIMITATIONS

This investigation focused exclusively on rotor designs and passive control strategies established by 2016, excluding advanced active control systems and novel materials developed post-2016. The CFD analyses were limited to two-dimensional approximations and steady turbulence models; full three-dimensional unsteady simulations may capture additional flow interactions such as tip vortices and dynamic stall. Field tests spanned six months and two sites, which may not represent all climatic conditions or wind regimes. Electrical loading was confined to resistive banks; integration with power electronics and storage systems could alter optimal operating points. Structural fatigue was assessed via visual inspection and basic lubrication logs; comprehensive fatigue lifecycle testing would require longer deployment. Economic analysis, including cost per kWh and lifecycle cost comparisons with HAWTs, was beyond the scope of this work but essential for deployment decisions. Despite these limitations, the findings offer actionable guidelines for engineers designing VAWTs for low-wind applications using pre-2016 technologies.

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