



# Computer-Aided Design and Analysis of Vertical Axis Wind Turbines for Low-Cost Energy Solutions

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**ABSTRACT:** The increasing global demand for renewable energy sources has intensified research on wind energy technologies, especially Vertical Axis Wind Turbines (VAWTs), which offer several advantages for small-scale and low-cost energy generation. Unlike traditional Horizontal Axis Wind Turbines (HAWTs), VAWTs have a simpler design, are omnidirectional, and can operate efficiently in turbulent and urban wind conditions. This study focuses on the computer-aided design (CAD) and computational analysis of VAWTs aimed at optimizing performance while maintaining low manufacturing costs.

Using CAD software, multiple VAWT blade geometries were designed, including Darrieus and Savonius types, with modifications to blade curvature and aspect ratios. Computational Fluid Dynamics (CFD) simulations were conducted to analyze aerodynamic performance, including torque generation, power coefficient, and starting behavior under various wind speeds. The simulations employed the Reynolds-Averaged Navier-Stokes (RANS) equations with the k- $\epsilon$  turbulence model to predict flow fields and aerodynamic forces.

Results show that hybrid Savonius-Darrieus configurations outperform traditional designs in terms of starting torque and overall efficiency at low wind speeds, which are common in urban environments. Parametric studies indicate that blade profile and rotor aspect ratio critically influence turbine performance and structural stability. Furthermore, manufacturing cost analyses suggest that additive manufacturing techniques and locally available materials can substantially reduce production expenses without compromising structural integrity.

This work highlights the potential of CAD and CFD tools to facilitate the rapid design and optimization of VAWTs for decentralized energy applications, particularly in developing regions. The findings encourage further experimental validation and development of scalable manufacturing methods to promote widespread adoption of low-cost wind energy solutions.

**KEYWORDS:** Vertical Axis Wind Turbines, Computer-Aided Design, Computational Fluid Dynamics, Renewable Energy, Low-Cost Energy Solutions, Darrieus Rotor, Savonius Rotor, Aerodynamic Analysis, Urban Wind Energy, Additive Manufacturing.

## I. INTRODUCTION

Renewable energy technologies have become pivotal in addressing climate change and energy security concerns worldwide. Wind energy, among the most mature renewable resources, is typically harnessed using Horizontal Axis Wind Turbines (HAWTs). However, HAWTs face limitations in urban and low-wind-speed environments due to their need for wind direction alignment and relatively high maintenance costs.

Vertical Axis Wind Turbines (VAWTs) offer a promising alternative, especially for small-scale and decentralized energy production. Their design allows them to capture wind from any direction, making them suitable for turbulent and fluctuating wind conditions prevalent in urban areas. Moreover, VAWTs have fewer moving parts, enabling easier maintenance and potentially lower manufacturing costs.

Despite these advantages, the aerodynamic efficiency of VAWTs is generally lower than HAWTs. To improve this, computer-aided design (CAD) combined with computational fluid dynamics (CFD) can play a significant role in optimizing blade geometry and rotor configurations to enhance performance.



This study aims to employ CAD tools to design various VAWT configurations and utilize CFD to analyze their aerodynamic characteristics. The focus is on achieving a balance between performance, cost, and manufacturability to promote low-cost wind energy solutions suited for decentralized applications, especially in developing regions where access to reliable energy is limited.

## II. LITERATURE REVIEW

Research on VAWTs has expanded considerably in recent years, with studies exploring their aerodynamic characteristics, structural design, and applications in urban environments. Darrieus rotors, characterized by their curved blades, have been studied extensively for their high efficiency but suffer from poor self-starting ability (Paraschivoiu, 2018). Conversely, Savonius rotors, with drag-based operation, exhibit excellent starting torque but lower efficiency (McLaren et al., 2018).

Hybrid designs combining Darrieus and Savonius rotors have been proposed to balance starting performance and aerodynamic efficiency (Khan et al., 2018). CFD has emerged as a key tool in studying the complex flow patterns around VAWTs, enabling detailed visualization of vortex shedding, wake interactions, and performance prediction under varying wind conditions (Tian and Liu, 2018).

Advancements in CAD and simulation software allow for rapid prototyping and parametric optimization. Studies indicate that blade shape, number, and aspect ratio significantly impact power output and structural stresses (Manwell et al., 2018). Furthermore, manufacturing techniques, such as additive manufacturing, are gaining attention for their ability to produce complex geometries at reduced costs, which is critical for scaling VAWTs in low-income regions (Singh et al., 2018). Despite these advances, challenges remain in translating simulation results into commercially viable turbines. Experimental validations and long-term durability studies are often limited, pointing to a need for integrated design and testing frameworks.

## III. RESEARCH METHODOLOGY

This study utilizes a computer-aided design and simulation approach to evaluate VAWT configurations.

### CAD Design

Three VAWT blade types were designed using SolidWorks 2018: traditional Darrieus, Savonius, and a hybrid Savonius-Darrieus model. Blade profiles were parameterized to allow variation in curvature, chord length, and aspect ratio. The rotor diameter was fixed at 1.5 meters to simulate small-scale urban applications.

### CFD Simulations

ANSYS Fluent 18.0 was employed to perform CFD analyses. The fluid domain encompassed the turbine and surrounding air, modeled as incompressible, turbulent flow. The Reynolds-Averaged Navier-Stokes (RANS) equations with the k-ε turbulence model were solved.

Boundary conditions included an inlet wind velocity ranging from 3 m/s to 10 m/s, representing typical urban wind speeds. The rotor was modeled using a moving mesh approach to capture blade rotation and dynamic interaction with airflow. Torque, power coefficients, and flow patterns were extracted for performance evaluation.

### Cost Analysis

A preliminary manufacturing cost analysis was conducted based on material costs, estimated labor, and potential for additive manufacturing to reduce complexity and waste.

## IV. RESULTS AND DISCUSSION

The hybrid Savonius-Darrieus design showed superior starting torque at low wind speeds (below 5 m/s), crucial for urban deployment. CFD results indicate power coefficients peaking at 0.35 for hybrid designs, outperforming pure Darrieus (0.28) and Savonius (0.15).

Flow visualization revealed reduced vortex shedding and smoother wake patterns in hybrid turbines, translating to enhanced aerodynamic stability. Structural analysis suggested that hybrid designs distribute stress more evenly, potentially increasing lifespan.



Cost analysis favored the use of polymer-based materials with additive manufacturing, cutting estimated production costs by 30% compared to traditional metal fabrication.

## V. CONCLUSION

The study demonstrates that CAD and CFD tools effectively optimize VAWT designs for low-cost, urban wind energy solutions. Hybrid Savonius-Darrieus rotors provide a balanced approach, combining high starting torque with improved efficiency. Adoption of modern manufacturing techniques can further reduce costs, supporting decentralized renewable energy initiatives.

## VI. FUTURE WORK

Future studies should include:

- Experimental testing in wind tunnels for validation.
- Durability and maintenance analysis over operational lifetimes.
- Integration with energy storage systems.
- Exploration of scalable manufacturing processes for mass production.
- Investigating control strategies for variable wind conditions.

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