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(RESEARCH ARTICLE)

Aerodynamic Optimization and Cost-Benefit Analysis of Savonius-Darrieus Hybrid Wind Turbines for Rural Mozambique

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Abstract

This study presents the simulation and optimization of a hybrid vertical axis wind turbine (VAWT), combining Savonius and Darrieus wind turbine configurations, tailored for low wind conditions in Mozambique, specifically in Tete Province. Advanced tools such as Fusion 360, ANSYS Fluent, QBlade, XFOIL, Xoptfoil, and Python were used for 3D modeling, CFD simulations, and aerodynamic optimization. Three NACA profiles (0018, 4415, and 63-415) were analyzed, with NACA 63-415 showing the highest lift coefficient (CL) and the most favorable lift-to-drag ratio (CL/CD). Optimization identified an ideal angle of attack of 8°, and the Darrieus rotor with four blades operating at a tip speed ratio (TSR) of 2.0 achieved a power coefficient (Cp) of approximately 0.45. The hybrid turbine demonstrated efficient performance, with the Savonius rotor providing startup torque and the Darrieus rotor ensuring sustained energy conversion. A Python-based computational model was developed to automate turbine configuration based on regional wind data. The economic analysis estimated a total construction cost of 92,700 MZN, annual maintenance of 5,400 MZN, and annual amortization of 9,270 MZN, resulting in a cumulative 15-year cost of 220,050 MZN, compared to 1,165,500 MZN for a diesel pump system. The results indicate that the hybrid turbine is a technically and economically viable solution for rural and peri-urban communities in Mozambique.

Keywords: Low Wind Speed; Savonius-Darrieus Configuration; CFD Simulation; Economic Feasibility

1. Introduction

The global energy transition towards renewable sources has become a strategic priority, driven by increasing concerns over climate change, the depletion of fossil fuels, and the need to promote sustainable development [1,2]. Among the various renewable options, wind energy stands out due to its cleanliness, abundance, and low environmental impact.

Traditionally, wind energy conversion is achieved through Horizontal Axis Wind Turbines (HAWTs), which perform efficiently in regions with strong and consistent winds. However, these systems face significant limitations in areas with low wind speeds and variable direction conditions commonly found in rural and urban zones of developing countries [3].

Vertical Axis Wind Turbines (VAWTs) emerge as a viable alternative in such contexts. They operate effectively under low-intensity and unstable wind conditions and offer advantages in terms of maintenance, compact installation, and integration into urban environments. Among the most studied VAWT types are the Darrieus turbines, known for their aerodynamic efficiency, and the Savonius turbines, valued for their simplicity and self-starting capability.

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The hybrid configuration combining Savonius and Darrieus rotors has gained attention for merging the strengths of both systems: the Savonius rotor provides the initial torque required for startup, while the Darrieus rotor ensures efficient energy conversion once in motion. This approach is particularly relevant in regions like Mozambique, where low wind speeds coexist with urgent energy needs[4].

Despite technological advances, there remains a significant gap in the modeling and optimization of hybrid turbines for real-world low-wind conditions. Understanding aerodynamic behavior, evaluating blade geometries, and developing robust computational simulations are essential steps toward decentralized, sustainable, and accessible energy solutions.

This study contributes to that effort by developing and optimizing a computational model of a hybrid vertical axis wind turbine tailored for low wind conditions, with a specific focus on Mozambique. The research aims to validate the aerodynamic performance of the hybrid Savonius-Darrieus configuration and provide technical foundations for its application in rural and urban communities.

2. Material and methods

2.1. Research Design

This study adopted a quantitative, exploratory, and computational approach, aiming to develop and optimize a hybrid vertical axis wind turbine (VAWT) composed of Savonius and Darrieus configurations. The research focused on 3D modeling, computational fluid dynamics (CFD) simulations, and aerodynamic profile optimization for efficient operation under low wind speed conditions, particularly in regions such as Tete Province, Mozambique.

2.2. Tools and Software

To ensure precision in modeling and simulation, the following tools were employed:

- Fusion 360: For 3D modeling of turbine geometries [5].
- ANSYS Fluent: For advanced CFD simulations, analyzing flow behavior, pressure distribution, and aerodynamic forces [6].
- QBlade: For calculating lift (CL) and drag (CD) coefficients of NACA profiles under varying wind speeds and angles of attack [7].
- XFOIL and Xoptfoil: For aerodynamic profile analysis and optimization, especially under low Reynolds number conditions [8].
- Python: For data processing and development of scripts to automate turbine configuration based on regional wind data [9].
- Microsoft Excel: For organizing simulation data and generating performance tables and graphs[10].

2.3. Aerodynamic Profile Selection

Three NACA profiles were analyzed: 0018, 4415, and 63-415, selected based on their documented performance under low Reynolds numbers[11]. The selection was guided by theoretical efficiency, structural simplicity, and suitability for small-scale wind turbines [12].

2.4. CFD Simulation Setup

- Computational Domain: A two-dimensional rectangular domain with dimensions of 15C × 5C (C = chord length).
- Mesh: Triangular mesh refined near blade surfaces, with inflation layers to capture boundary layer effects.
- Turbulence Model: SST k-ω, suitable for low-speed flows and accurate prediction of flow separation [13].
- Boundary Conditions:
- Inlet: Constant wind velocity of 3.66 m/s.
- Outlet: Zero static pressure.
- Blade surfaces: No-slip wall with rotational motion.
- Domain walls: Symmetry condition.

2.5. Optimization Parameters

The optimization process considered the following variables:

- Angle of Attack: Varied between 0° and 15° to identify the point of maximum aerodynamic efficiency.
- Tip Speed Ratio (TSR): Evaluated within the range of 0.5 to 3.0.
- Number of Blades: Configurations with 2, 3, and 4 blades were modeled for comparative analysis.
- Blade Geometry: Adjusted based on simulation feedback and operational stability criteria.

2.6. Economic Feasibility Assessment

To evaluate the practical viability of the proposed hybrid wind turbine system, an economic feasibility study was conducted. This analysis aimed to compare the total cost of implementing the hybrid turbine system with conventional diesel-powered water pumping systems commonly used in rural Mozambique[14].

The assessment included:

- Component Cost Estimation: Identification and pricing of all materials required for turbine construction, including blades, shaft, connectors, and mechanical pump.
- Operation and Maintenance Costs: Estimation of annual maintenance expenses based on inspection frequency, lubrication, and part replacement.
- Investment Amortization: Calculation of annual amortization over a 10-year lifespan.
- Comparative Cost Analysis: Long-term cost comparison between the hybrid turbine and a diesel pump, considering fuel consumption, maintenance, and cumulative expenses over 15 years.
- Data Sources: Local market prices, technical specifications from suppliers, and operational benchmarks from similar systems.
- This subsection complements the technical modeling by providing a financial perspective, essential for assessing the system's sustainability and scalability in low-income communities.

2.7. Validation Region

The Province of Tete, Mozambique, was selected as the critical validation region due to its low average wind speed (≈3.66 m/s) and deep-water table, which demands higher pumping power. Environmental data were sourced from institutional reports, including the National Institute of Meteorology (INAM)[15] and the Ministry of Public Works.

3. Results

3.1. Aerodynamic Profile Comparison and Selection

Three NACA profiles—0018, 4415, and 63-415—were simulated under low Reynolds number conditions. The NACA 63-415 profile showed the highest lift coefficient (CL) and the most favorable lift-to-drag ratio (CL/CD), making it the most suitable for low-speed wind applications [16] as shown in Figure 1.

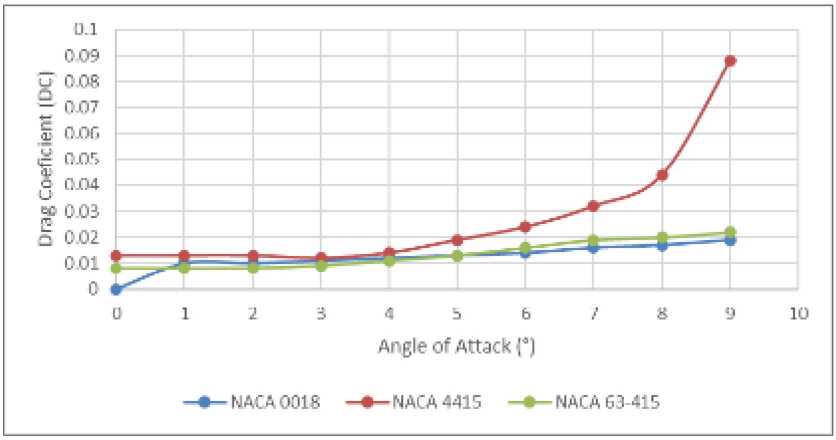

Figure 1 Drag Coefficient VS Angle of Attack Graph

As the NACA 63-415 showed stable behavior with low drag, a desirable characteristic to improve the efficiency of the Darrieus turbine, it was optimized.

3.2. Profile Optimization and Angle of Attack

Using Xoptfoil and CFD simulations, the NACA 63-415 profile was optimized. The optimal angle of attack was 8°, corresponding to peak aerodynamic efficiency, validated through regression analysis and CL/CD curve interpretation (Figure 2).

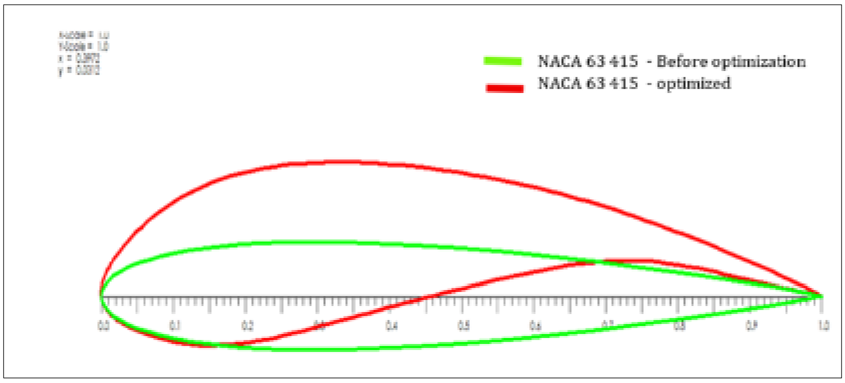

Figure 2 Angle of Attack optimization

The optimization reduces drag by refining the airfoil's geometry to improve airflow. In the case of the NACA 63-415, minor changes in curvature and thickness along the chord will help maintain laminar flow for longer, preventing early flow separation and reducing turbulence. This leads to lower aerodynamic resistance and enhances the airfoil's efficiency.

3.3. Darrieus Rotor Performance

Simulations were conducted for rotor configurations with 2, 3, and 4 blades, varying the Tip Speed Ratio (TSR) from 0.5 to 2.5. The 4-blade configuration at TSR ≈ 2 achieved the best performance, with a power coefficient (Cp) ≈ 0.45 and stable torque generation [17].

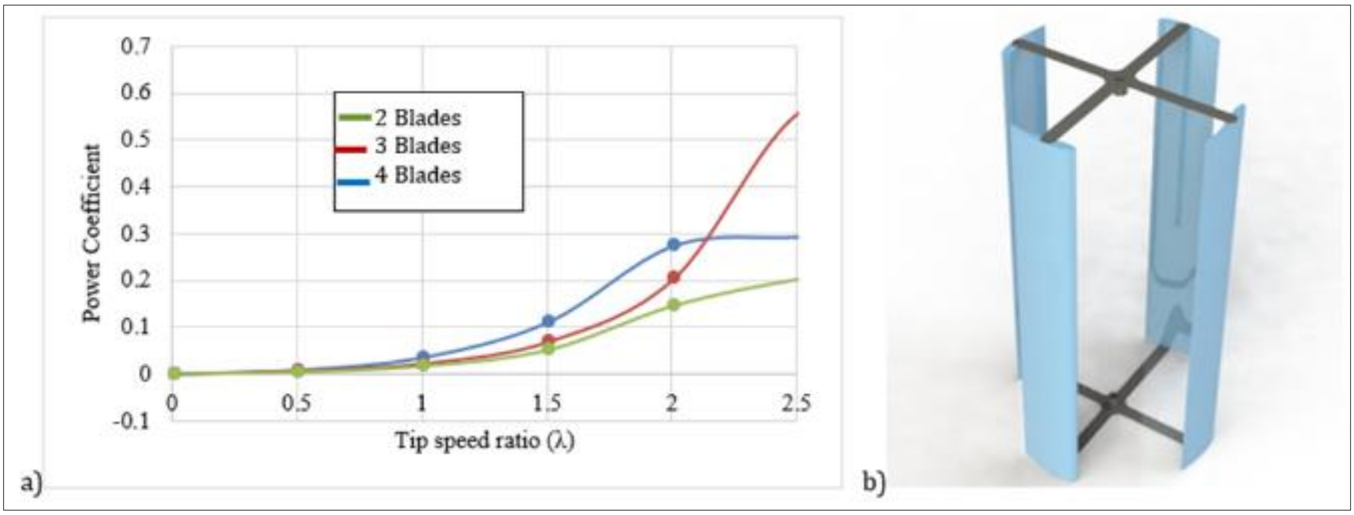

Figure 3 a) Analysis of the number of Darrieus rotor blades b) Darrieus rotor with four blades

3.4. Savonius Rotor Analysis

The Savonius rotor was evaluated for its starting torque capability. CFD simulations revealed significant pressure differentials between the concave and convex blade surfaces, confirming its effectiveness in initiating rotation under low wind speeds as illustrate the figure 3. [18].

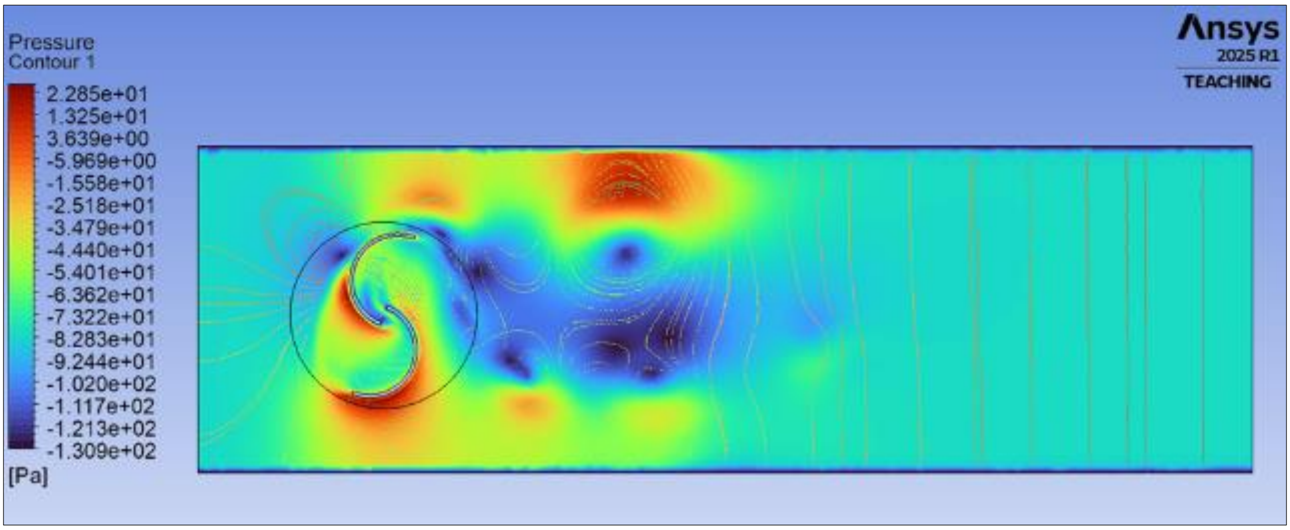

Figure 4 Pressure distribution along the Savonius turbine

Figure 4 it illustrates how pressure is distributed across the domain, with values ranging from approximately −130.9 Pa (dark blue, low pressure) to 22.85 Pa (red, high pressure). The circular region on the left shows significant pressure variation, indicating an obstacle or boundary condition affecting the flow.

3.5. Hybrid Turbine Integration

The hybrid configuration combined the Savonius rotor (inner) and the Darrieus rotor (outer) on a shared vertical axis. CFD simulations confirmed that the Savonius rotor provides the initial torque for startup, while the Darrieus rotor ensures efficient energy conversion during sustained operation [19].

3.6. Pressure and Velocity Distribution

CFD visualizations comparing optimized and non-optimized profiles showed improved flow behavior in the optimized case, with smoother acceleration, reduced flow separation, and higher lift generation (Figure 5).

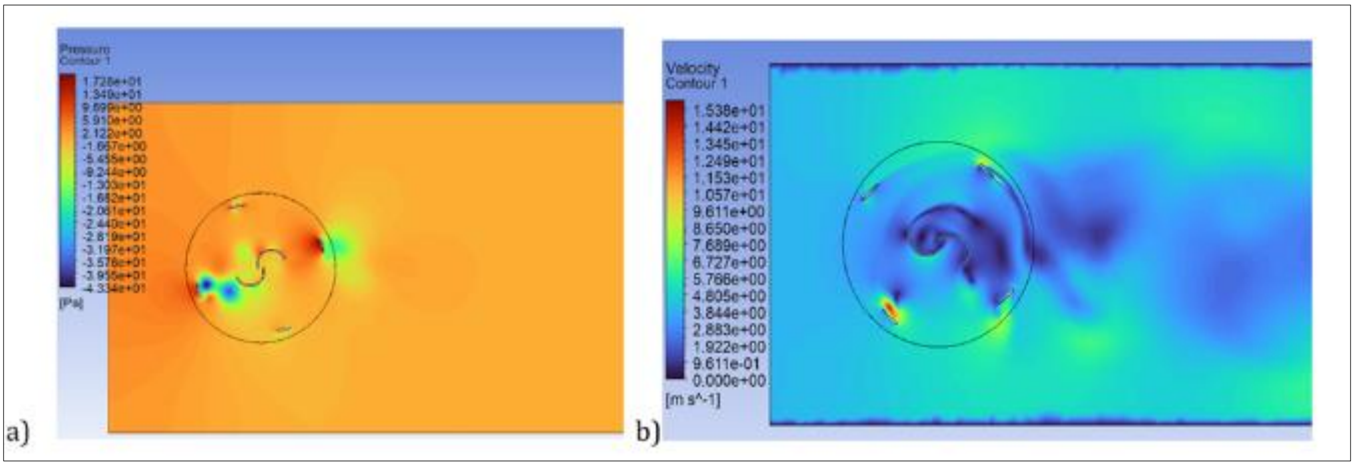

Figure 5 Static pressure and velocity distribution in the turbine

Figure 5 illustrates the combined action of Savonius and Darrieus rotors in the flow field around the hybrid turbine. The strategically placed Savonius rotor generates a localized low-pressure region that facilitates the system's startup, while the Darrieus rotor begins to develop stronger acceleration zones as angular velocity increases. The velocity distribution confirms that, after the initial boost from Savonius, the flow reorganizes and acts more efficiently on the Darrieus blades.

3.7. Python-Based Computational Model

A Python-based model was developed to automate turbine configuration based on regional wind data and desired output power. The model provides recommended dimensions and parameters for both rotors, enabling rapid adaptation across Mozambique's provinces the summary of results is presented in figure 6 below. [20].

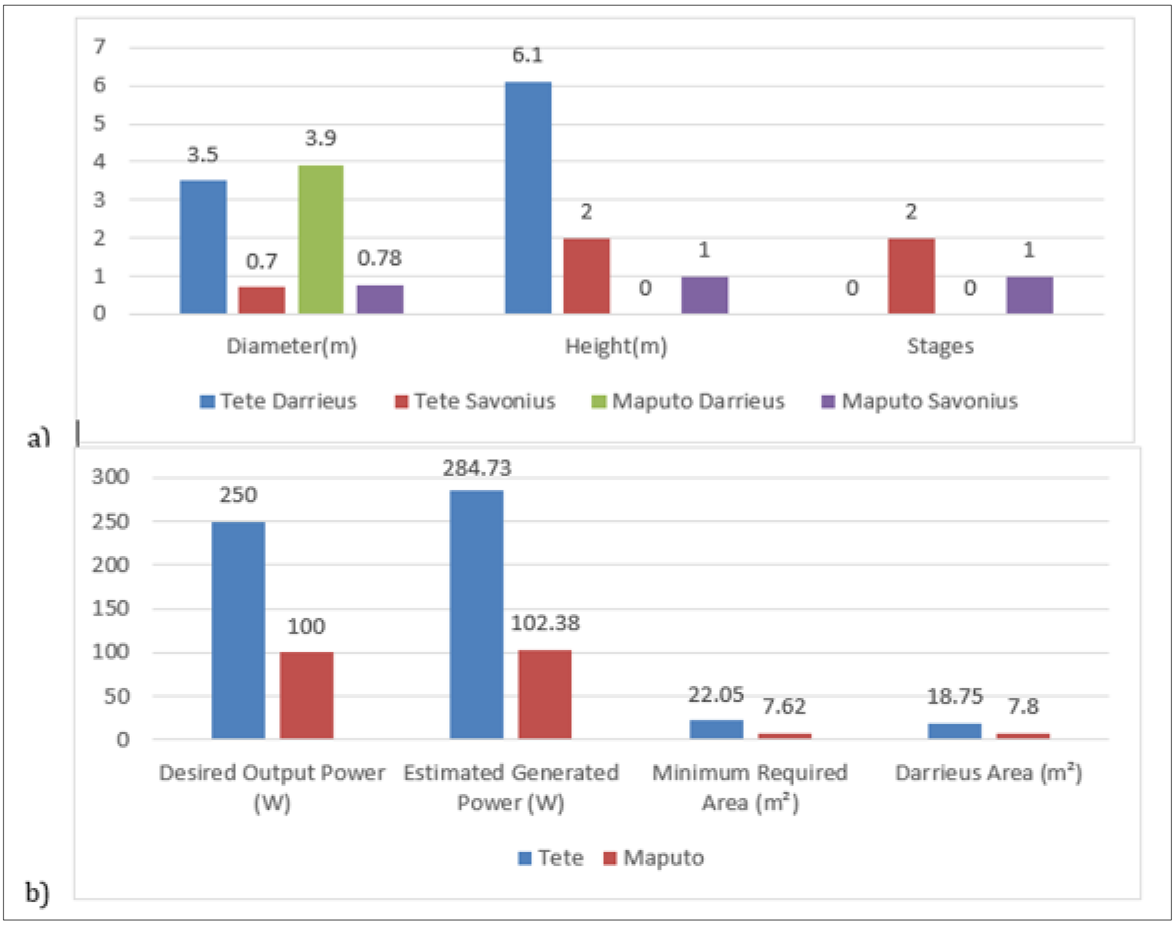

Figure 6 a) Rotor Dimensions of Hybrid Wind Turbines in Tete and Maputo and b) Comparative Analysis of Power and Area Requirements for Hybrid Wind Turbines in Tete and Maputo

3.8. Economic Feasibility

The total estimated cost for constructing the hybrid turbine system was 92,700 MZN, with annual maintenance costs of 5,400 MZN. Annual amortization is 9,270 MZN, resulting in a total annual cost of 14,670 MZN. Over 15 years, the cumulative cost is 220,050 MZN, compared to 1,165,500 MZN for a diesel pump system [14].

4. Discussion

The aerodynamic superiority of the NACA 63-415 profile aligns with findings by Erkan and Özkan [16], who highlighted its performance under low Reynolds conditions.

The Darrieus rotor configuration with 4 blades and TSR ≈ 2 confirms the results of Meziane et al. [17], who identified similar setups as optimal for hybrid turbines.

The Savonius rotor's torque generation is consistent with the CFD analysis by Michna and Rogowski [18], emphasizing the role of pressure differentials in startup performance.

The enhanced discussion highlights how the hybrid integration strategy aligns with El-Nenaey et al. [19], reinforcing the complementary roles of Savonius and Darrieus rotors. The Savonius rotor, positioned to exploit low wind conditions, initiates rotation by generating localized low-pressure zones. As angular velocity increases, the Darrieus rotor progressively takes over, benefiting from reorganized flow and developing efficient acceleration zones. This transition is consistent with Paraschivoiu (2002) and Saha et al. (2008), who emphasize Savonius's role in torque generation at low wind speeds and Darrieus's dominance in energy conversion. The pressure and velocity contours visually validate this synergy, confirming that Savonius ensures reliable self-starting while Darrieus maximizes aerodynamic performance during sustained operation.

The Python-based model reflects the parametric modeling approach proposed by Saint-Drenan et al. [20], supporting turbine adaptation to environmental conditions.

Finally, the economic feasibility results reinforce the conclusions of Macamo et al. [14], demonstrating the long-term cost-effectiveness of hybrid wind systems in rural Mozambique.

4.1. Study Limitations

The study was limited to 2D simulations, excluding full 3D effects such as tip vortices. No experimental validation was conducted, and wind conditions were assumed to be steady and laminar. These simplifications may affect real-world applicability but provide a solid foundation for future prototyping and field testing.

5. Conclusion

This study developed and refined a computational model for a hybrid vertical axis wind turbine (VAWT) engineered to perform efficiently in areas characterized by low wind speeds, such as Tete Province, Mozambique. The hybrid design, incorporating both Savonius and Darrieus rotors, has been demonstrated to offer a technically sound solution for decentralized water pumping applications within rural and peri-urban communities.

Aerodynamic analysis identified the NACA 63-415 profile as optimal for operation under low Reynolds number conditions. Further optimization at an attack angle of 8° led to significant enhancements in lift generation and overall system efficiency. The Darrieus rotor, configured with four blades and operating at a tip speed ratio (TSR) of 2, achieved notable power output and rotational stability, whilst the Savonius rotor ensured consistent starting torque, facilitating autonomous functionality even during periods of weak wind.

The integration of both rotors into a hybrid system was substantiated through CFD simulations, which verified the complementary performance of each rotor across distinct operational phases. Moreover, the implementation of a Python-based computational tool facilitated automated turbine configuration, calibrated to regional wind profiles, and required power output, thereby improving both adaptability and scalability.

From an economic perspective, the hybrid turbine presents a cost-effective alternative to diesel-powered pumps, reducing long-term operational expenditures and eliminating reliance on fuel. This innovation supports sustainable development objectives by increasing access to renewable energy, minimizing environmental impact, and fostering local technological advancement.

Recommendations

For future work and practical implementation, the following recommendations are proposed:

- Prototype Development and Field Testing. Construct and test physical prototypes of the hybrid turbine to validate simulation results and assess real-world performance under variable wind conditions.
- Dynamic Control Systems. Integrate mechanical or electronic systems to decouple the Savonius rotor once optimal TSR is reached, minimizing drag and maximizing Darrieus efficiency.
- Adaptive Blade Pitch Mechanism. Develop a pitch control system to dynamically adjust blade angles based on wind speed, improving performance across a wider range of conditions.
- 3D CFD Simulations. Extend the numerical analysis to three-dimensional simulations to capture complex flow phenomena such as tip vortices and inter-blade interactions.
- Economic Scaling Models. Explore cost-reduction strategies for mass production and community-level deployment, including modular designs and use of locally sourced materials.
- Integration with Smart Monitoring Systems. Equip the turbine with sensors and IoT-based monitoring tools to track performance, predict maintenance needs, and optimize energy output.

These recommendations aim to improve the design and practical use of the hybrid wind turbine. Building and testing prototypes will help confirm simulation results. Adding control systems and adjustable blades can boost efficiency. Using 3D simulations will give better insights into airflow. Cost-saving strategies and smart monitoring tools will support wider use, especially in rural areas where clean energy is most needed.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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