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Optimizing vertical-axis wind turbine designs: A comparative CFD analysis of savonius, darrieus, and savonius-darrieus configurations

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Abstract: This study aims to evaluate the performance of vertical-axis wind turbines (VAWTs) with three different configurations, including Savonius, Darrieus, and a Savonius-Darrieus hybrid wind turbine, using Computational Fluid Dynamics (CFD) simulations. The methodology involves 3D geometry modeling, simulation parameter setup, meshing, and post-simulation analysis using SolidWorks 2022 software. The simulation results indicate that the Savonius turbine achieves the highest power coefficient (C_p) and torque coefficient (C_t) among the three designs, with a maximum C_p value of 0.5 at a Tip-Speed Ratio (TSR) of 0.4. Conversely, the hybrid turbine demonstrates lower efficiency, although it theoretically offers potential for improving performance at low wind speeds. Pressure and flow velocity distributions reveal that the Savonius turbine maintains the most stable pressure pattern compared to the other configurations. These findings highlight the potential of the Savonius turbine as a small-scale renewable energy solution, particularly in urban areas with low wind speeds. Further research is recommended to optimize hybrid turbine designs using machine learning approaches and empirical validation through field experiments to support the achievement of Sustainable Development Goals (SDGs), particularly Goal 7, affordable and clean energy.

Keywords: renewable energy; aerodynamic efficiency; power coefficient; vertical axis wind turbine; computational fluid dynamics

1. Introduction

Since the turn of the century, global warming has emerged as a critical environmental challenge, leading to increasingly severe natural disasters such as droughts, extreme temperatures, heavy rainfall, and hurricanes [1], [2], [3]. Data from the Japan Meteorological Agency (JMA) covering 1990-2020 indicate a concerning trend, showing that global average temperatures have increased by more than 2°C over the past 120 years, accompanied by a significant rise in the number of days with temperatures exceeding 35°C [1], [2], [3]. This temperature rise is primarily attributed to the increased greenhouse gas emissions, including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), resulting from extensive dependence on non-renewable energy sources such as fossil fuels.

The extraction, processing, and combustion of fossil fuels contribute significantly to CO_2 and methane emissions, intensifying the greenhouse effect and accelerating global warming [4], [5]. The consequences of climate change, such as polar ice melt, rising sea levels, and extreme weather events, highlight the urgency of transitioning toward renewable energy sources, including solar, wind, and hydropower. Aligned with this need, Sustainable Development Goal (SDG) 7, set by the United Nations, underscores the importance of developing accessible, affordable, and clean energy systems [6], [7], [8], [9]. Wind energy, in particular, has gained attention as a promising renewable resource capable of reducing greenhouse gas emissions [10], [11], [12]. Wind turbines are generally categorized based on rotor orientation into horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). Although HAWTs are widely adopted due to their high aerodynamic efficiency, VAWTs offer distinct advantages for small-scale power generation in complex or low-wind environments, particularly urban areas where wind speed is relatively low and unstable (3-20 m/s) and turbine dimensions typically range from 1-10 m [13].

This study addresses the performance limitations of VAWTs by evaluating three turbine designs: Savonius, Darrieus, and a Savonius-Darrieus hybrid configuration. Performance assessment focuses on two key parameters, the power coefficient (C_p) and torque coefficient (C_t). By employing detailed computational modelling and CFD simulation, this research aims to identify the configuration with optimum aerodynamic performance. By integrating Savonius and Darrieus rotor characteristics, this study introduces a hybrid configuration designed to enhance wind energy harvesting under low-speed conditions. This approach is expected to yield higher turbine efficiency and improved power capture in low-wind environments, while also providing a design with scalability potential for sustainable urban energy deployment, bringing an innovative hybrid approach, integrating Savonius and Darrieus designs to optimize turbine performance at low wind speeds. Anticipated outcomes include enhanced efficiency, cost-effectiveness, and increased environmental benefits, facilitating greater accessibility and widespread use of clean energy solutions, particularly in urban and low-wind regions. Employing detailed computational modeling and simulations, this research aims to identify the most effective turbine configuration suitable for broad application in renewable energy initiatives supporting SDGs.

2. Material and methods

This research utilized Computational Fluid Dynamics (CFD) to analyze the performance of vertical-axis wind turbines (VAWT), specifically a hybrid design combining Savonius and Darrieus turbines [14], [15], [16], using SolidWorks 2022 Research License software.

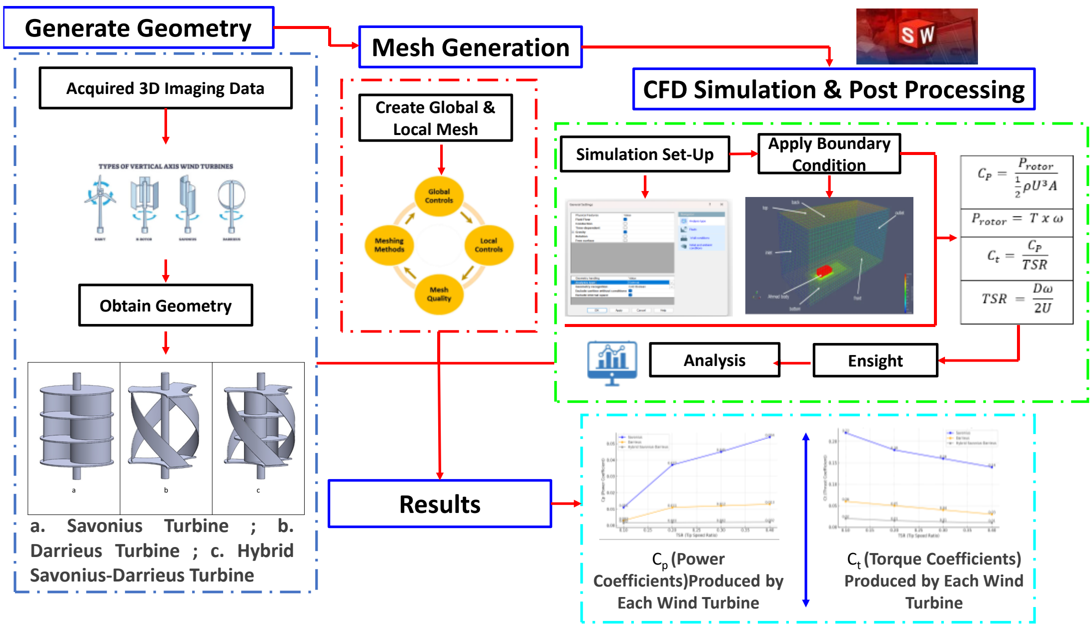


Figure 1. Flow diagram of the research process

Figure 1 describes the computational fluid dynamics (CFD) simulation process, which is divided into three main stages. The first step is geometry modeling, where the user created a 3D model of the object to be analyzed. The second step is simulation setup, where, after the geometry model was completed, the simulation parameters such as fluid properties, boundary conditions, and other configurations (like the solver type) were defined. This stage also involves meshing, where the geometry was divided into smaller elements for numerical simulation. The last step is flow simulation and post-processing. After the simulation, the results were analyzed through data visualization to examine flow patterns, velocity distributions, and other relevant parameters. Post-processing allows the user to understand how the fluid behaves within the modeled geometry and evaluate the performance of the design [17]. These steps are interconnected, beginning with geometry modeling and culminating in analyzing the simulation results to provide deeper insights into the system being studied.

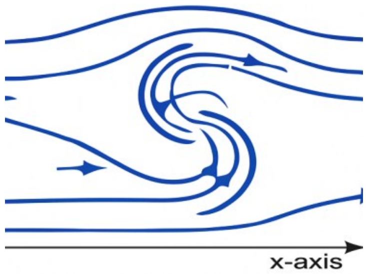


Figure 2. Wind turbine operating principle

The working principle of the wind turbine begins with the velocity of the wind in the x-direction (fluid flow direction). As the wind hits the turbine blades, it causes the turbine to rotate and generate torque, as shown in Figure 2. The efficiency of the Savonius, Darrieus, and the Savonius-Darrieus hybrid wind turbines were evaluated through a comparison of the Power Coefficient (C_p), calculated using Equation (1) [18]. This Equation relates the energy produced and the available power:

$$C_P = \frac{P_{rotor}}{\frac{1}{2}\rho U^3 A} \quad (1)$$

P_{rotor} is the turbine power, ρ is the fluid density, AAA is the turbine's swept area, ω is the angular velocity, and U is the fluid velocity. The torque P_{rotor} is given by:

$$P_{rotor} = T\ x\ \omega \quad (2)$$

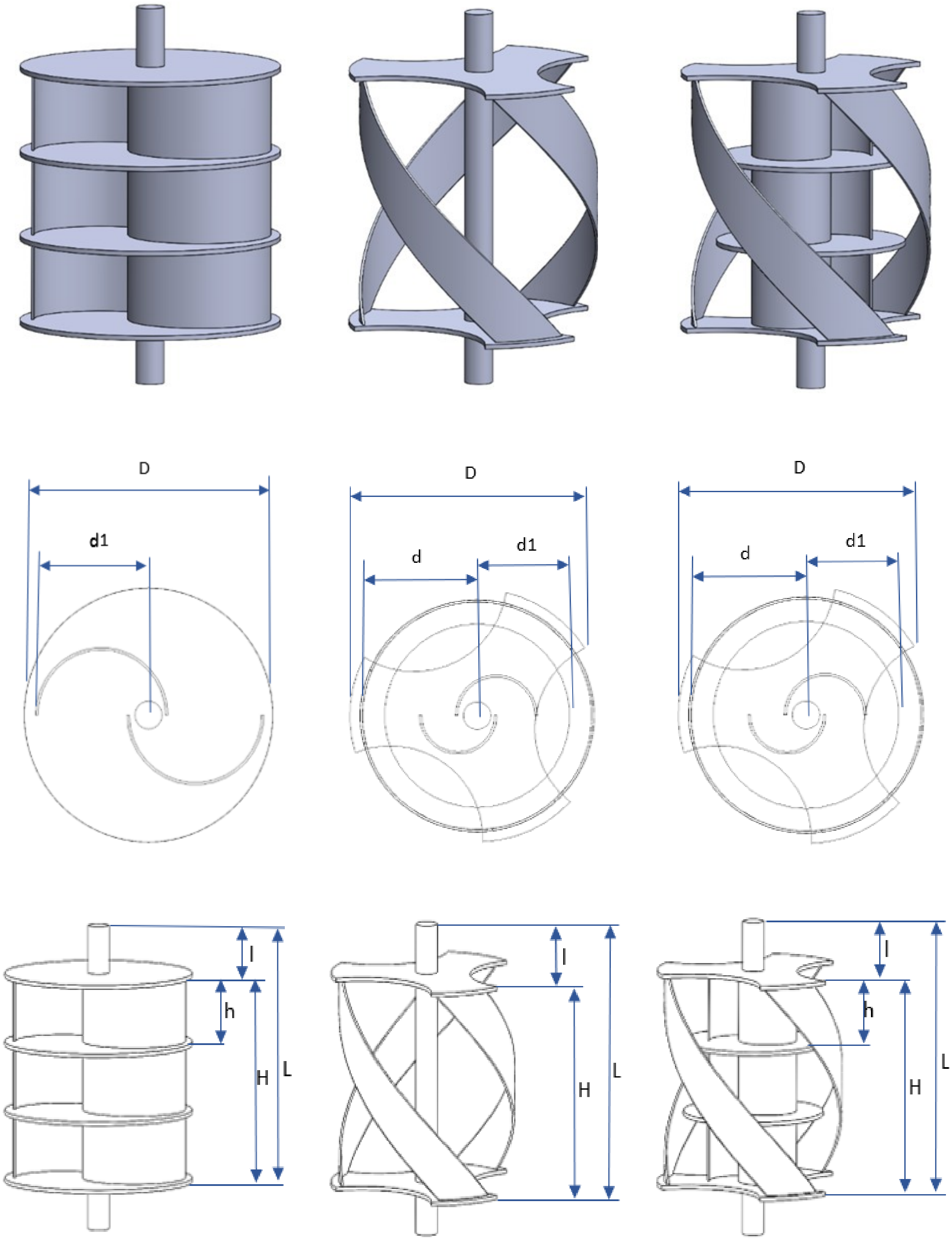
Another key parameter is the Torque Coefficient $C_{t,}$ which is influenced by the interaction between the Tip-Speed Ratio (TSR) and C_p, as shown in Equation (3) and TSR in Equation (4), where D is the turbine diameter.

$$C_t = \frac{C_P}{TSR} \quad (3)$$

$$TSR = \frac{D\omega}{2U} \quad (4)$$

2.1 Model geometry

This study uses three Vertical Axis Wind Turbines (VAWT) variations: Savonius, Darrieus, and the Savonius-Darrieus hybrid turbines. Modifications involve combining Savonius and Darrieus turbines. The Savonius turbine is designed with a three-stage rotor, as the best performance is achieved with a three-blade rotor in conventional designs [19]. The 3D model of the Darrieus turbine is adjusted to match the dimensions of the Savonius turbine. The Darrieus turbine is chosen for its simplicity in blade construction and lower sensitivity to turbulence, though it is more sensitive to wind direction [20]. The Savonius-Darrieus hybrid turbine combines both designs, resulting in a dual-turbine system, as shown in Figure 3.



(a) (b) (c)

Figure 3. Geometry of the three wind turbine variations. a) Savonius, b) Darrieus, c) Savonius-darrieus hybrid

Table 1. Dimensions of the three wind turbine variations

Parameter	Savonius (mm)	Darrieus (mm)	Savonius-Darrieus hybrid (mm)
D	110	110	110
d1	50	-	40
d	-	50	-
L	135	135	135
l	25	25	25
H	110	110	110
h	34	-	34
T	2	2	2

2.2 Simulation setup

The simulation parameters of air as the fluid and wind speeds ranging from 0.7 m/s to 1 m/s is presented in Table 2. The analysis type is external flow, with a focus on fluid dynamics.

Table 2. Simulation parameter conditions

Analysis type	External
Gravity	-9.81 m/s²
Flow analysis type	Fluid Flow
Fluids	Air (gases)
Velocity parameters	Inlet, Outlet
Boundary conditions	Total Pressure, Velocity x, Torque y, Density (Air)

A stationary domain was selected for the computational domain. The stationary domain is a static area in the model, where boundary conditions are defined [18]. The wind enters from the wind inlet, and the outlet is defined as the pressure outlet. The dimensions of the stationary domain by $0.535 \times 0.240 \times 0.215\ m$ connect the rotary and stationary with the overall schematic layout. The walls are defined as no-slip walls, as shown in Figure 4.

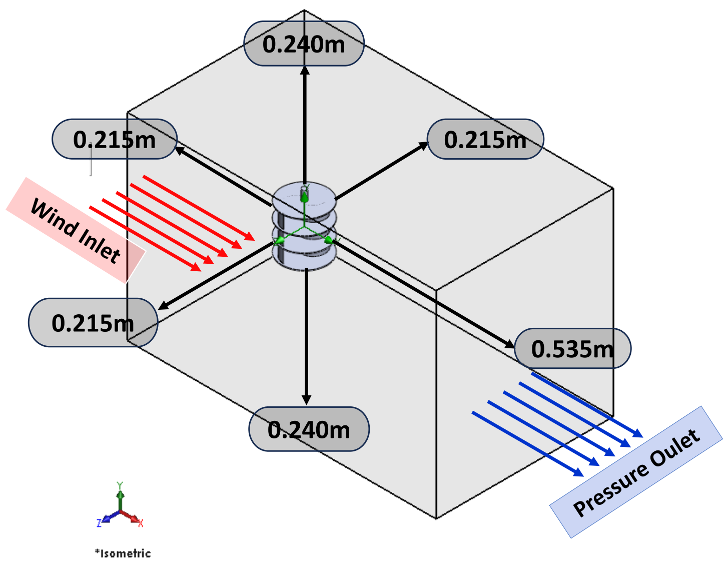


Figure 4. Stationary domain

Determining the type of mesh and mesh density plays a crucial role in a simulation, as the mesh is an essential part of the simulation process. A good mesh affects the calculation results of a simulation [21]. An independent mesh study is also necessary to achieve optimal computation time and satisfactory results, with an estimated time, which may be affected by adding cells, as shown in Figure 5. The most effective number of elements is 1,883,498, without significant changes in torque [19]. In this study, the number of meshes used, with a total of 2.8 million cells, brings the simulation results closer to the actual results.

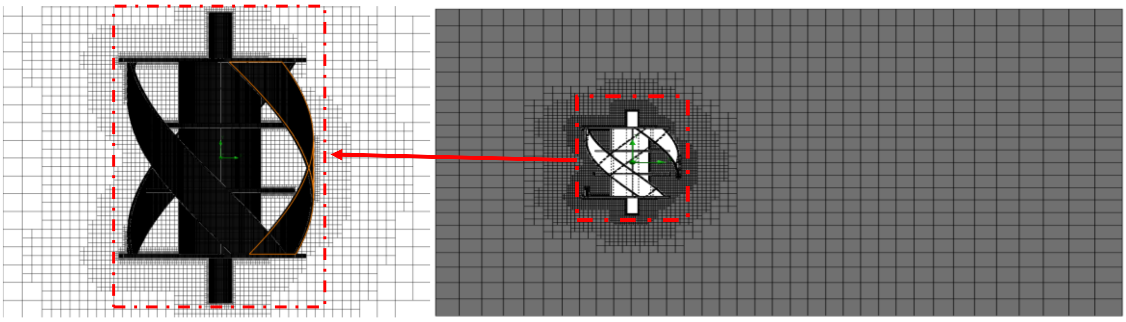


Figure 5. Meshing details for CFD simulation

3. Results

The CFD modeling of the Savonius, Darrieus, and Savonius-Darrieus hybrid wind turbines produced several outputs, including torque values, pressure contours, and velocity contours. Equations 1 and 3 subsequently converted these torque values into aerodynamic performance. Comparative graphs of the three turbines are presented in Figures 6 and 7. Figure 6 shows the Power Coefficient (C_p), while Figure 8 displays the Torque Coefficient (C_t) for all three wind turbines. The simulation results indicate that the maximum C_p (Cp_max) for the Savonius wind turbine occurs at a TSR of 0.4, with a value of 0.5. For the Darrieus and the Savonius-Darrieus hybrid wind turbines, C_p_max values are 0.002 and 0.013, respectively, at a TSR of 0.4. The Savonius wind turbine exhibits the highest Cp_max among the three models, indicating superior aerodynamic efficiency.

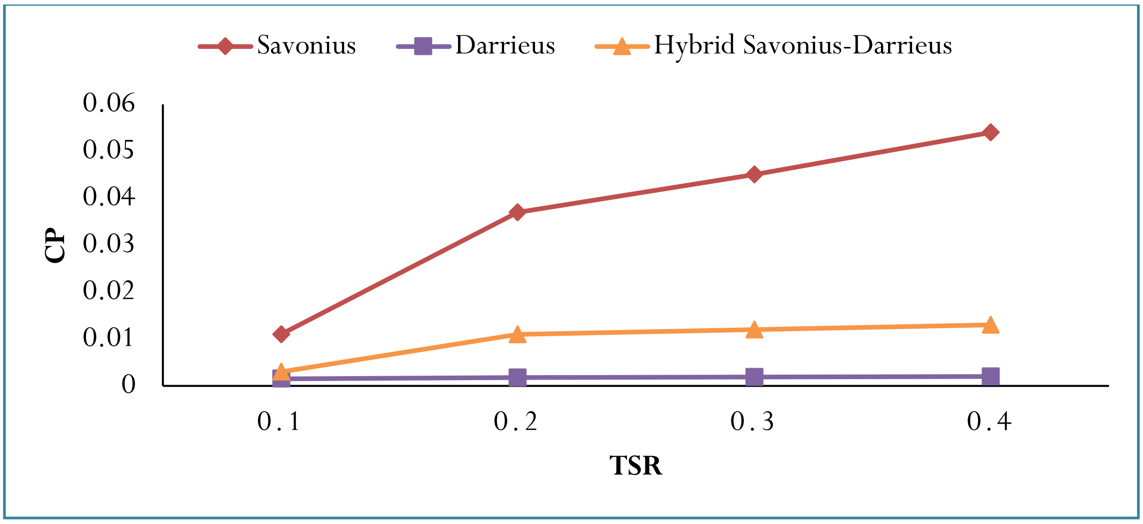


Figure 6. Power coefficients produced by each wind turbine

Another performance metric, the Torque Coefficient (C_t), consistently decreased across all three turbines. The highest Ct_max was observed for the Savonius wind turbine, with a value of 0.2,

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followed by the Darrieus wind turbine at 0.01 and the Savonius-Darrieus hybrid wind turbine at 0.06. The torque produced by all three turbines remained efficient at all four wind speeds. Notably, the Savonius wind turbine also generated the highest torque among the three.

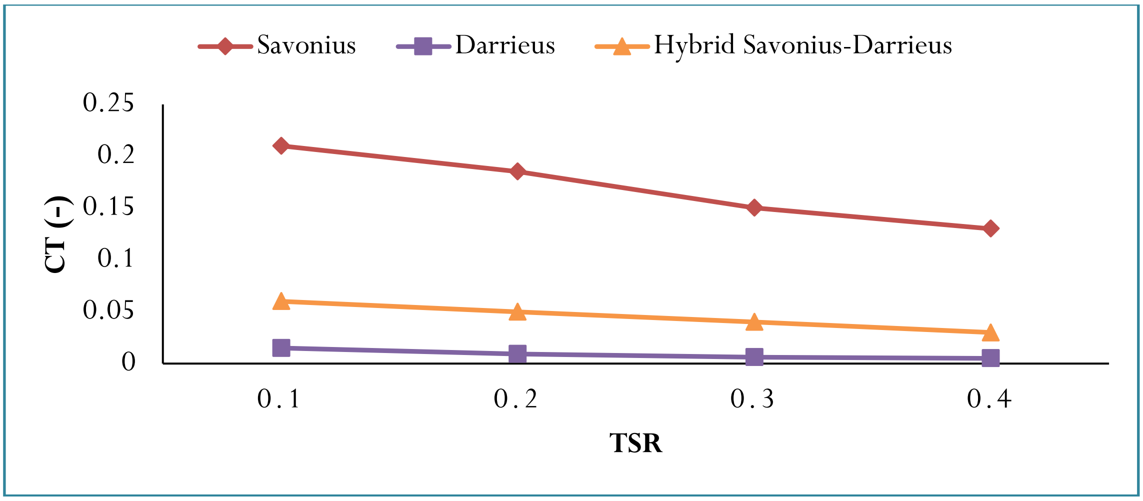
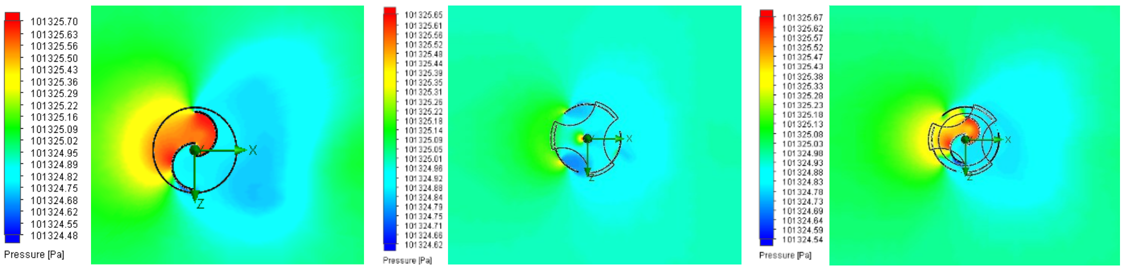


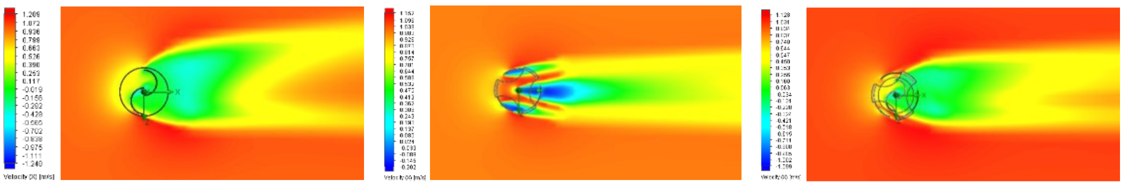
Figure 7. Torque coefficients produced by each wind turbine

Pressure distribution in the wind fluid is depicted in Figure 8. The pressure contours for each turbine show similarities and some variations. In the initial stage, all variations show a stable pressure distribution around 101325 Pa, although there are differences in the locations of the pressure distribution for each turbine. The Darrieus wind turbine, however, displayed an unstable pressure distribution between its blades, while the Savonius wind turbine produced the most stable pressure distribution.



(a) (b) (c)

Figure 8. Pressure distribution (a. Savonius wind turbine, b. Darrieus wind turbine, c. Savonius-darrieus hybrid wind turbine)



(a) (b) (c)

Figure 9. Wind Velocity Distribution (a. Savonius wind turbine, b. Darrieus wind turbine, c. Savonius-darrieus hybrid wind turbine)

4. Discussion

Previous research has extensively investigated renewable energy technologies as vital solutions to mitigate global warming and climate change, with numerous studies confirming the importance of transitioning from fossil fuels to cleaner energy sources. Consistent with the Japan Meteorological Agency's findings on the rapid increase in global temperatures due to greenhouse gas emissions, other studies have similarly emphasized the urgency of addressing climate change through sustainable energy practices. The effectiveness of wind energy as a significant component in reducing CO_2 emissions and supporting global energy demand has been highlighted in [22], [23].

Vertical Axis Wind Turbines (VAWTs), despite generally lower efficiency compared to Horizontal Axis Wind Turbines (HAWTs), have gained interest for their applicability in low-wind-speed environments, particularly urban areas. The present study's results demonstrate superior aerodynamic efficiency of the Savonius wind turbine relative to the Darrieus and the Savonius-Darrieus hybrid designs, aligning with prior findings on enhanced torque production and stable pressure distribution in Savonius-type turbines at lower wind speeds [24], [25]. This corroboration underscores the potential of Savonius turbines for decentralized, small-scale power generation.

However, the Savonius-Darrieus hybrid wind turbine introduced in this study offers a novel approach that addresses the limitations inherent in individual Savonius or Darrieus configurations. Although its efficiency in the present analysis was lower than that of the standalone Savonius turbine, further optimization of blade geometry and rotor configuration may enhance the performance of hybrid systems [26], [27]. Furthermore, the use of Computational Fluid Dynamics (CFD) in turbine performance evaluation, as applied in this study, has been regarded as a reliable approach for predicting aerodynamic characteristics [26], [27], [28]. CFD simulations have been shown to accurately represent fluid interactions with turbine blades, allowing turbine geometry to be optimized effectively before experimental validation.

Future research should extend these findings by exploring advanced computational methods, such as further incorporating machine learning algorithms to refine turbine geometries and conducting empirical field tests to validate simulation results. Such an integrated approach could significantly enhance the reliability and practical applicability of VAWTs, thus contributing effectively toward achieving global renewable energy targets and environmental sustainability goals.

5. Implications and Recommendations

The findings of this research provide valuable insights into the development and application of Vertical Axis Wind Turbines (VAWTs) as a viable renewable energy solution, particularly in urban and low-wind-speed environments. Considering the substantial effects of global warming and the urgent need to reduce greenhouse gas emissions, the optimization of wind turbine designs can significantly support the achievement of Sustainable Development Goals (SDGs), particularly Goal 7, which focuses on affordable and clean energy. The results highlight the effectiveness of the Savonius turbine configuration as a suitable option for decentralized and small-scale power generation, attributed to its stable torque output and strong aerodynamic performance under low wind speed conditions.

However, the Savonius-Darrieus hybrid turbine, despite its integrated design intended to leverage the benefits of both configurations, demonstrated lower-than-expected efficiency. Consequently, future research should further investigate optimization of the hybrid model's blade geometry and overall configuration, potentially through the use of advanced computational techniques, including machine learning, to enable more precise performance improvements. Furthermore, experimental field validation remains essential to verify simulation outcomes and ensure practical applicability.

Enhanced research and development in these areas could significantly improve the reliability, efficiency, and broader adoption of VAWTs, ultimately supporting global efforts toward renewable and sustainable energy generation.

6. Conclusion

This study comprehensively evaluated the performance of three distinct Vertical Axis Wind Turbine (VAWT) configurations, including Savonius, Darrieus, and the Savonius-Darrieus hybrid using Computational Fluid Dynamics (CFD) simulations. The Savonius wind turbine exhibited the highest aerodynamic efficiency among the tested models, as reflected by superior power coefficient (C_p) and torque coefficient (C_t) values. The findings further validate the effectiveness of Savonius turbines in low wind speed scenarios, showing consistency with existing literature. Conversely, the lower efficiency observed in the Savonius-Darrieus hybrid turbine indicates substantial potential for further optimization and design refinement. Overall, this research offers meaningful contributions to ongoing global efforts, supporting renewable energy development and climate change mitigation by providing critical insights into turbine performance and identifying strategic directions for continued improvement.

Author's declaration

Author contribution

Nelvi Erizon: Conceptualization, Methodology, Validation, data curation, original draft; **Refdinal Refdinal**: Validation, Review, and Editing; **Jasman Jasman:** Review and Editing; **Irzal Irzal:** Review and Editing; **Yufrizal A:** Review and Editing; **Muhammad Shadiq Fahreza:** Review and Editing; **Firza Fernanda Putra:** Review and Editing; **Egi Fadillah**: Review and Editing; **Ma Leona Maye B. Pepito**: Supervision and Validation.

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Data availability

The three-dimensional models of the Savonius, Darrieus, and Savonius–Darrieus hybrid turbines are available from the corresponding author upon reasonable request.

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Competing interest

The authors declare that there are no competing interests related to the research or publication of this article.

Ethical clearance

This research involved no human participants, and all simulation data were handled confidentially.

AI statement

Grammarly was used to improve the grammatical structure of this article. The authors reviewed and verified the accuracy of the content, and an English language expert validated the data and language used.

Publisher's and Journal's note

Universitas Negeri Padang as the publisher, and Editor of Teknomekanik state that there is no conflict of interest towards this article publication.

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