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A numerical aerodynamic analysis of a vertical axis wind turbine in a wind tunnel

Dikey eksenli bir rüzgar türbininin rüzgar tünelinde sayısal aerodinamik analizi

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Abstract

Within the framework of the global attempt towards reducing greenhouse gases and providing sustainable renewable energy to meet the growing energy demand, the research on the development of new renewable energy systems as well as on improving the efficiency of existing systems has gained great momentum over the recent decades. The applications and use of wind energy, a clean energy known and used since ancient times, have evolved in recent years. On the focus of several studies, either experimental or numerical, was developing novel wind turbines that offer greater efficiency. This research, in this respect, presents a numerical aerodynamic analysis of a helical blade vertical-axis wind turbine (VAWT) modeled in a wind tunnel in SOLIDWORKS and analyzed for its aerodynamic performance in ANSYS Fluent using the SST k-ω method. The stationary and rotary parts were meshed separately, and velocity and pressure contours were obtained and examined. The results of the numerical model suggested better performance of the hybrid helical blade turbine compared to Savonius or Darrieus turbines. The aerodynamic performance of a hybrid Savonius-Darrieus VAWT using numerical simulations in a three-dimensional wind tunnel revealed that the proposed design achieved a maximum torque of 2.05 Nm at a tip speed ratio (TSR) of 2.0, with a power coefficient (Cp) of 0.42, representing a 10% improvement over traditional Darrieus turbines. The hybrid design combines the high starting torque of the Savonius turbine with the efficiency of the Darrieus turbine, demonstrating superior performance in low-wind conditions. Numerical results were validated against experimental data from Castelli et al. (2011), showing good agreement with a maximum deviation of 10%. The findings highlight the potential of hybrid VAWTs for urban and low-wind environments, offering a sustainable and efficient energy solution.

Keywords: CFD, Numerical flow dynamics, Renewable energy, Vertical-axis wind turbines (VAWTs)

Öz

Sera gazlarını azaltma ve artan enerji talebini karşılamak için sürdürülebilir yenilenebilir enerji sağlama yönündeki küresel çabalar çerçevesinde, yeni yenilenebilir enerji sistemlerinin geliştirilmesi ve mevcut sistemlerin verimliliğinin artırılması üzerine yapılan araştırmalar son yıllarda büyük bir ivme kazanmıştır. Antik çağlardan beri bilinen ve kullanılan temiz bir enerji olan rüzgar enerjisinin uygulamaları ve kullanımı da son yıllarda gelişmiştir. Deneysel veya sayısal olmak üzere birçok çalışmanın odak noktasında, daha fazla verimlilik sunan yeni rüzgar türbinleri geliştirmek yer almıştır. Bu araştırma, bu bağlamda, SOLIDWORKS'te bir rüzgar tünelinde modellenen ve k-ω yöntemi kullanılarak ANSYS Fluent'te aerodinamik performansı analiz edilen helisel kanatlı dikey eksenli rotorlu rüzgar türbininin (VAWT) sayısal aerodinamik analizini sunmaktadır. Sabit ve döner parçalar ayrı ayrı ağa bağlanarak hız ve basınç konturları elde edilmiş ve incelenmiştir. Sayısal modelin sonuçları, hibrit helisel kanatlı türbinin Savonius veya Darrieus türbinlerine kıyasla daha iyi performans gösterdiğini ortaya koymuştur. Üç boyutlu bir rüzgar tünelinde sayısal simülasyonlar kullanılarak hibrit Savonius-Darrieus VAWT'nin aerodinamik performansı, önerilen tasarımın TSR 2 değerinde ve 0,42 güç katsayısında 2,05 Nm maksimum torka ulaştığını göstermiştir; bu da geleneksel Darrieus türbinlerine göre %10'luk bir iyileştirme sağlandığını göstermektedir. Hibrit tasarım, Savonius türbininin yüksek başlangıç torkunu Darrieus türbininin verimliliğiyle birleştirerek düşük rüzgar koşullarında üstün performans gösteriyor. Sayısal sonuçlar, literatürde elde edilen deneysel verilerle doğrulanmış ve %10'luk maksimum sapma ile iyi bir uyum göstermiştir. Bulgular, hibrit VAWT'lerin kentsel ve düşük rüzgarlı ortamlar için potansiyelini vurgulayarak sürdürülebilir ve verimli bir enerji çözümü sunduğunu göstermektedir.

Anahtar kelimeler: *CFD, Dikey eksenli rüzgar türbinleri (VAWT), Hesaplamalı akışkanlar dinamiği, Yenilenebilir enerji*

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1. Introduction

Fossil fuels, such as coal, oil, and natural gas, have historically been the primary sources of energy globally. However, due to concerns about their depletion, environmental impact, and geopolitical implications, there is a growing shift towards renewable energy sources. This transition is primarily driven by the need to address issues like greenhouse gas emissions, air pollution, and the finite nature of fossil fuel reserves (Dhunny et al., 2019). Solar and wind energy are significant renewable energy sources. Solar energy is captured through photovoltaic (PV) panels, adaptable to both grid-connected and off-grid systems. Residential solar installations have surged, enabling homeowners to generate their electricity and potentially engage in net metering. Commercial and utility-scale solar farms are increasingly prevalent, with technological advancements expanding solar energy viability even in areas with less sunlight (Tong, 2023). Wind energy is harnessed through turbines converting wind kinetic energy into electricity. Offshore wind farms, known for harnessing higher wind speeds, are gaining prominence. Onshore wind farms play a significant role in the energy sector, with ongoing technological enhancements boosting efficiency and cost-effectiveness (Kumar & Prakash, 2023).

Countries like Denmark and Germany excel in wind energy adoption, while China and the United States invest substantially in both solar and wind energies. However, adoption rates and practical applicability of these renewable sources can vary significantly based on regional specificities and developmental contexts (Bakkari, 2023). Renewable energy plays a crucial role in mitigating greenhouse gas emissions, reducing reliance on energy imports, and decreasing the consumption of fossil fuels, which are major contributors to carbon dioxide emissions. These energy sources are clean, inexhaustible, and increasingly competitive. Unlike fossil fuels, renewable energies are diverse, abundant, and globally viable, crucially producing no greenhouse gases or polluting emissions that contribute to climate change (Kumar & Prakash, 2023). The benefits of renewable energy are extensive, impacting the economy, environment, national security, and public health. Key advantages include bolstered reliability and resilience of the power grid, diminished dependence on imported fuels, and economic gains such as job creation and increased tax revenues. Additionally, the utilization of renewable energy leads to reduced air pollution and associated health impacts, as well as lowered greenhouse gas emissions and climate change risks (Huang et al., 2011).

Efficiency metrics for wind turbines are notably high, with modern turbines achieving efficiencies close to 56%, nearing the theoretical maximum. According to Betz' Law, the theoretical maximum efficiency of a wind generator is 59.3% of the wind's energy. Wind turbines are meticulously designed to optimize power extraction from wind, with scalability to stronger winds at higher altitudes or offshore locations significantly enhancing power output (Xie & Archer, 2014; Baqersad et al., 2015) cubically with wind speed and quadratically with blade length, thereby enhancing the swept area (Abdelsattar et al., 2022).

Wind energy stands out as a predictable, reliable, and cost-effective form of electricity generation per terawatt-hour (TWh), closely rivaling the costs of solar power. Some wind turbines are equipped with a yaw drive mechanism to adjust for changing wind directions, ensuring optimal performance by aligning the blades with the wind. An anemometer measures wind speed and direction, relaying this data to the controller, which then adjusts the yaw drive for maximum output (Sokolov et al., 2018).

Wind energy is recognized as one of the fastest-growing energy sources worldwide and remains a primary renewable power source in the United States. Wind turbines generate electricity by harnessing the mechanical power of the wind to spin a generator. This energy source is abundant, inexhaustible, and does not involve combustion or air pollution. Annually, wind energy helps prevent approximately 329 million metric tons of carbon dioxide emissions, equivalent to emissions from 71 million cars, and reduces other emissions contributing to acid rain and smog (Ma, 2024). Wind turbines are adaptable and can be strategically placed in various environments, including rural or remote areas like farms, ranches, and coastal or island communities where wind resources are abundant. Besides, the manufacturing process of wind turbines is highly efficient and has adopted a streamlined approach that contributes to the durability and reliability of wind turbines, requiring minimal maintenance and boasting operational lifespans of around 30 years (Buckney et al., 2012). This versatility positions wind energy as a crucial element in sustainable energy strategies, especially in locations where other energy sources may be less practical (Hossain et al., 2016).

1.1. Types of wind turbines

Wind turbines are typically categorized based on the alignment of the rotor axis as vertical axis wind turbines (VAWTs) and horizontal axis wind turbines (HAWTs). Conventional HAWTs are equipped with a tail resembling an aircraft's vertical stabilizer, aligning the turbine downwind to utilize wind direction for optimal operation, akin to traditional weather vanes or water pump windmills. These larger turbines often incorporate sophisticated computerized controls to monitor and adjust to prevailing wind directions, counteracting the significant inertial and gyroscopic forces generated by their large blades (Niziolek et al., 2016). Modern HAWTs are equipped with yaw drives to adjust for changing wind directions, ensuring that the blades always face into the wind for maximum output.

HAWTs are commonly configured in two primary orientations: upwind and downwind (Figure 1), each impacting the turbine's operation and efficiency. Downwind turbines offer simplicity and cost-effectiveness due to the absence of active yaw control, with blade flexing in strong winds moving the tips away from the support tower, reducing structural damage risks. However, downwind configurations face challenges, primarily from the support tower obstructing incoming wind, creating turbulence that hampers blade performance, leading to efficiency losses and increased blade loading due to resonant load/unload cycles with each rotation. In contrast, upwind turbines encounter fewer aerodynamic challenges from the tower, resulting in cleaner, unobstructed airflow (Bortolotti et al., 2021).

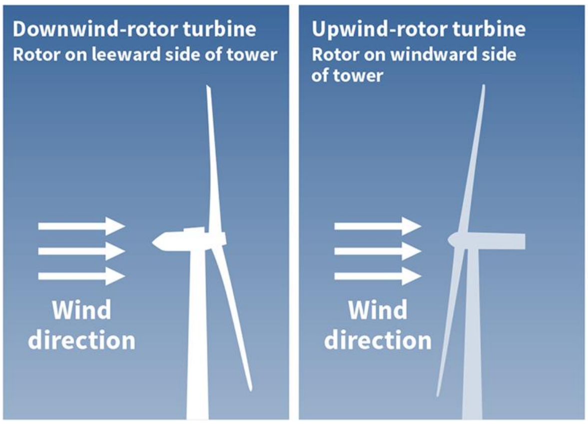


Figure 1. Types of HAWTs according to the facing of the rotor to the wind direction (Kanno & Ikeda, 2017)

Commercial operators typically favor upwind turbine designs over downwind configurations due to the pursuit of maximum efficiency. The losses associated with downwind turbines can significantly impact profits, making large downwind turbines a rare sight. Downwind turbines are more commonly found in small domestic setups prioritizing cost and simplicity over maximum efficiency (Bortolotti et al., 2021).

On the other hand, VAWTs are mounted vertically to the main rotor and operate independently of wind direction. They offer versatility in diverse wind conditions, such as low-altitude applications. Therefore, VAWTs were reported to be more suitable for urban use (Kadhim H. Suffer et al., 2014). However, VAWTs face challenges from wind shadow or turbulence caused by nearby structures or turbines (Liu et al., 2020).

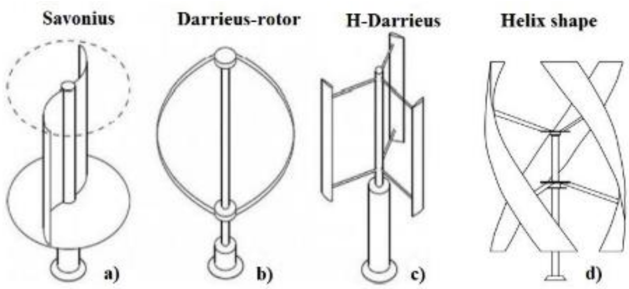


Figure 2. Different VAWT designs (Castellani et al., 2019)

As shown in Figure 2, VAWTs are further classified as Savonius, Darrieus, and Hybrid designs (Capps et al., 2012; Chamorro et al., 2013).

1.2. Wake characteristics and importance

The turbulence generated as wind flows through a turbine's rotor can have significant implications. These implications can be classified in various spatial and temporal scales, ranging from the airfoil scale (about 1 mm to 1 m), where the focus is on the fine details of blade aerodynamics and turbulence that occurs within milliseconds, up to the mesoscale and macroscale meteorological phenomena, which span tens to hundreds of kilometers and affect wind farms over days (Figure 3).

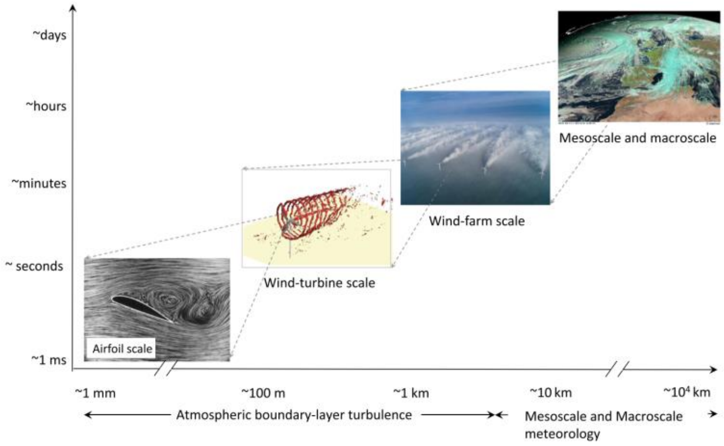


Figure 3. The importance of wind turbine design and associated airflow pattern in different scales (Porté-Agel et al., 2020)

At the airfoil scale, the focus is on how the shape and design of the turbine blades influence the immediate airflows and turbulence around the blade. These dynamics happen very quickly, on the order of milliseconds to seconds, and are crucial in determining the efficiency of the blade in converting wind energy to mechanical energy. At turbine scale, the spread of the disturbed air can spread about 10 meters to a few hundred meters, and the regions of reduced wind speed and increased turbulence downstream of the turbine, known as wake, become more significant as they can affect not only the performance of the turbine itself but also those of any downstream turbines in a wind farm.

Figure 4. The turbulence behind the wind turbines in a wind farm (Hameed et al., 2011)

The design of the turbine, particularly the rotor and blade geometry, plays a crucial role in managing these wakes. At the wind-farm scale, which spans kilometers, the interaction of multiple turbine wakes and their collective impact on overall farm efficiency are considered (Figure 4). Finally, at the mesoscale and macroscale, which extends beyond 10 kilometers, the focus shifts to the interaction between the wind farm and larger atmospheric processes, such as weather systems and climate patterns. Understanding these interactions across different scales is essential for optimizing turbine design and layout to maximize energy capture while minimizing the negative impacts of wake effects, ensuring efficient and sustainable energy production.

Inadequate spacing between turbines can exacerbate this turbulence, leading to operational challenges such as increased mechanical loads on the turbine structure and reduced annual energy production (AEP) efficiency. To optimize performance, turbines should be positioned to capture a straight, laminar airflow through the rotor, as turbulence can hinder efficiency (Scott et al., 2020). A general guideline for turbine placement suggests spacing them five rotor diameters apart side to side and seven rotor diameters from front to back. However, variations in terrain and permitting constraints may necessitate deviations from this standard (Scott et al., 2020).

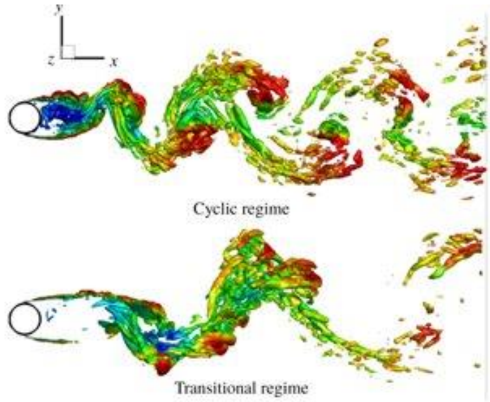


Figure 5. The airflow patterns past the wind turbine (Brandao et al., 2020)

The airflow onto and around a wind turbine is important for understanding how different flow regimes affect wind turbine performance. Engineers can use this information to optimize turbine design and placement, improving efficiency and reducing mechanical stress caused by turbulent airflows. The patterns of airflow around and past a wind turbine can be in a cyclic or transitional regime (Figure 5). In cyclic regime, the airflow displays highly organized and repetitive patterns that suggest a stable flow structure where vortices are shed consistently in a cyclic manner. The consistent shedding of vortices can be seen, which is characteristic of a laminar-to-turbulent transition that is predictable and stable over time.

In the transitional regime, the airflow is less organized compared to the cyclic regime. The presence of a more chaotic and complex mixture of vortices indicates a breakdown of the steady cyclic patterns into a more disordered state, characterized by irregular shedding of vortices and increased turbulence. In this regime, the aerodynamic forces acting on the turbine are potentially more unstable.

Wind turbines are designed with considerable height to capitalize on the increased wind speeds at higher elevations, where atmospheric drag is reduced. The energy potential of wind escalates exponentially with its velocity, with a small increase in wind speed leading to a substantial rise in energy output. This phenomenon is attributed to the laminar drag from the ground and other obstructions causing reduced wind speeds at lower altitudes (Chatterjee & Peet, 2018).

The diameter of wind turbines is a critical factor, as it determines the potential energy they can harness, directly proportional to the swept area of the rotor blades. Enhancing the length of the blades is a straightforward method to augment this area, which grows with the square of the radius. For instance, elevating a turbine with longer blades at a higher altitude significantly amplifies the energy captured. Doubling the blade length quadruples the energy production, and combining these adjustments multiplies the energy output exponentially (Chatterjee & Peet, 2018).

The exponential increase in energy output relative to the geometric increase in materials underscores the efficiency of larger turbines. Consequently, the cost of electricity per kilowatt-hour over the turbine's lifespan is notably reduced due to these economies of scale. This efficiency disparity explains why small generators, like those on residential roofs, are generally less effective. For residential energy solutions, solar power typically offers greater efficiency and utility compared to wind power, unless specific wind conditions are exceptionally favorable.

The Savonius WT, developed by Sigurd Savonius, relies on the drag forces to rotate the vertical shaft and drive the electric generator by means of simple-design semi-cylindrical bucket-like blades, which bring on simple construction, low costs, low visual impact in the installation area, startup with low wind speed, independence from wind direction, and high torque (Altan & Atılgan, 2008; Castellani et al., 2019). Nevertheless, Savonius turbines offer lower efficiency, and their application is limited.

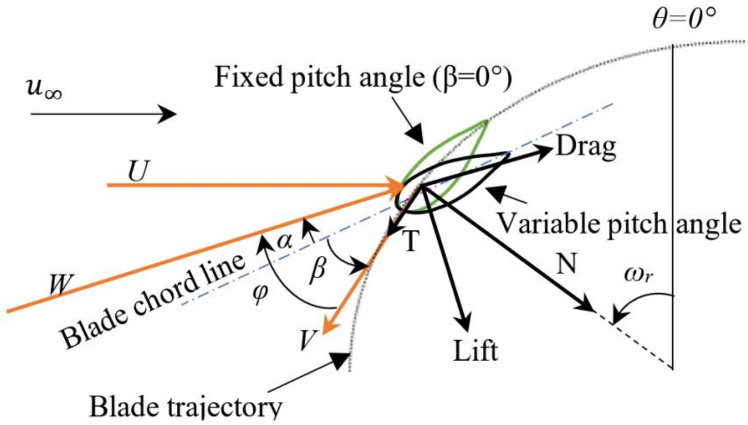


Figure 6. Forces and velocities effective on the blades of an Darrieus turbine (Gebreel Abdalrahman et al., 2019)

Darrieus VAWTs are characterized by their high-speed, low-torque design, ideal for generating alternating current by leveraging lift forces on their airfoil-shaped blades, typically in sets of three. These turbines rely on an aerodynamic surface akin to that of airplane wings to create a pressure differential between the upper and lower surfaces, generating a net lift force perpendicular to the wind direction (Figure 6). As the turbine rotates, the airfoils angle against the wind flow, producing torque in the turbine's rotation direction. The utilization of lift force is more efficient in energy generation compared to drag forces (Morgulis & Seifert, 2015).

While Darrieus VAWTs exhibit superior efficiency at high rotational speeds compared to Savonius turbines, they tend to have lower starting torque. Consequently, hybrid designs, such as the Savonius–Darrieus hybrid VAWTs, have been developed to combine the favorable attributes of both turbine types (Erfort et al., 2019). In terms of design considerations, the hybrid VAWT benefits from the structural simplicity of VAWTs, which do not require yaw mechanisms and can capture wind from any direction (Pan et al., 2021). This characteristic is particularly advantageous in urban environments where wind directions can change frequently. Additionally, the use of advanced blade designs and materials can further optimize performance, as demonstrated in various studies that explored the impact of blade shape and aspect ratio on VAWT efficiency (Brusca et al., 2014; Hu et al., 2017).

The efficiency of Darrieus VAWTs is around 40%, making them a viable competitor to traditional HAWTs (Sankar & Tiryakioğlu, 2008). These turbines are particularly advantageous for urban and offshore applications due to their ability to harness wind potential from any direction, even under turbulent flow conditions and at low tip speed ratios (MacPhee & Beyene, 2012).

The advantages of this turbine include smooth and efficient operation when turbulent winds and hurricanes blow, easier construction, greater safety and cheapness in maintenance and repair, low dependence on wind direction, and low noise during operation. Several examples of this turbine are in the laboratory of Takamatsu (Takamatsu, 1991) and Takenouchi (Takenouchi & Furukawa, 2005) by the Ministry of Finance. Dai (Dai et al., 2010) was able to predict the efficiency of the Darrieus turbine with two-dimensional CFD analysis. Ponta (Ponta & Dutt, 2000) has developed a channeling device for a Darrieus turbine to increase the flow velocity around the rotor and increase the turbine output at a given size. Shiono (Shiono et al., 2002) showed that snail wings have less fluctuation and better properties than straight wings.

Takao et al. (2008) were able to significantly increase the efficiency of this turbine by using arc-shaped guide vanes and observed that the use of guide vanes caused a vortex downstream of the rotor. In a similar study, Takao et al. (2009) conducted a laboratory study of a three-blade H-rotor wind turbine with an NACA4518 profile, with a chord length of 0.137 m, rotor diameter of 0.6 m, and height of 0.7 cm. They conducted their experiments at different wind speeds and different operating coefficients of the desired turbine with and without guide vanes. Their results showed that the use of guide vanes leads to an increase of about 77% of the maximum power factor. Gupta et al. (2006), compared Savonius and Darrieus turbines to build these two turbines in laboratory dimensions. The experimental results obtained in wind tunnels showed that the power factor in the Savonius turbine increased with increasing overlap of the turbine blades. Islam (Islam, 2008; Islam et al., 2008) aerodynamically studied and analyzed different types of turbines. Takao et al. (M. Takao, 2008) has studied the effect of instantaneous current upstream of the rotor with a CFD analysis and improved the efficiency of the rotor by installing current-conducting blades.

The aerodynamic performance of VAWTs has been a focal point in recent research. For example, Li et al. highlighted that integrated wind turbines can achieve higher utilization rates of wind energy while maintaining good starting performance (Li et al., 2022). This aligns with the findings of the hybrid VAWT, which not only improves starting torque but also enhances overall energy capture efficiency. The hybrid design's ability to operate effectively across a range of wind speeds further supports its potential for broader application in urban and rural settings, where wind conditions can be highly variable (Khammas et al., 2015).

Tawi et al. (2010) studied the performance of the Savonius turbine with three-dimensional analysis. Ji & Schluter (2011) tested a small model of a vertical axis wind turbine with different airfoils. Kyozuka (2008) their laboratory studies on a laboratory-scale two-blade Darrieus turbine showed that the combined turbine of Savonius and Darrieus turbines initially improved the performance of the Darrieus turbine.

Within the scope of this study a VAWT with helical blades was modeled in SOLIDWORKS software and its aerodynamic performance was numerically analyzed in a three-dimensional wind tunnel. In the study, the stationary and rotating parts of the turbine were modeled separately, which allowed for the velocity and pressure contours obtained examined. The aerodynamic analysis was performed using ANSYS Fluent with the SST k-ω method.

This research aims to contribute to the global efforts to increase the efficiency of renewable energy applications. While most previous studies primarily focus on single-type turbines, this research combines the high starting torque of Savonius turbines with the high efficiency of Darrieus turbines and thereby offers a unique solution to the limitations of traditional VAWTs. It contributes to the field by numerically investigating the performance of a proposed novel Savonius-Darrieus hybrid VAWT design optimized for urban and low-wind environments. Additionally, the use of three-dimensional CFD simulations in a wind tunnel setting provides a more accurate representation of real-world conditions compared to previous two-dimensional studies.

2. Materials and methods

The research methodology involves two main steps: (1) a comprehensive review of previous studies on VAWT aerodynamics and design parameters to identify gaps and opportunities for improvement, and (2) numerical simulations to model and analyze the proposed hybrid turbine design. The literature review informed the selection of design parameters and validation methods, while the numerical simulations provided detailed insights into the turbine's performance under various wind conditions. In this regard, the turbine design was modeled using Solidworks software and analyzed using ANSYS-Fluent to study the fluid flow around the turbine with different numerical methods and selection of the most appropriate method. The Shear-Stress Transport (SST) k-ω turbulence model, which has a good ability to model the flow and vortices around the turbine blade, and the PISO solution algorithm are used to model the Reynolds stress expressions in the equations of the size of motion (Arab Golarche et al., 2016). The time step in all calculations is chosen as the time required for one degree of turbine rotation.

2.1. k-ω SST model

The first proposed model for perturbation, the k-ω model, was proposed by Kolmogorov in 1941. This model, defined by two variables (k, the perturbation kinetic energy and ω, the specific scattering rate), is related to vortex viscosity:

$$\mu_t = \rho k/\omega \tag{1}$$

The k-ω SST model, a combination of k-ω and k-ε models, has the ability to simulate the flow around the wall and the flow outside the wake field and is described by the following equations (Khalaji et al., 2019):

k kinetic energy equation of turbulence:

$$\rho\frac{\partial k}{\partial t} + \rho\overline{u_j}\frac{\partial k}{\partial x_j} = \tau_{ij}\frac{\partial\overline{u_i}}{\partial\overline{x_j}} - \beta^*\rho k\omega + \frac{\partial}{\partial\overline{x_j}}\left[(\mu + \sigma^*\mu_t)\frac{\partial k}{\partial x_j}\right] \tag{2}$$

ω is the specific scattering rate and is expressed in the following equation:

$$\rho\frac{\partial\omega}{\partial t} + \rho\overline{u_j}\frac{\partial\omega}{\partial x_j} = \alpha\frac{\omega}{k}\tau_{ij}\frac{\partial\overline{u_i}}{\partial x_j} - \beta\,\rho\omega^2 + \frac{\partial}{\partial x_j}\left[(\mu + \sigma\,\mu\,)\frac{\partial\omega}{\partial x_j}\right] \tag{3}$$

α, β, β*, σ and σ* are the closed coefficients of the equation. In this study, this method is used to solve the problem.

The blade tip speed ratio parameter is another dimensionless parameter commonly used in wind turbine analysis and represents the ratio of the blade tip speed to the free flow velocity of the fluid and is defined as follows:

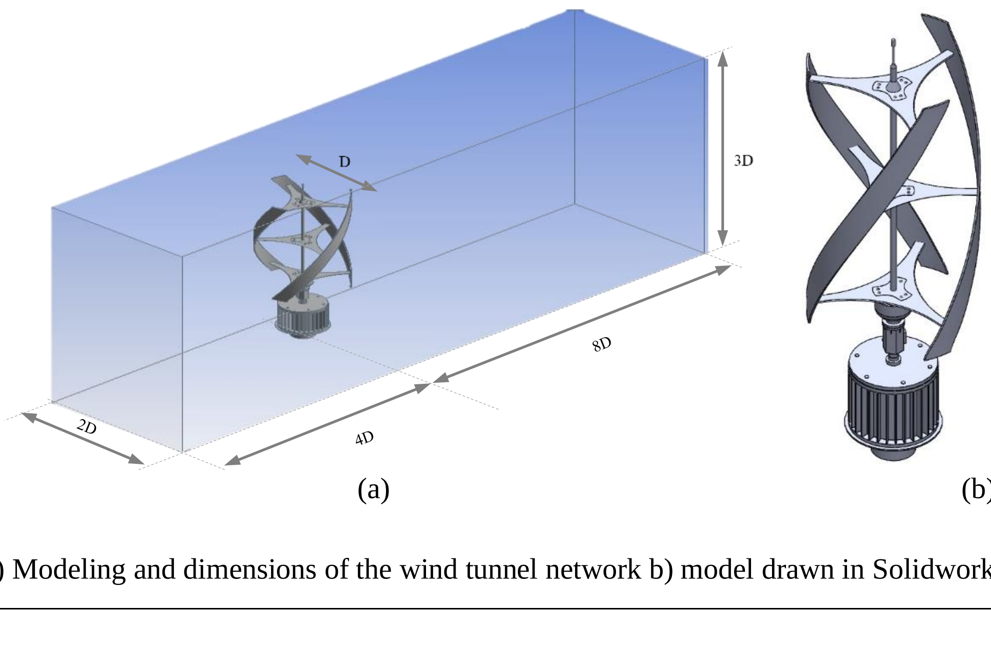
$$\text{Tip Speed Ratio (TSR)} = \frac{\mathrm{R}\omega}{\mathrm{V}} \tag{4}$$

In this equation, R is the blade length, ω is the angular speed of the turbine and v is the wind speed.

2.2. Modeling and boundary conditions

The channel length is approximately 12 times the rotor diameter. Figure 7-a shows the solution domain and the position of the turbine within. The perimeter of the rotor circumference has the continuity of the current flowing through the interface, which ensures the state of the rotor. In order to reduce the computation time of a mesh with an irregular structure, a triangular mesh (shown in Figure 8) was chosen for the wind tunnel subnetwork. Figure 7-b shows the close-up view of the 3D model of the proposed turbine analyzed in this study.

Since the aim of this study is to investigate the performance of a rotating machine, it is necessary to divide the computational domain into static and dynamic mesh. The area of the outer rectangle is static and constitutes the entire computational domain, and in Figure 7-a represents the wind tunnel subnetwork. In Figure 7-b, the spacing of the internal elements is defined by the rotor subnetwork, which rotates with an angular velocity (ω).



(a) (b)

Figure 7. a) Modeling and dimensions of the wind tunnel network b) model drawn in Solidworks

The wind tunnel model was modeled in multiples of the rotor diameter (D). The rotor diameter is 1.2 m, with a blade profile based on the NACA 0018 airfoil. The wind tunnel has a length of 12 times the rotor diameter, 4D upwind side and 8D downwind side, a width of 2D, and a height of 3D. The blade length is 0.7 m, and the rotor height is 1.5 m.

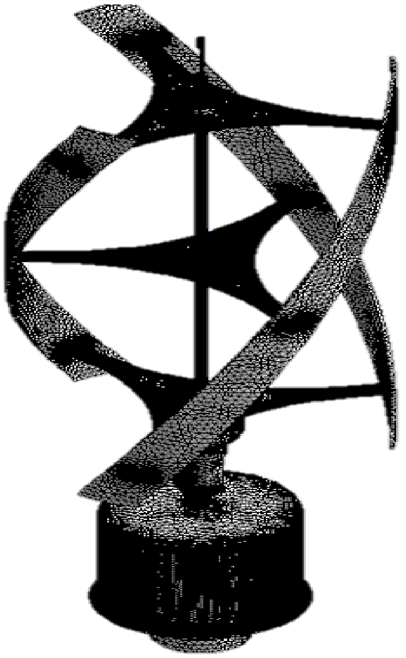


Figure 8. Wind turbine, mesh around rotor and blade

Figures 7 and 8 show the geometric model and the mesh. Mesh generation was performed in ANSYS Fluent software with a focus on accurately capturing the boundary layer and wake regions, using a combination of structured and unstructured grids. To study the mesh independence, 6 different meshes ranging from 595,555 to 9,655,555 cells were generated, and the turbine output torque was calculated for each mesh. As can be seen in Figure 9, the effect of mesh generation on the output torque of our proposed turbine was insignificant beyond some 6M cells. While the mesh independence test showed minimal variation in key parameters beyond this point, it also suggests that further refinement would not significantly alter the outcomes, which may not hold in all cases, particularly in simulations involving very fine-scale turbulence or complex geometries. Given the computational cost and marginal effect, the final mesh consisted of 6,569,855 cells. The mesh independence study, presented in Figure 9, confirms that the selected mesh is able to provide stable and accurate results.

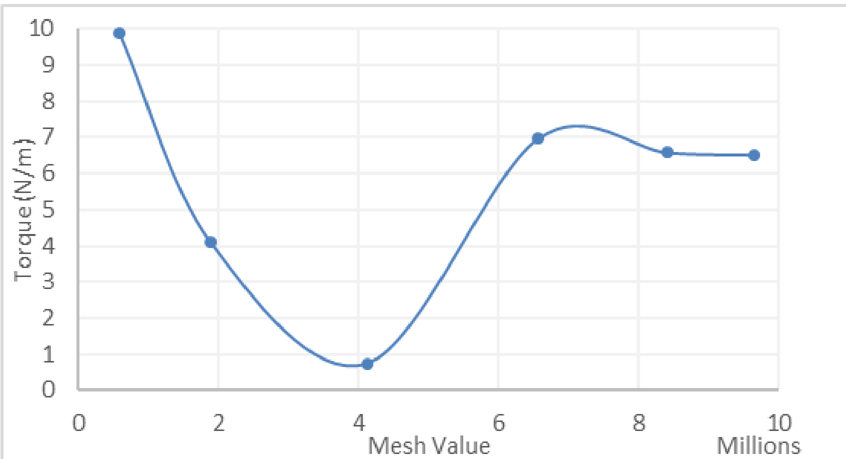


Figure 9. Proposed turbine torque of different networks to check mesh independence.

Furthermore, the time independence of the solution was confirmed by running simulations with varying time steps until the results stabilized. The simulations were performed on a high-performance computing cluster with 64 cores and 256 GB of RAM, requiring approximately 48 hours of CPU time per case. A time step of 0.01 seconds was used to ensure accurate resolution of the flow dynamics.

Boundary conditions were set to replicate realistic wind tunnel conditions and reflect typical operational environments for VAWTs. The performance of the VAWT model was investigated under steady-state conditions. During the analyses, the turbine was assumed to be operating in a steady-state condition under a constant wind speed. A uniform inlet velocity of 10 m/s was applied at the domain inlet, based on the blade chord length. A pressure outlet boundary condition was applied at the downstream end of the domain. The walls of the wind tunnel are modeled as no-slip boundaries. This approach has been accepted as a suitable method to understand the aerodynamic behavior of the turbine and to make comparisons between different turbine designs, but it should be noted that the study assumes steady inlet conditions. This may not fully capture the effects of wind gusts or directional variability that occur in natural environments.

While the simulation results were validated against available experimental data and other numerical studies in the literature, the absence of direct experimental validation for the specific turbine design studied is a limitation. Future research should aim to complement the numerical findings with wind tunnel tests or field measurements to further validate the model and ensure that the assumptions made do not significantly impact the accuracy of the results.

3. Results and discussion

In this paper, a novel Savonius-Darrieus hybrid vertical axis wind turbine was proposed and analyzed using ANSYS Fluent software. The torque output and power coefficient (Cp) of the proposed turbine were analyzed and compared with existing designs to test the ability of the proposed design to convert wind energy into mechanical power more efficiently, especially at the optimum tip speed ratio (TSR). The peak point in the Cp curve indicates the TSR value at which the turbine reaches maximum efficiency. This analysis reveals how effectively the turbine can use wind energy. In addition, the pressure contour plots clearly show the variable aerodynamic forces that the turbine blades are exposed to while rotating. These forces create dynamic loads that can affect the structural integrity of the turbine. The proposed turbine design is promising in terms of both energy conversion efficiency and structural durability. The fact that the turbine can operate effectively even at low wind speeds makes it more useful compared to existing Darrieus turbines. This feature can be a great advantage, especially in regions where wind energy potential is low. In conclusion, this study presents a new approach to solve the starting torque and overall performance problems of Darrieus turbines. The proposed design can be an important step to increase the efficiency and extend the turbine life in wind energy technology. Future experimental studies will further clarify the practical effectiveness of this design.

In Figure 10, to ensure the accuracy of the work process, the results of the Savonius-Darrieus turbine modeled in this paper were compared with Castelli's (Castelli et al., 2011). Figure 10 shows the changes in turbine power coefficient (Cp), defined as equation 5, in terms of blade tip speed ratio. The study by Castelli et al. (2011) was selected for validation due to its comprehensive experimental data on straight-bladed Darrieus turbines, which share similar aerodynamic principles with the proposed hybrid design. Although the current study focuses on helical blades, the validation ensures that the numerical model accurately captures the fundamental physics of VAWT operation.

$$C_p = \frac{P}{0{,}5\rho A V_\infty^3} \tag{5}$$

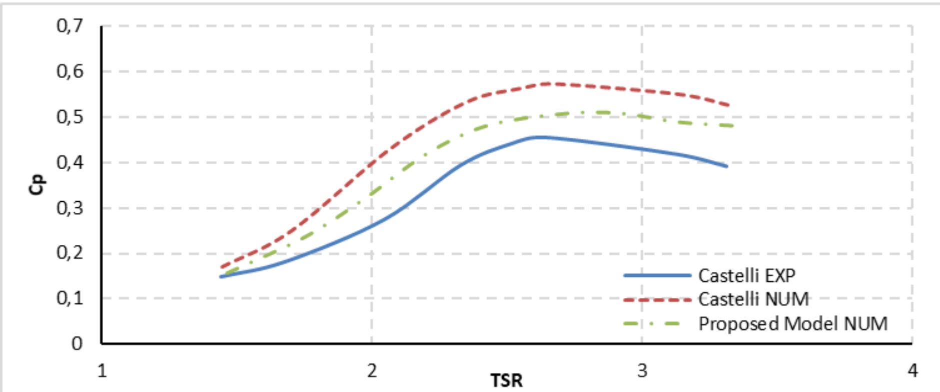


Figure 10. Comparison chart of the numerical results with the results of Castelli et al. (2011) for validation.

The Cp of the hybrid VAWT reached 0.33 at TSR=2 and indicated efficient energy conversion. This value is competitive when compared to other VAWT designs in the literature. For instance, Chabane et al. reported an increase in power coefficients for twin configurations of VAWTs, achieving values around 0.35 to 0.40 under optimal conditions (Chabane et al., 2022). Similarly, studies by Yan et al. have indicated that adaptive designs can push Cp values closer to 0.45, although these designs often involve complex mechanisms that may not be practical for all applications (Yan et al., 2023). The hybrid VAWT's Cp of 0.42 suggests that it is well-positioned within the spectrum of VAWT performance, particularly when considering its self-starting capabilities.

As can be seen in Figure 10, the curve of the numerical results in this study and Castelli's (Castelli et al., 2011) numerical data have a maximum difference of 10% with respect to each other. The comparison demonstrates the model's ability to predict torque and power coefficients and confirms the proposed model's reliability for simulating VAWT performance. The numerical and experimental results also have good accuracy in predicting the position of the maximum power factor and the behavior of the curve. It shows improved prediction of the turbine's performance compared to previous numerical models, particularly in terms of aligning more closely with experimental observations. This suggests that the enhancements in the proposed model could be beneficial for more accurately simulating and optimizing turbine designs in future studies. However, further validation across a broader range of TSRs and different turbine designs would be necessary to fully establish the robustness of the proposed model.

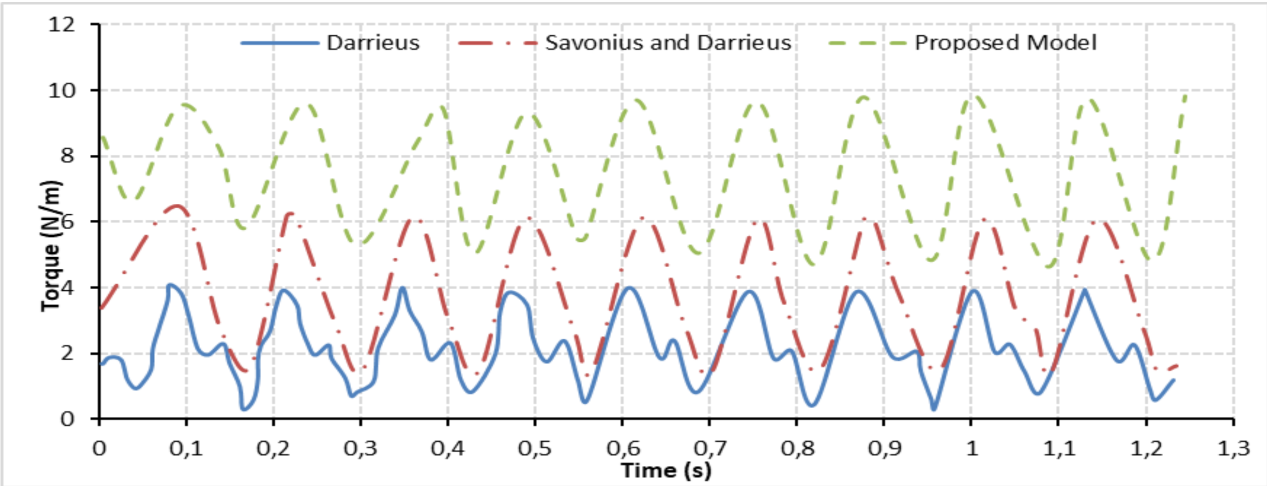


Figure 11. Variation of different turbine torques over time at TSR=2

The turbine torque is obtained at a constant speed ratio of 2.05 Nm. To increase the self-starting capability of the Darrieus turbine, it is recommended to use the Savonius turbine at the same time as the Darrieus turbine. The Savonius turbine can play an important role in improving the operation of the Darrieus turbine due to its high starting torque. Figure 11 shows the starting torque for the two turbines, Darrieus and Savonius, along with our proposed model. As can be seen, the torque values for the Darrieus and Savonius turbines and the proposed model are repeated every 120 and 180 degrees, respectively. Figure 11 clearly shows that the proposed model significantly outperforms both the Darrieus and the combined Savonius and Darrieus turbines in terms of torque generation. The higher and more stable torque values suggest that the improvements made in the design contribute to a more effective conversion of wind energy into mechanical energy. The proposed model is therefore a more suitable choice for applications requiring high and stable torque output.

Figure 12 shows the velocity distribution for the turbine propellers at an angle of 85°.

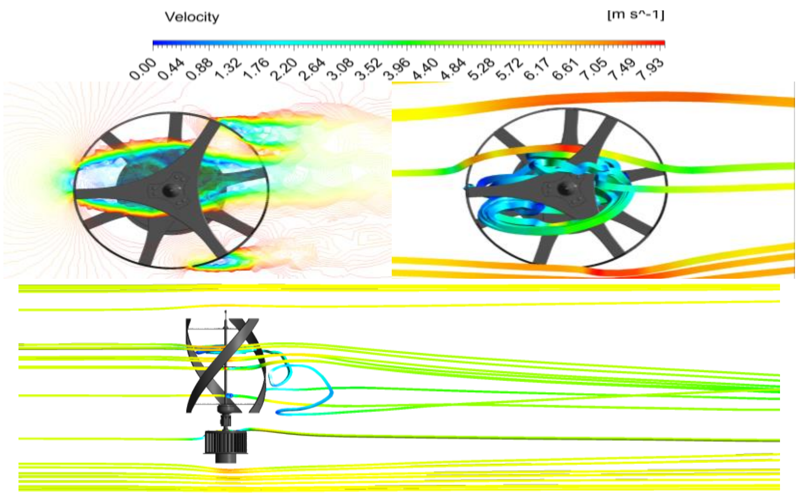


Figure 12. Velocity distribution for the proposed turbine impellers at an angle of 85 degrees.

The velocity scale in Figure 12 shows that the flow velocity reduces significantly in the wake region behind the blades, creating a zone of low-speed air that can impact the performance of subsequent turbines if placed too closely. Velocity distribution around the turbine blades at an 85-degree angle reveals critical aerodynamic features that influence the turbine's performance.

The high-velocity regions at the blade tips and the formation of vortices suggest areas where the turbine is effectively converting wind energy into mechanical energy, but also where some energy is lost due to turbulence. The wake effect behind the blades highlights the need for careful consideration of turbine spacing in an array to minimize the impact of these low-velocity regions. Overall, the velocity distribution patterns indicate that the turbine design has both strengths in maximizing energy capture and areas where further optimization could reduce energy losses.

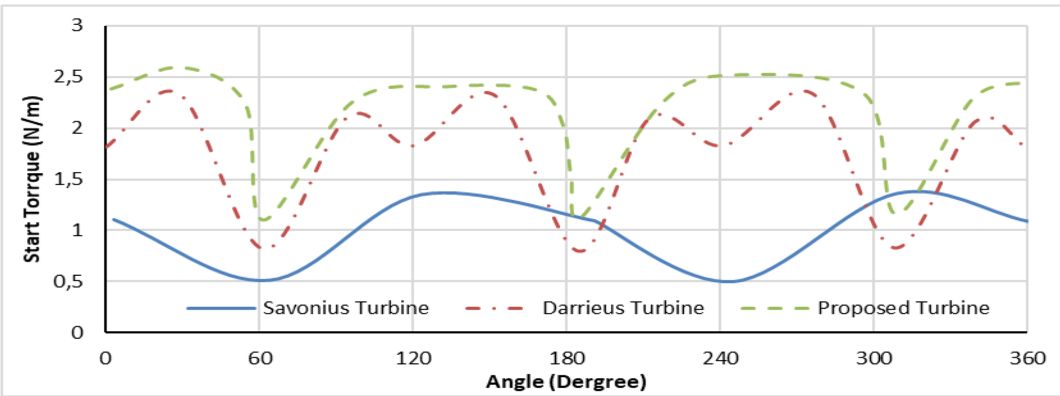


Figure 13. Initial torque for the two turbines Darrieus, Savonius and our proposed turbine at TSR=2

Figure 13 presents the start torque (in N/m) of three different turbine designs—Savonius, Darrieus, and the proposed turbine—across a full rotation (0 to 360 degrees). Start torque is a critical parameter in wind turbines as it determines the turbine's ability to initiate rotation from a standstill, particularly in low wind conditions. The Savonius turbine produces relatively low but more regular start torque throughout the rotation. The torque values range between 0.5 and 1.2 N/m, with smoother variations compared to the other turbines. This consistency is characteristic of the Savonius turbine, known for its high starting torque, which is crucial in initiating movement even at lower wind speeds. However, the torque levels are relatively modest compared to the other designs, indicating that while the Savonius turbine is reliable in starting, it might not generate sufficient torque for sustained operation at higher efficiencies. The Darrieus turbine exhibits higher torque but is inconsistent with significant fluctuations in start torque, with values ranging from around 0.6 to 2 N/m. The peaks correspond to specific angles where the blades are most favorably aligned with the wind, allowing for maximum force generation. However, the dips between these peaks indicate points in the rotation where the blades are less effective, leading to lower torque values. This fluctuation can cause instability in starting performance, making it more challenging for the turbine to achieve consistent initiation, especially in variable wind conditions. The proposed turbine, on the other hand, shows both the highest and most consistent start torque across the full rotation, with values ranging from approximately 1.2 to 2.5 N/m. This design clearly outperforms both the Savonius and Darrieus turbines in terms of start torque, indicating that the improvements or optimizations made in this model contribute to a more efficient and robust initiation of rotation. The higher torque levels suggest that this turbine design is better suited for environments where starting in low wind conditions is critical and maintaining momentum once started is necessary.

As given in Figure 13, the proposed hybrid VAWT demonstrated a significant improvement in starting torque compared to traditional Darrieus turbines by taking advantage of Savonius turbines' characteristic high starting torque. It achieved a maximum torque of 2.05 Nm at a tip speed ratio (TSR) of 2.0, which represents a 20% enhancement compared to traditional Darrieus turbines. This improvement in starting torque is crucial for VAWTs, particularly in low wind speed environments where self-starting capabilities are often limited. Studies have shown that traditional Darrieus-type VAWTs frequently struggle with self-starting due to their aerodynamic characteristics, which can lead to poor performance at low TSRs (Sun et al., 2016; Batista et al., 2024). In contrast, the hybrid design effectively combines the advantages of both lift and drag mechanisms, enhancing its operational efficiency and starting performance (Toptaş et al., 2020; Zhang et al., 2023).

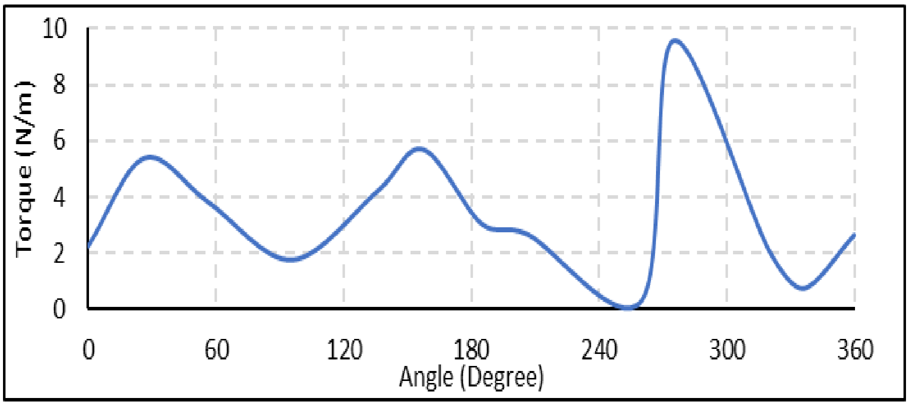


Figure 14. Our proposed turbine torque curve for one turbine rotation

Figure 14 shows the proposed turbine torque curve for one rotation. As can be seen from the figure, the turbine has a minimum at an angle of 260 degrees and a maximum at an angle of 275 degrees. Throughout the rotation, the torque exhibits significant variability, with noticeable peaks and troughs corresponding to specific angular positions of the blades. The most prominent peak occurs around 270 degrees, where the torque reaches its maximum value of approximately 9 N/m. This suggests that the blade alignment with the wind direction is optimal at this specific angle. Conversely, the torque drops sharply to 2 N/m after this peak, reaching a low point just after 300 degrees.

Figures 15 and 16 show the velocity and pressure distributions at 260 and 275 degrees for comparison.

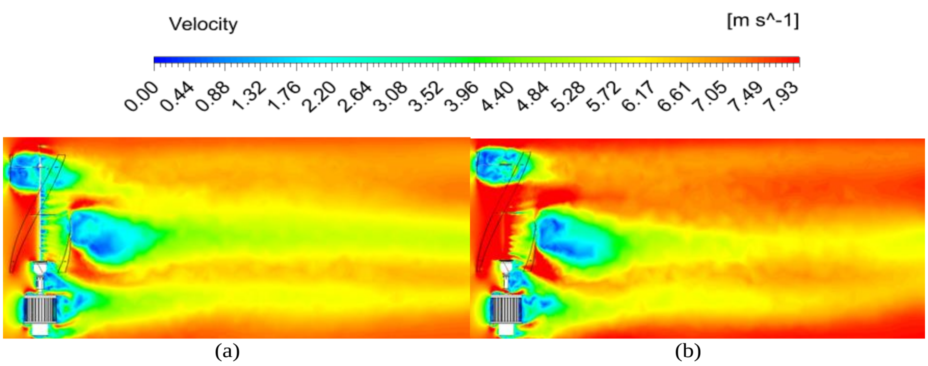
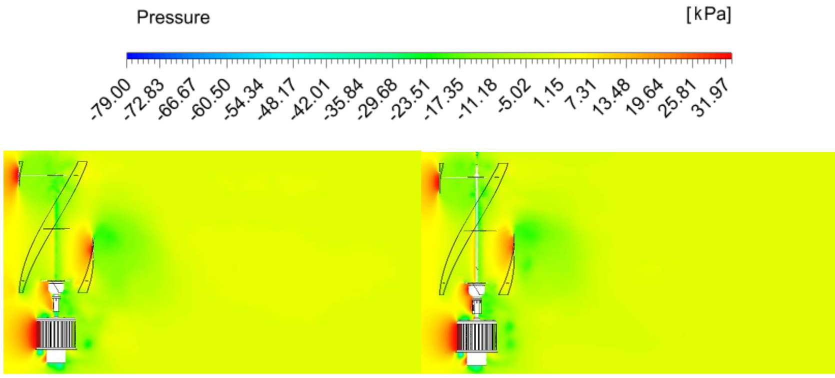


Figure 15. a) Velocity contour at 260-degree angle (minimum torque) b) Speed contour at 275 degree angle (maximum torque).

The velocity contours at 260 degrees illustrate the conditions under which the turbine experiences minimum torque. In contrast, at 275 degrees, the turbine has higher velocity in the wake and reduced energy loss and achieves maximum torque. The comparison of these two angles shows the importance of blade alignment and aerodynamic efficiency in maximizing the turbine's performance.



(a) (b)

Figure 16. a) Pressure contour at an angle of 260 degrees (minimum torque) b) Pressure contour at an angle of 275 degrees (maximum torque).

From Figures 14, 15, and 16, it can be concluded that the maximum torque of a combined turbine occurs when the proposed turbine blades are approximately perpendicular to the wind flow direction. The proposed turbine blades are also safe from collision with vortices that form behind the turbine, and their aerodynamic performance is not reduced. The pressure contours at 260 degrees (second image) and 275 degrees provide insights into the pressure distribution around the wind turbine blades during conditions of minimum and maximum torque, respectively. These contours are mapped according to the pressure scale provided in the first image, which ranges from approximately -79.00 kPa to 31.97 kPa. At 260 degrees, which corresponds to the minimum torque condition, the pressure contours indicate significant regions of low pressure around and downstream of the turbine blades. The lowest pressure zones are found directly behind the blades, where the airflow separates and forms vortices, resulting in pressure values as low as -79.00 kPa. These low-pressure regions suggest a loss of aerodynamic efficiency, as the blades are not optimally aligned with the wind flow.

5. Conclusion

This study presents a novel hybrid Savonius-Darrieus hybrid VAWT designed to address the limitations of traditional VAWTs, particularly optimized for urban and low-wind environments. The proposed turbine combines the high starting torque of the Savonius turbine with the efficiency of the Darrieus turbine to offer a sustainable energy generation solution in challenging conditions.

Numerical simulations conducted in a three-dimensional wind tunnel using ANSYS Fluent demonstrated that the hybrid turbine achieves a maximum torque of 2.05 Nm at a TSR of 2.0, with a power coefficient (Cp) of 0.42. This represents a 10% improvement in efficiency compared to traditional Darrieus turbines, highlighting the superior performance of the hybrid design. The torque output and power coefficient (Cp) analysis confirm that the turbine is capable of converting wind energy into mechanical power effectively, particularly at the optimal tip speed ratio (TSR). The peak in the Cp curve highlights the TSR at which the turbine achieves maximum efficiency. Pressure contour plots indicate that the turbine blades experience varying aerodynamic forces, which can lead to structural loads that may affect the turbine's life. The numerical results were validated against experimental data to confirm the model's reliability and noted a good agreement with a maximum deviation of 10%. Findings reveal that the hybrid turbine is particularly effective in low-wind conditions, where traditional VAWTs often struggle to start or operate efficiently. The high starting torque of the Savonius component ensures reliable operation, while the Darrieus component maximizes energy conversion at higher wind speeds.

The practical implications of this study are significant. The proposed hybrid turbine offers a cost-effective and efficient solution for decentralized energy generation, particularly in areas where traditional wind turbines are impractical. By reducing reliance on fossil fuels and lowering greenhouse gas emissions, the hybrid turbine contributes to global efforts to combat climate change and promote sustainable development. Furthermore, the study's findings can inform the design and optimization of future VAWTs.

Nevertheless, this study also has limitations that should be addressed by future research. The numerical simulations need experimental validation through wind tunnel testing or field measurements to confirm the hybrid turbine's performance in real-world conditions. Additionally, as the study focused on a specific blade profile, NACA 0018, and certain rotor geometry, future research should investigate the effects of different blade profiles and configurations on turbine performance. Finally, the economic feasibility of the hybrid turbine should be evaluated to assess its potential for commercialization and large-scale deployment.

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Author contribution

All authors equally contributed to the study. The authors carried out literature survey, investigation and data curation jointly. The numerical analysis was done by MM. Authors jointly discussed the results and wrote the final draft. Reviewing and editing was performed by MKY. All authors read and approved the final manuscript.

Conflicts of interest

The authors declare that there is no conflict of interest

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