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REVIEW OF EXPERIMENTAL AND NUMERICAL STUDIES ON THE PERFORMANCE OF SAVONIUS WIND TURBINES

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ABSTRACT

Due to its simplicity, omnidirectionality, and low-wind start, the Savonius vertical-axis wind turbine (VAWT) may be suitable for small-scale renewable energy production. Its low power coefficient (Cp) compared to lift turbines hinders its large-scale use. This review examined recent experimental and numerical studies to solve this constraint. Key geometric elements include aspect ratio, blade number, overlap ratio, arc angle, blade profile, and operating techniques contribute to performance. The current study reviews recent improvements including improved aerodynamic modifications, crescent-like and omnidirectional deflectors (which increase Cp by up to 125%), curtain-fins, and new blade designs like the SR5050 profile, making it unique. The review also synthesises discoveries in advanced configurations including multi-stage rotors and hybrid Darrieus-Savonius systems, which combine the best of both worlds. Validating performance improvements and design optimization requires CFD. Results show that deliberate design adjustments can increase Cp values to 0.38, a significant improvement. We have achieved this, but future studies must include scalability, cost-effective production of intricate geometries, and field trials to decrease the efficiency gap and realize Savonius VAWTs' renewable energy potential.

Keywords: VAWTs, CFD, Power coefficient, Savonius rotor, and aerodynamic optimization.

NOMENCLATURE

Symbols	Description
Δ	Inner bucket space (m)

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Symbols	Description
A	Swept area (m^2)
AR	Aspect ratio
CFD	Computational fluid dynamics
Cm, CT	Torque coefficient
Cp	Power coefficient
D	Rotor diameter (m)
Do	Plate diameter (m)
E	Overlap size (m)
H	Rotor height (m)
HAWT	Horizontal-axis wind turbine
P	Output power (W)
Q	Bucket radius (m)
T	Torque (N.m)
TSR	Tip speed ratio
V	Flow velocity (m/s)
VAWT	Vertical-axis wind turbine
Ψ	Inner bucket arc angle (deg)
Ω	Angular velocity (rad/s)

INTRODUCTION

The world faces a pressing challenge: an ever-increasing need for energy, alongside a limited supply of fossil fuels. This exhaustion, coupled with stringent environmental laws and global warming, has elevated the transition to renewable energy sources to the forefront of governments. In 2015, 78.4% of the global energy consumption was from fossil fuels, and renewable energy consumption was only 19.3%, with the remaining 2.3% from nuclear energy consumption (Ghasemian et al., 2017; Roy & Ducoin, 2016;) .

The most promising solutions for addressing the increasing energy demands of humanity and as alternatives to fossil fuels are renewable energy sources including wind, solar, and hydropower. Among these, wind power is believed to be the cheapest and fastest-growing technology. (Mohammadi et al., 2018). Since 1996, wind power has taken the lead in renewable energy and its capacity has increased exponentially. It is a pioneering country such as China, the U.S., or Germany that led to this expansion. In the main case, the global annual renewable capacity will increase from 666 GW in 2024 to almost 935 GW in 2030. Solar PV and wind are forecasted to account for 95% of all renewable capacity additions through 2030 because their generation costs are lower than for both fossil and non-fossil alternatives in most countries as presented in Fig. 1. Renewables, I. E. A. (2024). Global shift wind turbines (VAWTs) are among the multiplicity of wind power converters that have certain unique benefits in certain scenarios, especially when the wind direction is not constant, space is limited, and low wind speeds must be met (Casini, 2016).

The Savonius VAWT, a drag-driven rotor with a simple S-shaped blade geometry, has become a leading competitor in this category because of its inherent operational strengths. Nevertheless, its broader use has traditionally been limited by a fundamental drawback: less aerodynamic efficiency and power coefficient Cp than liftoff-based turbines, such as the Darrieus VAWT or Horizontal Axis Wind Turbines (HAWT) (Mohan Kumar et al., 2019; Roy & Saha, 2013). It is a review of a voluminous body of experimental and numerical analysis into removing this constraint by experimentally addressing the geometric, operational, and aerodynamic enhancements that optimize the performance of Savonius turbines.

Savonius rotors are popular for their many benefits. Due of their simple mechanism, they are cheap, easy to make, and low-maintenance. It can power streetlights, traffic lights, and electric car charging in rural and isolated locations, cities, and niche markets (AR et al., 2019; Mittal et al., 2023). More crucially, its omnidirectional wind-harnessing eliminates the need for complicated yaw systems. In addition, the Savonius turbine has a self-gradual quality that generates a positive torque even at extremely low wind speeds (typically 4-5 m/s), when most turbine models stop and produce a big starting torque. These properties make it suitable for turbulent or low-wind situations where standard turbines fail. Despite these benefits, the main issue is the relatively low power coefficient. Semicircular blade Savonius rotors can typically reach a maximum of 0.593 and tend to be less efficient or even worse than other types of turbines as demonstrated in Fig. 2 (Dhamotharan et al., 2015).

Drag-based operating principles generate this inefficiency. The wind's heavy drag on the advancing blade's concave side propels it ahead, while the returning blade's convex side drags in the opposite direction at a negative torque. Thus, much of the wind's kinetic energy is wasted to fight this drag on the returning blade instead of being used for spinning. To evaluate and optimize Savonius performance characteristics, extensive study has been done using experimental wind tunnel testing, field experiments, and advanced CFD models. This study carefully evaluates the key differences from prior assessments by combining the latest advances (2020-2025). This study examines innovative blade profiles and hybrid systems, the state-of-the-art in Savonius VAWT studies, as well as Axisymmetric Omnidirectional Deflectors (AODs) and advanced curtain-fin designs. In combination with state-of-the-art CFD research and experimental tests, the proposed study will provide a comprehensive and future view of Savonius turbine performance optimization prospects.

Geometric parameters

Aspect Ratio (AR = H/D)

There is strong evidence that higher aspect ratios (usually above 0.80) tend to increase the power coefficient and optimal tip speed ratio (TSR) by reducing the amount of losses due to the three-dimensional flow effects imposed by end plates (Roy and Saha, 2013) According to experimental evidence presented in Fig. 3, the relationship between aspect ratio and power coefficient is positive, and this is also expected to improve end plate flow guidance.

Blades

There is an optimum number of blades, which is a tradeoff. In spite of the fact that two-bladed rotors are easier to make and can reach even higher peak power at very high speeds, three-bladed rotors are often deemed as the most appropriate ones to produce maximum torque and overall performance, particularly at lower wind speeds because of their superior torque distribution and lower pulsations (Prabowo et al.; Rahman et al., 2018). Nevertheless, other researchers have demonstrated that four-blade designs are more efficient than three-blade designs at higher wind speeds (6 m/s and above) or certain helical designs (Gumilar et al., 2019; Soegiharto et al., 2024). The comparative torque (CT) and power coefficients (Cp) of the two- and three-blade rotors are shown in Fig. 4 and Fig. 5, respectively, and indicate the performance differences throughout the TSR.

Overlap Ratio (overlap distance (e)/diameter (d)

This ratio has a strong effect on the contact between the blades and the reduction of the negative torque acting on the returning blade. The best range of 0.15-0.18 is commonly reported for the maximum CP of different blade profiles (Karimi et al.,2023; Hassanshahi et ai, 2024; Ebrahimpour et al.,2019). Low ratios (e.g., 0.15) could be more appropriate with very low wind velocities (less than 4 m/s), whereas all the higher ratios (e.g., 0.30) could be more suitable in a turbulent environment (Tania et al., 2018). Fig. 6 shows the manner in which the negative torque was proven to be lower with the overlapped designs than with the non-overlapped ones.

Blade Arc Angle

The angular range of the blade greatly influenced the drag force and flow dynamics obtained. Previous studies have shown that an arc angle of 160 °produces the best performance (obtaining CP = 0.2836, an 8.37 percent higher increase than the traditional 180 °) (Mao and Tian, 2015) and 180° (with the highest torque coefficient Cm = 0.501) (Akhlaghi and Ghafoorian, 2023).

Blade Profile (Shape Factor)

The shape factor is an important geometrical parameter, or a measure of the extent to which the shape of a blade is distorted by being not a semicircle. This curvature or fullness has a significant impact on the aerodynamic performance of the turbine. Hence, central research has taken a step further and left the conventional semicircular form. As an example, new profiles, including SR5050, which is based on hydrofoils, have demonstrated impressive results, with a power coefficient (Cp) that is 0.38, or 39.19% higher (Babu and Patel, 2024). Other designs studied by researchers include designs with modified blade fullness (Tian et al., 2015), elliptical profiles (AR et al.,2019), and Modified Bach profiles, which have shown performance gains of 825% (Prabowoputra & Prabowo, 2022; Saeed et al., 2022; Chang et al., 2021). On the same note, the addition of linear arms has been observed to affect the blade shape factor and increase performance.

Whereas the geometric structure forms the blueprint of the turbine, its operation is equally determined by the environment in which it operates and through its dynamics with the wind. Thus, the next section considers the main operational parameters, including the inlet wind velocity, and presents external aerodynamic systems that are aimed at active control of the flow around the rotor.

Operational parameter

Inlet Wind Velocity

The Wind speed is also a factor that influences the performance. Studies have been conducted to improve the low-wind performance by modifying the blades (dimples and fins) (improving performance at approximately 10 m/s) (Aher and Singh,2024) and zigzag surfaces on the concave side (raising the drag coefficient and Cp by 29% at 5 m/s) (Sumiati et al., 2024). Usually, the faster the performance, the better the relative gain (Cp) tends to decrease at high Reynolds numbers, but the torque gain is larger.

Aerodynamic Augmentation Systems

To direct airflow and reduce negative torque, other scientists have examined external mechanisms, including the following:

Deflectors

Deflectors were found to have strong effects, with crescent-shaped deflectors before the coming blade boosting the power coefficient (Cp) by 19.51% (Hedayati et al., 2024). Axisymmetric Omnidirectional Deflectors (AODs) can achieve even more dramatic gains (a 125% improvement in Cp at certain angles) and have high efficiency in any wind direction (Aboujaude et al., 2024).

Curtain Systems

Curtains that are strategically placed on top of the blades, and in most cases, a combination of curtains with blade fins helps to shield the returning blade against harmful wind and decrease the adverse torque. Single- and counter-rotating configurations recorded experimental and CFD Cp gains of 4248% (Shouman et al., 2022; Shouman and Helal,2023). Alternative curtain designs also significantly influence the torque produced in a complete rotation cycle.

Surface and Structural Modifications

Local modifications of the flow patterns and pressure distributions were shown to be efficient for blades with slotted blades (Ramarajan & Jayavel, 2021), layered blades (Kurniawan et al., 2020), and stator blades (in particular, curved blades that can achieve up to 7.59 times × efficiency) (Hedayati et al., 2024).

Based on the optimization of various individual geometrical and operational aspects, researchers have developed more advanced systems that combine various ideas. Such sophisticated designs, such as multi-stage rotors and hybrid designs, aim to achieve synergy in performance benefits, and a discussion of the computational tools that enable them to be analyzed can therefore be made.

Advanced Configurations

To further improve performance, researchers have developed several advanced configurations. Designs with:

Multipacket Rotors

Designs incorporating more than two or three blades (e.g., multiple semicircular blades) have shown an average Cp improvement of 8.43% (Soegiharto et al, 2024). Semi-elliptical subbuckets can generate additional positive torques (Meziane et al., 2020).

Hybrid Systems

Another intriguing method uses Savonius and Darrieus rotors. This combined the Savonius VAWT's self-starting capabilities and low TSR torque with the Darrieus rotor's operational TSR efficiency. Innovations like dual-shaft designs and Savonius rotor speed regulation to minimize high TSRs have raised hybrid Cp by 35% and 25% at low and high TSRs, respectively (Ghafoorian et al., 2025). The optimization process uses CFD. Researchers have employed sliding mesh approaches to simulate transients with SST k-omega, RNG k-epsilon, and realizable k-epsilon turbulence models. This shows complex flow patterns, pressure fields, and torque shifts. These data can quantify parametric study performance gains (Dhamotharan et al., 2015; Ebrahimpour, 2019; Babu and Patel, 2024; Al-Gburi, 2023). Testing numerical understandings against experimental wind-tunnel results provides a solid foundation for design modifications. This review critically examines parametric optimization and increased design improvements in Savonius VAWT optimization. This shows that high Cp values of 0.38 and above are now possible under the best conditions, which is a big step forward from older designs. Lift-based turbines still differ in efficiency. The conclusion suggests scaling up production of optimized geometries (e.g., telescopic or new blade geometries), implementing and testing hybrid systems in real urban environments, and using more advanced time-dependent simulations using CFD to de-mystify unsteady flow interactions and improve designs. The combined knowledge from experimental work and advanced numerical models makes the Savonius VAWT a more viable and effective option for using wind energy in a variety of conditions, including low-wind, and improving the renewable energy framework.

Computational Fluid Dynamics (CFD)

plays a very important role in the design and analysis of these complicated geometrical and operational strategies. It is a potent numerical instrument that enables the detailed visualization and quantification of flow phenomenon that is challenging to measure experimentally hence can give a deeper explanation of the performance enhancements presented throughout this review.

CFD Validation and Limitations of the Computations

The issues of the Computational Fluid Dynamics (CFD) use in understanding Savonius VAWTs have two critical pillars, which are good validation of the experimental findings and awareness of the restrictions present in the calculation. Though CFD may provide an unparalleled learning of the complex flow processes, the forecasts need to have a foundation on the reality.

Validation Methods: Experiment Anchoring Simulations.

Strict CFD studies involve complicated validation procedures. The most frequent way is to compare global performance characteristics like power coefficient (Cp) and torque coefficient (Cm) with wind tunnel test data using dynamometers or torque sensors. By comparing the simulated and experimental Cp-TSR curves by 5%, Shakya et al. (2025) proved Bach's 2D transient CFD model's ability to forecast model performance.

Scientists use flow-field diagnostics to validate the solver's capacity to include underlying physics. For this, Particle Image Velocimetry is best. PIV proviShakyades nonintrusive, high-resolution velocity vector measurements in the flow plane. Bajuri et al. (2022) studied Savonius turbine dynamic stall and presented a great example. They compared their unsteady Reynolds-averaged Navier (URANS) simulations with time-resolved PIV measurements of dynamic stall vortices from the convex surface of the returning blade to determine how well the CFD parameters captured their nature. In this experiment, vortex convection speed disparities indicate regions where even sophisticated turbulence models failed. In their Savonius-Darrieus hybrid system investigation, Pouransari, and Behzad. (2024) used PIV to validate the simulated wake structure and velocity deficit behind the rotor, which is necessary to measure turbine array interactions.

Another validation uses pressure tap measurements on blade surfaces to compare the torque-causing pressure distribution. Advanced experimental methods need confirmation beyond performance matching and simulated flow physics verification.

Widespread Computational Limitations and Problems: Notwithstanding the current development of computational power, there are still a number of common challenges limiting the CFD analyses of Savonius turbines.

Turbulence Modeling of the Transient Flows

An unsteady Savonius rotor has a massive flow division, vortices, and stall movement. On one hand, URANS models such SST k-w, which may anticipate flow separation, are popular because they balance cost and accuracy. However, they have limits. Zheng et al. (2023) found that URANS models over-dissipate turbulent structures and fail to anticipate dynamic stall situations. Complex methods like Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) are better at capturing large-scale unsteadiness, but their computational cost is orders of magnitude higher than simpler methods, making them unsuitable for design optimization.

Mesh Resolution and Moving Geometry

The overset mesh or sliding mesh methods of the model rotor rotation result in complicated dynamic interface regions. The attainment of a good-quality and adequately fine mesh in these areas and the vicinity of the blades is computationally challenging. A mesh with excessive coarseness cannot capture the important dynamics in the boundary layer and vortex structures, thereby yielding incorrect torque predictions. Al-Gburi et al. (2023) clearly outlined their mesh sensitivity analysis and demonstrated how the estimated Cp values varied until a grid-independent solution was obtained. This process is dynamic and increases the time and computational costs of the study.

Theory of Complex Geometries and Add-ons

More recent versions of Savonius VAWT may have geometric additions, including deflectors, curtains, and slotted or twisted blades. These include sharp edges, small gaps, and complex interactions, which contribute to increasing meshing challenges. To capture the flow with a blade slot or the action between a fixed deflector and a moving blade, a very localized mesh refinement is needed to capture the flow, which further adds to the number of cells and the simulation time.

WORKING PRINCIPLE

The Savonius vertical-axis wind turbine (VAWT) uses differential drag. This simple, inexpensive structure can be used on rooftops or the ground. A typical Savonius wind turbine has two or more S-shaped semi-circular blades to convert wind energy at low wind speeds. These aerodynamic turbines use wind on two or three half-cylinder vertical blades. A two-bladed rotor has a distinctive cross-sectional form (S), as depicted in Fig. 7. Wind picks up airflow and rotates the concave blade under positive torque. Another convex blade receives the same wind. Depressed drag on such a surface causes the turbine to rotate steadily around its center axis.

The curvature reduces the drag force (Fconvex) on the blades as they approach the wind, making it substantially lower than Fconcave. The half-cylinder with its concave side facing wind will spin the rotor due to its larger force than the other blades. Critical nondimensional geometric parameters of these rotors are overlap ratio (e/d= delta), aspect ratio (H/D= AR), gap ratio (p/d= G), and blade shape. where e is overlapping distance, d is chording length, H is rotor height, D is total diameter, and p is blade distance, as shown in Fig. 8.

The Savonius turbine is driven by the differential drag principle, which extracts much less wind energy than comparatively sized lift-type turbines. This is because even the convex bit of the blade will cause drag, which will generate a retarding torque and decrease the efficiency. This is in contrast to lift-based designs, which primarily generate a positive force. In a three-blade Savonius VAWT, three half-cylinders are mounted at 120-degree intervals with regard to each other as expressed in Fig. 9, (Ali,2013).

Differential Drag Principle

The Savonius VAWT employs drag force to provide a rotating motion. The semi-circular blades have a different drag effect in that one part of the blade has a stronger drag than the other parts to draw the rotor into rotation (Dhamotharan et al., 2015). This is further amplified by the design of the blades, which usually form an S-shaped form that helps the turbine capture wind energy (Farozan & Indartono, 2024).

DESIGN AND OPTIMIZATION

There have been several experiments devoted to the optimization of the Savonius turbine design regarding its aerodynamic optimization. Other methods that were employed to identify the optimal included the Taguchi method parameters of design (Dhamotharan et al., 2015). The outspoken form of Savonius turbines allows easy engineering and construction to be installed, which reduces the overall costs (Kumar et al., 2019). Competence has been enhanced by modifications, including the addition of blades or fixing the bend angle of the blades, and is mostly useful under low-wind conditions. As an illustration, an experimental wind tunnel project measured the changes in blades based on the amount (two or three) and rotor twist angles (270°, 360°, 270°, 180°, and 90°) in relation to different wind speeds (0 m/s, 5 m/s). The researchers concluded that perfect performance was under 3-blade design with a twist angle of 180°, which provided a cut-in speed of 1.51 m/s. This study demonstrated that certain design changes of the Savonius Helix VAWT have the potential to significantly enhance its functionality and effectiveness in low-wind environments.

APPLICATIONS AND PERFORMANCE

Savonius VAWT can start turning with low wind and produce strong torques, making them ideal for variable wind conditions (Prabowo et al., 2023). Savonius VAWTs are the least aerodynamically efficient turbines, but they are easy to build and have a convenient power generator for small-scale energy generation (AR et al., 2019). These attributes make it ideal for powering streetlights, traffic lights, and electric vehicle charging stations in areas without traditional cars (Mittal et al., 2023).

Designed, manufactured, and tested recently, a drag-based vertical-axis wind turbine rotor improves performance. This new type was efficient, output high, economically viable, and stable, making it ideal for roadside use. AR et al. (2019) created a Savonius blade with 0.2 overlap and modified inner concave surface. 3D printed the model and tested it in the wind tunnel at 6, 8, and 10 m/s. Performance and power coefficient of the experiment were 18% greater than the standard elliptical Savonius turbine in the lab.

The Savonius VAWT is not the most aero-efficient, but its simplicity and ability to work in low-wind circumstances make it a viable option. Continuous design research and innovation improve its performance and contribute to the renewable energy technology portfolio.

PERFORMANCE OF THE SAVONIUS TURBINE

A variety of studies have been devoted to enhancing the efficiency of Savonius turbines

Efficiency Enhancements

A crescent-shaped Deflector: An attached deflector in front of the Savonius hydrokinetic turbine blades was shown to augment the efficiency of the turbine by providing greater control of the flow and decreasing the adverse torque. One example provided was a configuration in an experiment in which a set of tips in the form of a deflector sustained a power coefficient (Cp) of 0.264 with a Tip Speed Ratio (TSR) of 0.8, which increased the effectiveness by 19.51 percent (Rehman & Ali, 2024).

Aerodynamic Blade Design

An advanced aerodynamic blade design was used to achieve a significant performance. For example, the appearance of the SR5050 blade shape led to a maximum power coefficient (Cp) of 0.38, which is 39.19 per cent higher than that of traditional designs (Babu & Patel, 2024).

Slotted Blades

Alterations to incorporate slotted blades have also been effective, increasing the performance by 11%, indicating the possibility that design changes can be effectively used to improve efficiency (Ramarajan and Jayavel, 2021)

Wind Speed Adaptability

In wind speed adaptability study, Herlambang et al. (2021) experimentally tested a Savonius turbine by changing the inlet-to-outflow ratio of the blades (1:1 and 1:2). The turbine performance was tested experimentally at wind speeds of 5–12 m/s and lamp load of 5–40 turbine performance. The results showed that the single-blade turbine could produce 10 Watts with a maximum efficiency of 8.43 percent with a wind speed of 5 m/s. On the contrary, at 20 Watts, the double-blade turbine had a ratio of 1:2 and a maximum efficiency of 6.9%.

Omnidirectional Performance

Omnidirectional performance was found to be significantly increased by axial-ymmetric omnidirectional deflectors (AODs), and the power coefficient (Cp) has been shown to increase by as much as 125 percent in some cases (Aboujaoude et al., 2024). In one experiment, it was demonstrated that the modified design provided a Cp 61 percent greater than the identical Savonius design at an incidence angle of 0° and an incidence angle of 88 percent greater at an incidence angle of 20°. Notwithstanding this, the naturally low efficiency of Savonius turbines compared to other types of turbines is a problem. There should be endeavors to further develop their design and operating conditions by continuously conducting research to ensure that their utilization in the production of renewable energy is as universal as possible.

INFLUENTIAL PARAMETERS ON SAVONIUS VAWT PERFORMANCE

Aspect Ratio

An important parameter that affects the power coefficient, torque generation, and general aerodynamic efficiency of Savonius VAWTs is the aspect ratio (AR = H/D). Studies have indicated that increased aspect ratios (usually greater than 0.80) result in maximum power coefficients and optimum tip speed ratios (TSR). This is mainly because of the minimized end-plate losses and enhanced flow direction at the rotor height. The experimental research by Roy and Saha (2013) and Dorel et al. (2021) became clearly positive according to the correlation between AR and Cp, as shown in Fig. 2. This trend is further supported by complementary numerical studies by Sobczak (2018), which indicate that an increased AR indents the harmful diffusion of the wind around the ends of the rotor, thereby improving energy collection. As a result, although very low-AR designs can necessitate the use of end plates in order to reduce extreme performance power, maximizing a higher AR is a basic approach to the enhancement of the efficiency of the Savonius VAWT as shown in Fig. 3.

The graph shows the performance of five wind turbine designs with varying shape ratios. This demonstrates that shape ratio 2 (AR2) is the most efficient (CP≈0.125) at wind velocities of approximately 10 m/s; thus, it is the most effective design within this range. As a rule, the design efficiency of all designs rises as the wind speed rises until a peak, then decreases. The design with the lowest ratio (AR0.5) exhibits very poor performance compared to the others, while the taller designs (AR4 and 5) achieve good efficiency, especially at medium speeds, but their peak efficiency does not exceed that of AR2. It can be concluded that selecting the appropriate shape ratio (AR2) is crucial for maximizing wind energy utilization.

Number of Blades

The blades of the Savonius VWAT have a significant effect on the performance of the model because they affect the torque and power output. Although the number of blades can be increased to boost the starting torque, studies have shown that this could be at the expense of a reduction in total efficiency. The following sections discuss the effect of increasing the number of blades.

Two-blade-shaped

Two blades are better as opposed to multiple blades during fast wind speeds. This was supported by a study by Gumilar et al. (2019) on a Savonius L vertical-axis wind turbine. They analyzed that the turbine produced a maximum power of 643.52 W at wind speed of 20 m/s and a rotor speed of 50 rad/s, which is higher as compared to the previous research. The peak torque was also seen to be 47.64 N-M at a wind speed of 20 m/s and rotational speed of 1 rad/s. The hypothesis is that, at identical wind velocity, a two-blade turbine will be able to generate additional power than other turbines, despite the reduction in the rotor torque with a rise in the rotor speed.

Three-Blades

Three blade Savonius turbines will probably be effective in slow wind speed due to high power coefficient and high torque. As an illustration, Prabowo et al. (2023) conducted a study experimentally to reinforce this. Two and three blade numbers were tested and twisted in angles of 90 run, 180 run, 270 run and 360 run at a wind speed of 0 m/s to 5 m/s. They discovered that they had the best results with three blade design and twist angle of 180 and the result was low cut-in speed of 1.51 m/s.

Four-blade

The four-blade design may be more effective than the three-blades one particularly at high wind velocities because it provides more rotational velocities and power production. Soegiharto et al. (2024) analyzed this with a Savonius helical wind turbine with three and four blades with the help of Computational Fluid Dynamics (CFD). The simulation model dimensions were 0.008 m diameter of the shaft, 0.24m diameter of the outer part and 0.4m height.

The wind speed was set to 4, 5, and 6 m/s for both types of turbines. Simulation analysis of the two turbines revealed that the four-bladed turbine performed better than the three-bladed turbine. As an illustration, the four-blade turbine generated a higher peak power output (6,128 watts) at a lower rotational speed (498,216 rpm) than the three-blade turbine (4,391 watts and 545,656 rpm) with an airflow of 6 m/s. This variation in output is important because there has been an effort to change the number of blades in the winding turbine design to attain optimal output.

Increased Number of Blades

The impact of the number of blades on turbine performance is one of the key topics that has been researched, but increasing the number of blades increases the drag and reduces the efficiency of turbines under high velocities. Indicatively, (Kumar et al., 2025) used numerical analysis to establish the torque and power coefficients of two-, three-, and 4-bladed Savonius turbine. The study results indicated that the three-bladed design had the best performance, with a ratio of 1.0 tip speed between the other blade designs. In addition, a considerable improvement in the torque and power coefficients was noted in all the three designs with an increase in the free-stream velocity.

Complexity in Design

The blade number is a significant design solution that considers both performance and manufacturing complexity and cost because additional blades may increase complexity during construction (Soegiharto et al., 2024). The number of rotor blades has a direct effect on important performance features at different wind velocities. The experimental results of wind tunnels on two-bladed rotors with various combinations of blades (Ali, 2013) showed that the two-bladed rotor had better torque and power coefficients than its three-bladed counterpart. The findings of this study are presented in Fig. 4 and Fig. 5, which show the torque and power coefficients versus the Tip Speed Ratio (TSR).

Overlap Ratio

The overlap ratio has the power to significantly impact the performance of Savonius wind turbines because it influences the coefficient of power and torque under various conditions. Research has indicated that optimal ratios of overlap might be helpful, especially in situations where the wind speed is low, whereas gains can be defeated when the ratios of overlap are high. The findings are discussed in the following sections.

Ideal Ratios

Research has found that the ratio of optimal overlap 0.15 to 0.18) can significantly enhance the power coefficient of Savonius-type turbines, particularly when definite shapes are used, such as SR3345 and SR5050. For example, Karimi et al. (2023) compared two blade profiles in an open-circuit wind tunnel at a wind speed of 6 m/s. They experimented with the power and torque coefficients at overlap ratios of 0–0.3. These observations indicate that the SR3345 blade is the best when the tip speed ratio is lower than one and the SR5050 blade is the best when the tip speed ratio is greater. The analysis indicated that SR3345 and SR5050 might have minimum power coefficients at the central shaft at an overlap ratio of 0.0; the same happened at an overlap ratio of 0.18.

Torque Improvements

Overlapped rotors can be used to eliminate negative torque effects, which occur in non-overlapped designs and enhance the overall performance. Hassanshahi and Kharati-Koopaee (2024) determined the role of the overlap ratio using the Savonius rotor, whose inner blades are parallel to the main blade tips and roots. They discovered that at low overlap ratios, an inner blade with a tip parallel to the main blade root gives superior power and torque coefficients to any inner blade or to a standard rotor. They discovered that the inner blade design, in which the rotors overlapped, performed better than the non-overlapping design, which produced a negative torque. However, it was also found that in cases where the overlap ratio was high, a rotor with an inner blade failed to benefit at all in comparison with a normal rotor.

Arc Angle

The performance, especially the power and torque coefficients, of Savonius vertical-axis wind turbines (VAWTs) depends mostly on the arc angle (or camber angle of VAWTs). An important design factor was also shown to be the maximization of the arc of the blade to enhance the effectiveness of the turbine. As an illustration, other researchers have established that a two-bladed Savonius wind turbine with a 160 arc angle of the blade arc had a maximum (CP) of 0.2836, which was 8.37% higher than that of a standard Savonius turbine (Mao and Tian, 2015). Nevertheless, a second 3D numerical study suggested that the highest power and torque coefficients are 0.0261 and 0.501, respectively, at an arc angle of 180 degrees (Akhlaghi and Ghafoorian, 2023). Normally, it is important to note that rotations (rpm) and angular velocity (rad/s) at different TSRs accurately determine the power coefficient Cp and torque coefficient (Cm) values at similar arc angles. Fig. 10 and Fig. 11 represent the power factor and torque coefficients respectively of the arc angle versus the TSR.

Shape Factor

The geometry of a Savonius (VAWT) can be altered to enhance the turbine power coefficient and performance, although this entails a change in the shape factor. This is done by changing the rotor design, which entailed the quantity of blades, wholeness of the blades, and other geometrical variables, so that the interaction with the air is optimized.

The influence on Aerodynamic Performance

The shape factor determines the geometry of the rotor that is the amount of arms that is attached to the rotor that enhances the aerodynamic efficiency of the Savonius VAWT. This alteration increases the power coefficient (Cp), and overall torque, and, therefore, the efficiency of the turbine (Farajyar et al., 2023). The most critical aspects are the shape parameters of the blade fullness, which have to produce power. Tian et al. (2015) also in the same study reported that a blade fullness of 1 gave the maximum power coefficient. They investigated the influence of this and other geometric ratios on the power of a two-blade Savonius VAWT by investigating the flow as computational fluid dynamics (CFD). They measured the dependence of blade fullness and performance when Reynolds averaged Navigator (RANS) equations and a renormalization group turbulence model were considered. They reported a maximum Cp of 0.257, which was 10.98 percent greater than that of a typical Savonius turbine with a blade fullness of 1.

Rotor’s Modifications

The geometry of the Savonius rotor (e.g., aspect and overlap ratios) can be modified significantly to enhance the functioning of the turbine. Prabowoputra and Prabowo (2022) achieved an optimal overlap ratio between 0 and 0.3, to ensure that the performance was maximized. They varied most parameters of their research, including the aspect ratio, overlap ratio, type of blades, number of blades, and multi-stage layout. These changes caused the 8-25 percent growth in performance. The multistage arrangement can be used in combination with other design parameters to enhance performance. Two or three blades in a Savonius VAWT are usually the preferred choice in order to be able to perform better and to be more stable.

(Prabowo et al., 2023) experimentally demonstrated that a three-bladed arrangement of Savonius VAWT with a certain twist angle can be used to maximize performance, especially at low wind velocities. (Farajyar et al., 2023) determined the ideal design of a Savonius VAWT with Kriging method-specific geometric parameters, with a shape factor of 0.5, which was the most efficient at a given tip speed ratio. Their analysis involved examining the shape factor values of 0.2, 0.5, and 0.7 in comparison to the reference configuration, which is characterized as a complete semicircular shape with a shape factor of 0. Fig. 12 illustrates the Cp outputs for various shape-factor values.

Moreover, the addition of dimples and fins to Savonius VAWT blades has been shown to improve performance by reducing drag. (Aher and Singh, 2024) evaluated Savonius performance with and without dimples and fins under low incoming wind velocity conditions (5, 8, 10, and 12 m/s) using CFD analysis. The results indicate that the combination of dimples and fins on the blade surface of the Savonius vertical-axis wind turbine enhances performance at an air velocity of 10 m/s, resulting in increased torque and output power for electricity generation.

The other alteration that can be seen as influencing power improvement is the application of zigzag or wavy surfaces through amplification of the drag coefficient (CD). The concern of (Sumiati et al., 2024) is the impact of introducing wavy (zigzag) changes to the concave faces of Savonius blades on performance. The films were semicircular with a zigzag shape on a concave surface with thicknesses of t = 0.25, 0.75, and 1 mm. The data showed an increase in performance of 29 per cent compared with the traditional designs at 5 m/s. In this study, a 3D model of computational fluid dynamics was applied to a simulation with TSR = 0.6. The maximum drag coefficient was 1.817 for the zigzag model with a thickness of 1. It has a mean drag coefficient 14 percent greater than that of a conventional semicircular rotor. The largest Cpk (0.315) was equally thick (1 mm). As a result, the coefficient of power increased by 29% compared to that of the conventional semicircular rotor. The Savonius rotor performs better because the total stress on the blade is optimized to a zigzag pattern on the concave surface.

Blade Geometry

This as well as the optimization of the blade geometry, guide gap flow and variation of the blade profile have all played significant roles in the Savonius performance. The outcome of the conclusions presented by Al-Gburi et al. (2023) shows that the power coefficient had grown by 22.8 percent due to the influence of the geometric design on the improvement of performance. Availability of omnidirectional guide vans which influence direct wind flow can also enhance the power of the guide vanes and the torque coefficients of specific optimum tip speed ratio. The impact of the omnidirectional guide vanes (ODGV) on Savonius VAWT power and torque coefficients of an S-shaped VAWT was mathematically investigated (Alli & Jayavel, 2019).

They arrived at the conclusion that ODGV addition also boosts the power and torque and consequently boosts the performance of the VAWT when ODGV is present at a tip-speed ratio of 0.45-0.8. The most desirable ratio of the tip speed of VAWT was 0.6. Even though these studies are aimed to improve performance through the design modification, the consequences of the complexity and costs are to be taken into account.

They found that ODGV enhances power and torque, thereby improving performance of the VAWT at 0.450.8 tip-speed ratio of in an ODGV. The optimal tip-speed ratio of the VAWT was 0.6. Although these studies aimed at performance improvement by implementing design changes, it is necessary to consider the trade-offs associated with it, including further complications and possible cost effects. In addition, the efficiency of such adaptations can differ according to concrete environmental factors and turbine usage.

Wind Speed

Typically, an increase in the input wind speed results in a marginal increase in Cp values; hence, elevated Reynolds numbers do not substantially enhance turbine performance. Farajyar et al. (Farajyar et al., 2023) showed that the Cp value at TSR = 0.1 with inlet velocity Vin = 12 m/s, was 10% and 20% higher than the Cp values corresponding to Vin = 10 m/s and Vin = 8 m/s, respectively. However, at a high TSR, such as 0.5, the Cp values for Vin = 12 m/s were 3% and 10% higher than those for Vin = 10 m/s and Vin = 8 m/s, respectively, and the favorable pressure increased with increasing wind velocity which is presented in Fig. 13 (a). Furthermore, according to the information presented in Fig. 13 (b), the turbine's overall torque at Vin = 12 m/s exceeds that of the other operating circumstances.

Curtain

The performance of a Savonius vertical-axis wind turbine (VAWT) can be significantly enhanced by implementing a curtain system. In this method, stationary curtains are placed strategically to prevent the rotor from encountering the wind, but they are placed to block the wind prior to encountering the rotor against the wind, thus reducing the negative torque that hinders the rotation. Shouman et al. (2022) used numerical analysis to study how certain curtain lengths and angles in combination with fins affect Savonius VAWT. They have determined that an optimal curtain system is very efficient in the working of turbines. Specifically, the power coefficient also grew by 42 percent when a single fin and curtains with a certain angle (30 o and 50 o) and length (1000 and 1150 mm) were taken. The fins also play a significant role in enhancing the efficacy of the air passing through the blade. Shouman and Helal (2023) established that in counter-rotating Savonius turbines (CRSWT), the power coefficients in the turbines rose nearly by 48 per cent with efficient curtain layouts. They had computed the geometrical data optimization of the suggested curtain arrangements via computational fluid dynamics (CFD) Rajavasyam and had investigated the effect of inclusion of fins in the blade. The best power coefficient that was achieved was at blade lengths of 500 and 550 mm, angles of 50 and 30 degrees, and application of a single fin. However, curtain plates can be used to decrease negative drag, thereby enhancing the overall aerodynamic performance of the rotor.

Investigating the elliptical-bladed profile in combination with the curtain plate augmenter in front of the rotor blades (Alom, 2021), a two-dimensional unsteady numerical analysis was performed using the SST k-om turbulence model. The 2D unsteady findings indicated that elliptical plate blades with curtain plates offered superior aerodynamic performance. (Kurniyawan et al., 2020) Made modifications on the original Savonius turbine by fitting single and multiple-layer blades on the tip blade with the overlap ratio (OR) of 10 and 15, respectively.

Tests were conducted at wind speeds of 6.46, 6.99 and 7.27 m/s produced by blower fans in a 2 × 2 configuration. These findings suggest that, as the number of layers continues to grow, the Savonius power coefficient increases by 22.4 percent and 11.2 percent at operating ratios of 10 percent and 15 percent operating ratios, respectively. An overlapped turbine (90 layers) Savonius turbine with an overlap ratio (OR) of 10 percent yielded the highest power coefficient (Cp) of 0.12. Most of these arrangements, although they have been shown to enhance the performance of Savonius VAWTs, are feasible for their implementation in practice with trade-offs between complexity and cost. Such changes are crucial to the research of Shouman et al. (2022). They showed how curtain designs influence the power coefficient (Cp) of the turbine.

In their analysis, they depicted the turbine torque in complete rotation against the azimuth angle, demonstrating how the curtains minimize the negative torque on the returning blade. These are comprehensive statistics that point to the fact that this type of geometric extensions can lead to a much smoother and more powerful rotation. Fig. 14 (a) indicates the results of the effects of different curtain designs on Cp of the Savonius VAWT. It was plotted as a function of azimuth angle with a tip speed ratio (TSR) of 0.23 to show the torque of the whole turbine in full rotation. These results are shown in Fig. 14 (b) (Farajyar et al., 2023).

Blades Profile

Blade profile greatly affects Savonius VAWT efficiency, torque, and power output. Research has shown that changing the blade form, number, and structure can greatly affect turbine function. Various research has tried to maximize small vertical-axis wind turbine production by adjusting the design.

A numerical investigation of the number of blades in a Savonius-type turbine indicated that a three-bladed rotor was most productive (Saeed et al.,2022). Testing a Savonius turbine with U-shaped blades at 315 m/s determined torque, power, and rotation (Rizaldi and Brahmana, 2024). The results showed that wind speed increased rotational speed, torque, and power. This showed that the turbines could handle different wind speeds. Chang et al. (2021) found that the elliptical ratio affected the turbine's performance in a three-bladed Savonius VAWT. The goal is to use the best small-scale turbine designs from this article in later development phases.

Current studies highlighted how CFD simulation and the SST k-w model of turbulence can optimize Savonius turbine blade design. Using a 20% overlap semicircular blade, Rizk and Nasr (2023) lowered their torque coefficient to 0.3065. Shahriare et al. (2025) followed with two improved designs (M1 and M2) that increased power coefficients by up to 12.5. Nasef et al. (2025) studied unique add-on blade options, with the fin-shaped model performing best (38.5%). These studies suggest that improving the blades' structural optimization by changing the fundamental form or adding intelligent accessories could greatly improve Savonius turbine efficiency.

CONCLUSIONS

The Savonius vertical-axis wind turbine (VAWT) has been the object of intense research attention because of its structural simplicity, omnidirectionality, and self-starting ability, which makes it a promising target for small-scale and decentralized energy generation. This review summarizes experimental and numerical research that shows that performance can be optimized significantly by means of specific optimization. Some of the key findings are that an aspect ratio greater than 0.80, a three-blade design, an overlap ratio of 0.15-0.18, and advanced blade profiles (SR5050) have a large potential to increase the power coefficient (Cp). Moreover, crescent-shaped and omnidirectional deflectors, curtain systems with finite, and surface additions, such as slotted blades or zigzag blades, have been demonstrated as aerodynamic augmentation systems that reduce negative torque and increase Cp by up to 125 percent in the given designs. Computational Fluid Dynamics (CFD) has played a crucial role in the verification of these improvements by offering important information on complex flow structures and allowing parametric optimization to be performed with accuracy. All these combinations increased the peak Cp of the developed Savonius turbines to approximately 0.38 under ideal conditions, which is a significant advancement compared to the old semicircular turbines.

Nevertheless, an efficiency gap remains, which can be tangibly felt with lift-based turbines. Future studies must overcome existing practice obstacles and implement new trends to fill this gap and make the concept more widely adopted. Some promising research directions include the following:

Sophisticated Hybrid Systems

The creation of sophisticated hybrid structures, including the dual-shaft Darrieus-Savonius system, which makes use of the high-starting torque of Savonius rotors and the high-speed efficiency of Darrieus rotors, is one of the key steps in achieving a greater overall energy output.

AI-Assisted Optimization

Artificial Intelligence (AI) and Machine Learning (ML) combined with computational fluid dynamics (CFD) provides an efficient alternative for operating in complicated multi-parameter design spaces. These tools will be able to effectively determine non-intuitive optimal geometries and operation strategies that would be difficult to find using traditional methods.

Additive Manufacturing

With the introduction of 3D printing (additive manufacturing), it is now possible to manufacture complex, optimized blade geometries and integrated components at low cost, prototyping is now quicker, and specific turbines can be introduced to a particular location.

FIGURES AND TABLES

Table 1. Summary of key geometric and operational parameters, their optimal ranges, performance impacts, and associated trade-offs as identified in the literature.

Parameter	Typical Optimal Range	Performance Impact (Cp / Torque)	Key Trade-offs and Notes	Primary Validation Method(s)
Aspect Ratio (AR = H/D)	> 0.80	Higher AR increases Cp and optimal TSR by reducing end losses. (Roy and Saha, 2013; Dorel et al., 2021)	Very low AR requires end plates to mitigate severe performance drop. Increased structural considerations for very high AR.	Experimental (Wind Tunnel), CFD
Number of Blades	2-3 (Context-dependent)	2 blades: Higher peak power at high TSRs. (Gumilar et al., 2019) 3 blades: Superior for low-wind speed operation, better torque distribution, lower cut-in speed (~1.51 m/s). (Prabowo et al., 2023)	Increasing blades generally increases starting torque but can reduce peak efficiency and increase drag/complexity at high TSRs. (Xavier et al., 2018)	Experimental, CFD

Parameter	Typical Optimal Range	Performance Impact (Cp / Torque)	Key Trade-offs and Notes	Primary Validation Method(s)
		4 blades: Can outperform 3 blades at higher wind speeds (>6 m/s) in some helical designs. (Soegiharto et al., 2024)		
Overlap Ratio (δ = e/d)	0.15 - 0.18	Maximizes Cp by improving flow through the rotor and reducing negative torque on the returning blade. (Karimi et al., 2023; Ebrahimpour et al., 2019)	Lower ratios (e.g., 0.15) may be better for very low wind speeds; higher ratios can negate benefits. Optimal value can be blading profile dependent (e.g., SR3345 vs. SR5050).	CFD, Experimental
Blade Arc Angle	160° - 180°	160°: Reported Cp of 0.2836 (8.37% increase over 180°). (Mao and Tian, 2015) 180°: Reported max torque coefficient Cm = 0.501. (Akhlaghi and Ghafoorian, 2023)	This is an area of conflicting findings, indicating optimal angle may depend on other geometric factors and TSR. Represents a trade-off between captured drag and flow guidance.	CFD, Experimental
Blade Shape Factor / Profile	N/A (Discrete Profiles)	Novel Profiles (e.g., SR5050): Cp up to 0.38 (39.19% improvement). (Babu and Patel, 2024) Modified	Move away from standard semicircles. Trade-off involves manufacturing	CFD, Experimental

Parameter	Typical Optimal Range	Performance Impact (Cp / Torque)	Key Trade-offs and Notes	Primary Validation Method(s)
		Bach/Elliptical: 8-25% gains. (Prabowoputra & Prabowo, 2022; AR et al., 2019) Blade Fullness = 1: 10.98% Cp increase. (Tian et al., 2015)	complexity vs. performance gain.	
Aerodynamic Augmentation	N/A (System Dependent)	Deflectors (Crescent): +19.51% Cp. (Hedayati et al., 2024) Omnidirectional Deflectors (AOD): Up to +125% Cp. (Aboujaoude et al., 2024) Curtains with Fins: +42% to +48% Cp. (Shouman et al., 2022; Shouman and Helal, 2023) Stators (Curved): Up to 7.59x torque increase. (Hedayati et al., 2024)	Significant gains but add external complexity, cost, and structural load. May not be omni-directional (except AODs).	CFD, Experimental
Surface Modifications	N/A (Design Dependent)	Slotted Blades: +11% performance. (Ramarajan and Jayavel,2021) Zigzag Surfaces: +29% Cp at 5 m/s. (Sumiati et al., 2024) Layered Blades: +11.2% to +22.4% Cp. (Kurniyawan et al., 2020) Dimples and Fins: Improved	Modifies local flow/separation. Trade-offs include potential structural integrity issues and manufacturing cost.	CFD, Experimental

Parameter	Typical Optimal Range	Performance Impact (Cp / Torque)	Key Trade-offs and Notes	Primary Validation Method(s)
		performance at ~10 m/s. (Aher and Singh, 2024)		
Configuration	N/A (System Design)	Multi-Bucket Rotors: Avg. +8.43% Cp. (Soegiharto et al., 2024) Hybrid (Darrieus-Savonius): Leverages low-TSR torque of Savonius and high-TSR efficiency of Darrieus; dual-shaft config. boosted Cp by 35% (low TSR) and 25% (high TSR). (Ghafoorian et al., 2025)	Increased mechanical complexity and control requirements. Design must manage interference between rotor types.	CFD, Experimental

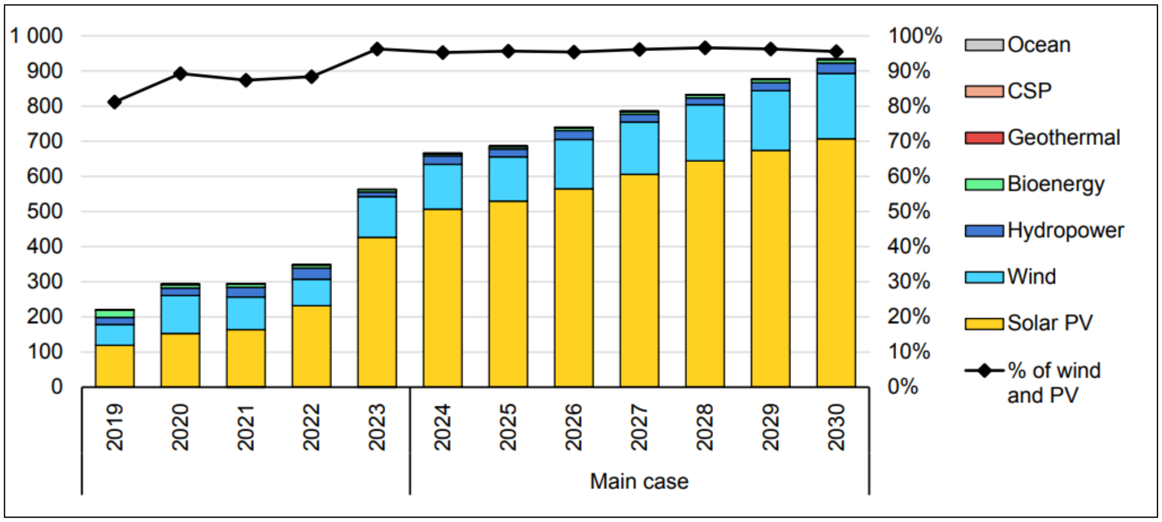

Fig. 1. Renewable electricity capacity additions by technology, main case, 2019-2030 Renewables, I. E. A. (2024).

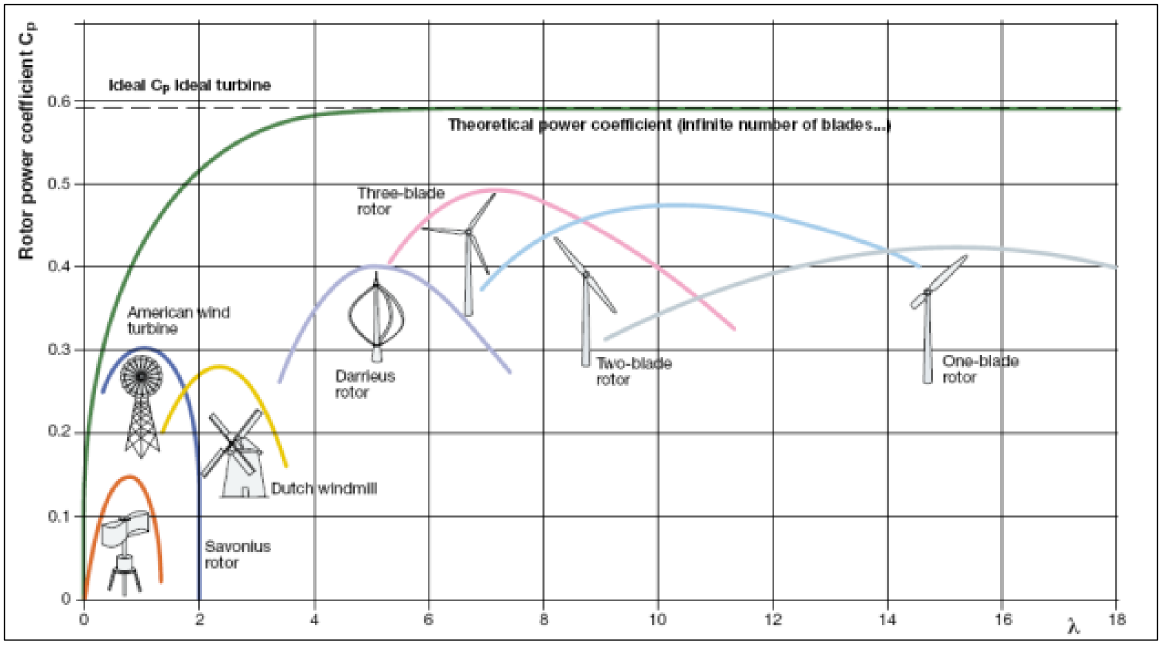

Fig. 2. Cp – TSR(λ) characteristics of different wind turbine blade designs (Ajayi, 2012).

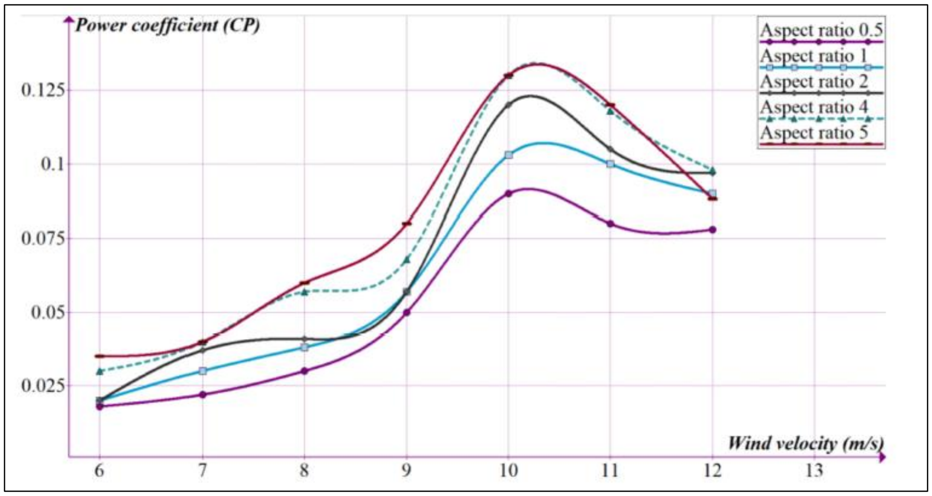

Fig. 3. Power coefficient for rotors with different aspect ratio values (Dorel et al., 2021).

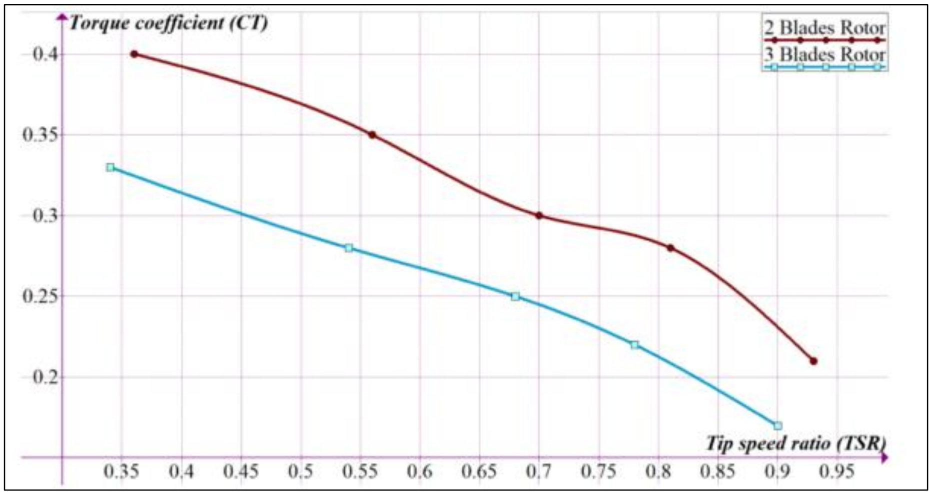

Fig. 4. Torque coefficient (CT) for two- and three-blade rotors (Dorel et al., 2021).

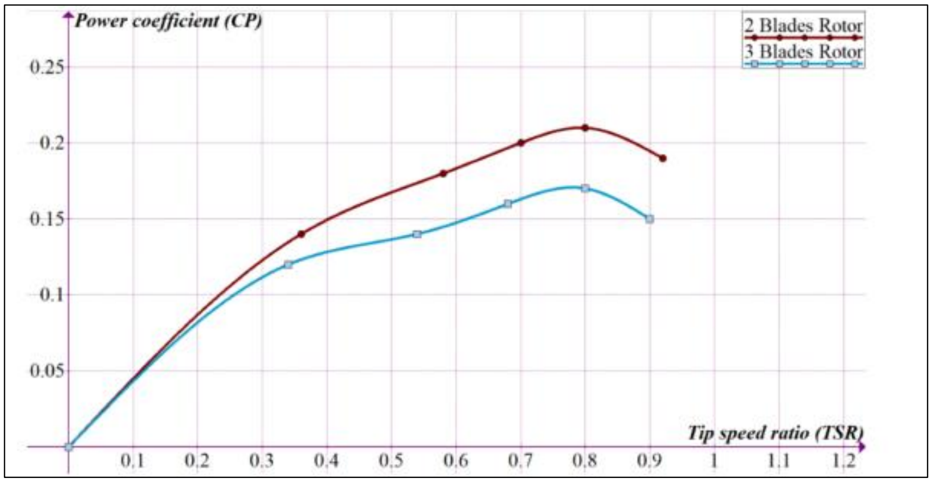

Fig. 5. Power coefficient (CP) for two- and three-blade rotors(Dorel et al., 2021).

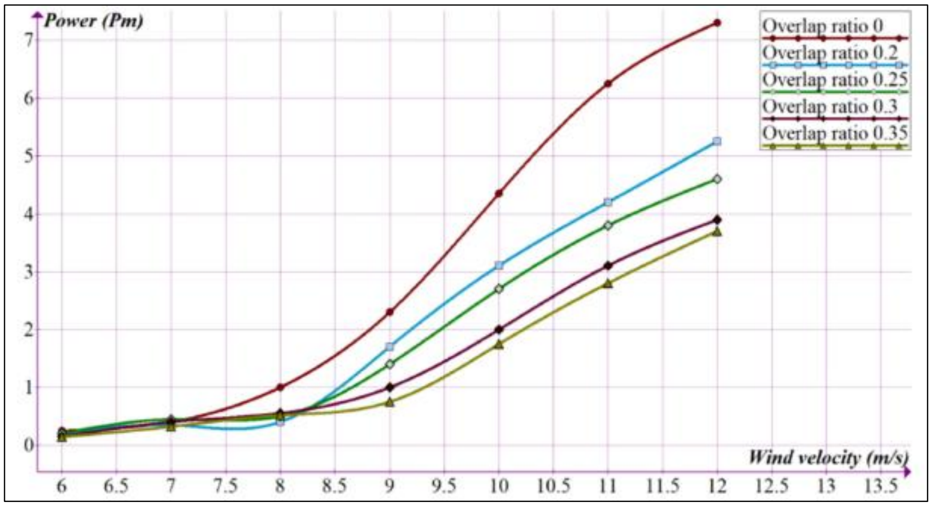

Fig. 6. Power obtained for different overlap ratio values (Dorel et al., 2021).

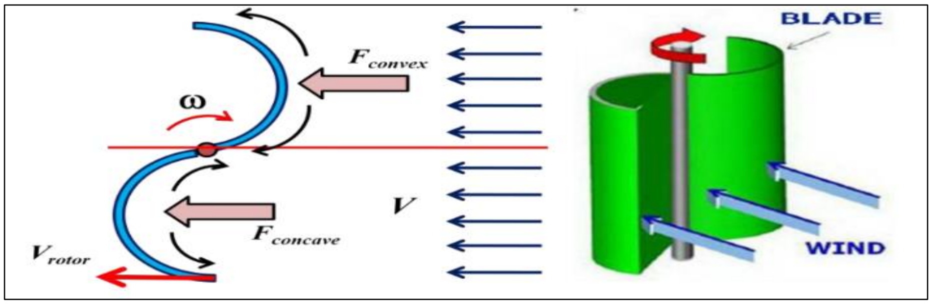

Fig. 7. A Schematic shows the drag forces exerted on a two-blade Savonius (Ali, 2013).

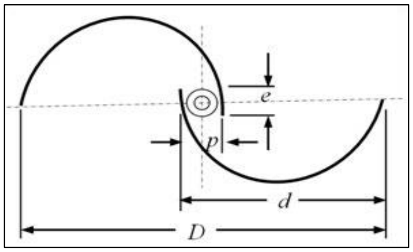

Fig. 8. A 2-blade Savonius rotor (Roy & Saha, 2013).

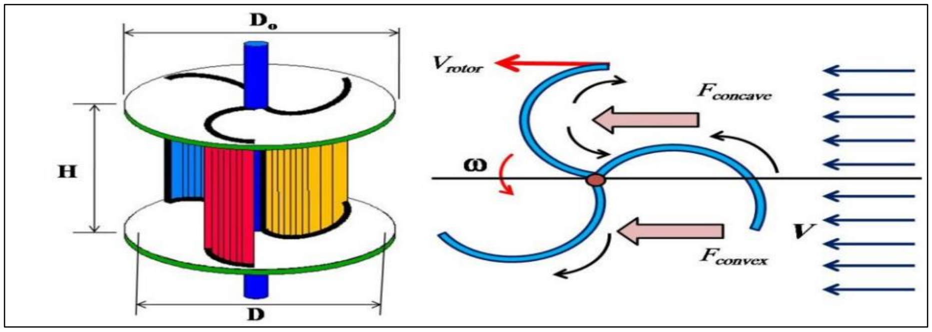

Fig. 9. A schematic shows the drag forces exerted on a three-blade Savonius (Ali, 2013).

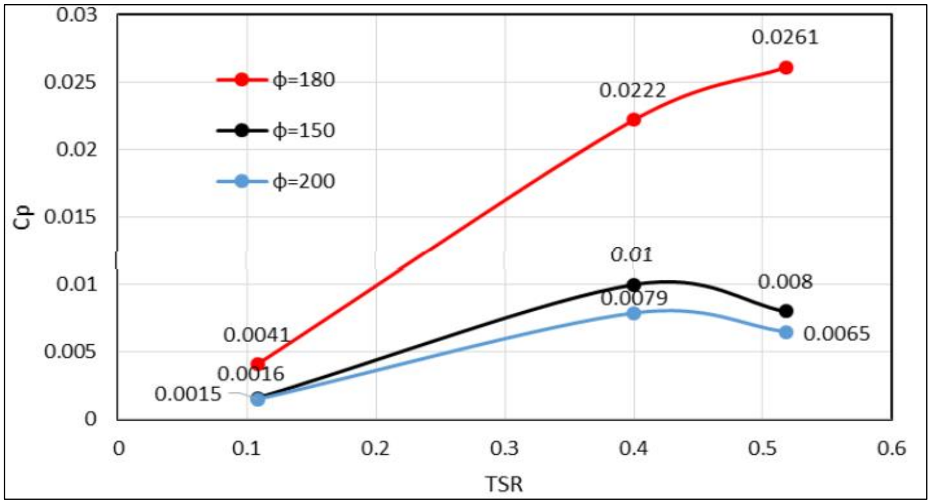

Fig. 10. Cp in terms of TSRs for different arc angles (Akhlaghi & Ghafoorian,2023).

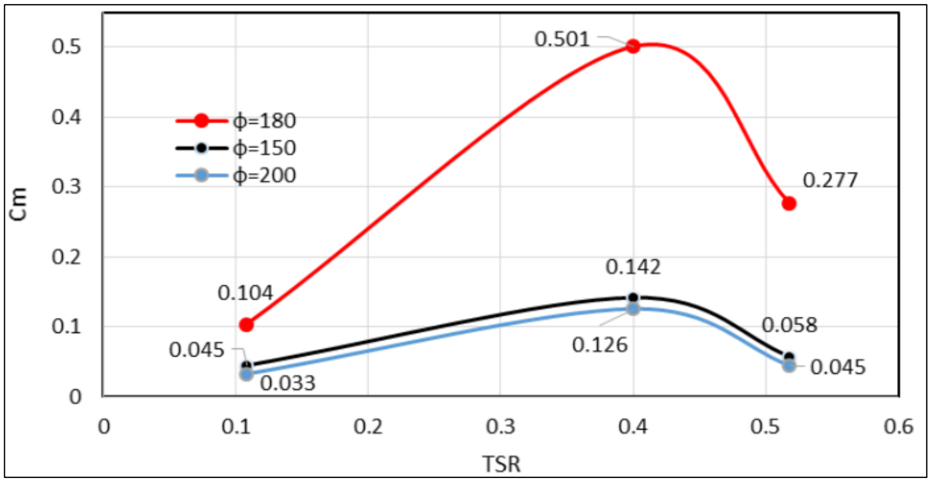

Fig. 11. TSR coefficient torque Cm with varied arc angles (Akhlaghi & Ghafoorian,2023).

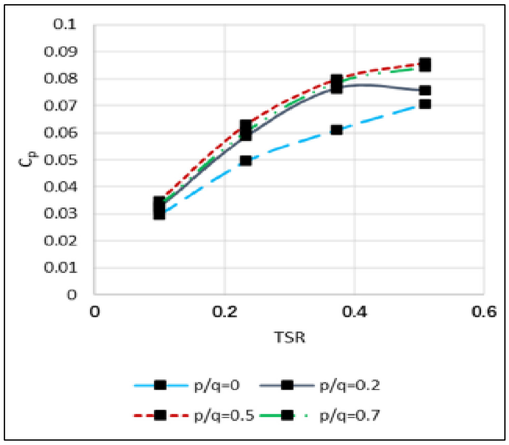

Fig. 12. Cp values for different shape factors (Farajyar et al., 2023).

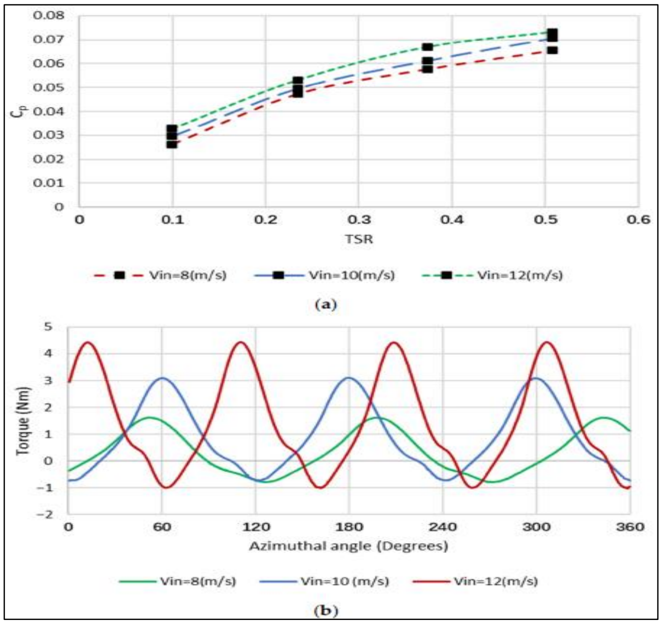

Fig. 13. (a) Cp for different inlet wind velocities; (b) Torque at TSR plot different inlet wind velocity values at TSR = 0 (Farajyar et al., 2023).

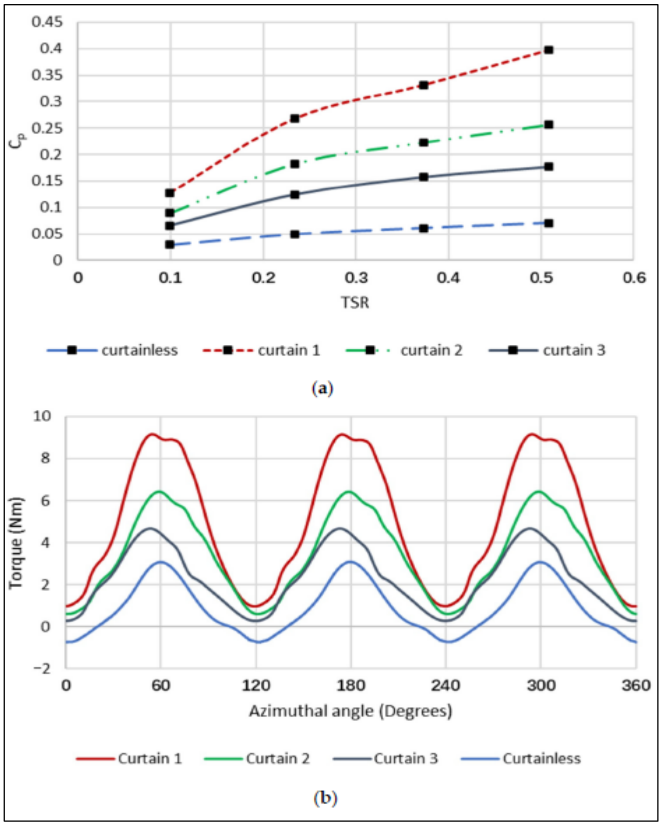

Fig. 14. (a) Cp values for different curtain configurations; (b) Torque plot for different curtain configurations at TSR=0.23 (Farajyar et al., 2023).

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