Innovations

A Review on Recent Significant Researches on Drag and Lift Type Vertical Axis Wind Turbines (VAWT)

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Abstract: *A vertical-axis wind turbine (VAWT) is a sort of wind turbine in which the rotor shaft is set perpendicular to the wind flow direction. There are mainly two types of VAWTs i.e. drag type and lift type. The Savonius wind turbine or rotor is a drag-type VAWT. Due to its simple and robust design with relatively poor efficiency, it is used whenever reliability is more significant than efficiency.Further Savonius turbines are broadly categorized into straight bladed and helical bladed. The Darrieus wind turbine is a lift-based VAWT. Being lift-type, the Darrieus wind turbines can extract more power from the wind compared to drag-type wind turbines.However, equipped with salient features such as easy to design, lower cost and high reliability, VAWTs have not gained much attraction for commercialization due to poor efficiency. The present paper summarizes the recent significant researches rendered inrecent years in the field of VAWTs.*

Keywords: *Vertical Axis wind turbine, Savonius turbines, Helical Savonius turbine, Darrieus Turbine, Coefficient of performance*

Introduction

A vertical-axis wind turbine (VAWT) is a kind of wind turbine in which the rotor shaft is normal to the flow direction of wind. The main components located at the ground (Gear box assembly, power shaft etc.). There are two main types of VAWTs i.e., drag-type and lift-type. Drag-type VAWTs, such as Savonius turbine, use the drag force of the wind to generate torque on the rotor shaft, while lift-type VAWTs such asDarrieus turbine, uses the lift force to develop power on the rotor shaft. Savonius turbines are simple to design with 2 or 3 blades on a rotor shaft. Compared to horizontal axis wind turbine, Savonius turbines have poor efficiencyHowever,they have higher reliability which makes them suitable for applications where reliability is prioritized over efficiency. Darrieus turbines, can extract more power from the wind due to lift-based design.Despite of advantages, including easy design, low-cost, and high-reliability, VAWTs are not widely commercialized due to their poor efficiency.

Recent researches (2021-2025) have focused on improving VAWT design and performance. Studies have explored new blade designs, and investigated the effects of turbine geometry and operating conditions on efficiency. Other research has examined the potential of VAWTs for urban wind energy harvesting and compared their performance to traditional horizontal-axis wind turbines. Overall, ongoing researches aims to address the performance improvements of VAWTs to improve their viability for commercial wind energy applications.

Savonius Turbines (Straight bladed)

A straight-bladed Savonius turbine is one in which the profile of the blades along the axis is perfectly uniform, as shown in Figure 1. Because of its simple design, Savonius rotors are self-starting, and its operation is independent of the direction of air flow (Modi, Roth, and Pittalwala 1981). Common applications of the Savonius rotor include: Running electric generators Pumping water Providing ventilation Agitating water to keep stock ponds ice-free during winter (Burton and Stern 1993; Vishwakarma 1999).

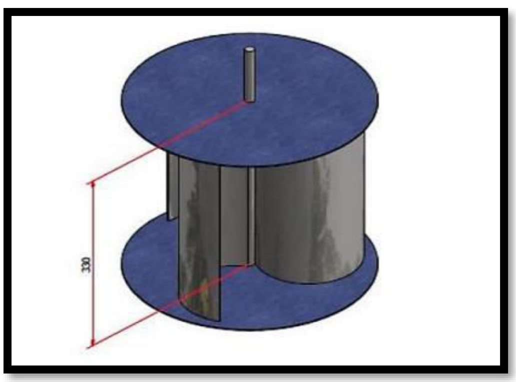

Figure1.A straight bladed Savonius by Lillahulhaq et. al. (2021)

Le et al. (2025) studied the effect of a new cylinder deflector system using 2D URANS simulation in CFD software.

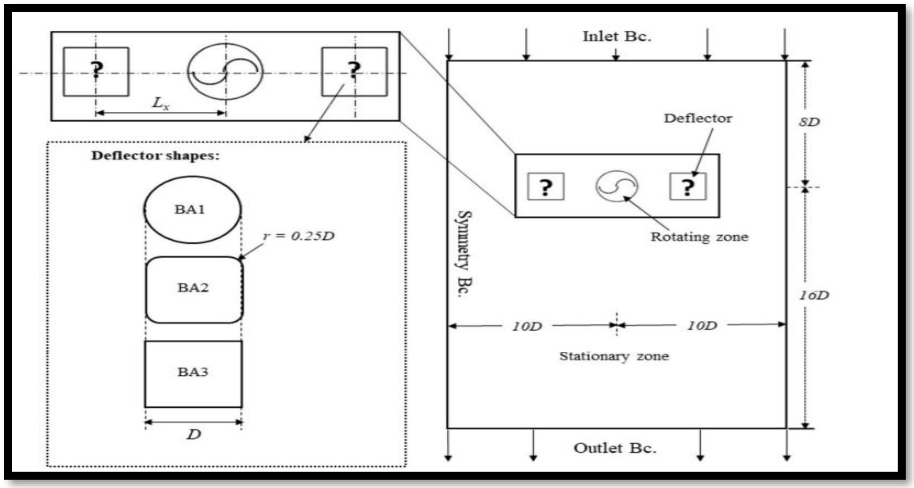

Figure 2. Computational domain and deflector shapes (Le et. al. 2025)

Its effect on the annual energy production (AEP) of the Savonius rotor was observed. Two deflectors were located in the centerline on either side of the turbine. The shape of the deflectors was evaluated in different flow fields. The results showed that different CPs can be achieved by the shape of the deflectors. A 133% increase in CP was found using the BA3 configuration. The advantages of this proposed design were proven.

Cui et al. (2025) in their research, showed about a new composite FB (floating breaker) which was constructed by combining Savonius hydrodynamic turbine (SHT) with double-pontoon FB. Based on traditional wave attenuation methods, wave energy was added to absorb and convert a part of wave energy so as to improve the wave-resisting performance. 2 key models were defined for the designed composite breakwater, including FB equipped with a fixed SHT (FS-FBS) and FB with a freely rotating SHT (S-FBS). The results showed that the composite FB integrated with SHT enhances the wave elimination performance by 20% and increases the wave resistance in surge, pitch and heave by 34%, 17% and 15%, respectively. The S-FBS also generated power from wave energy, with a generation performance of about 0.25, and demonstrated superior wave resistance with a wave resistance reduction of 45% compared with the FS-FBS.

Ahmed et. al. (2025)claimed that there is lot of research work conducted in the direction of noise reduction of wind turbines (Figure 3). The authors performed research and presented acomparison of different noise-reduction techniques of wind turbines. They found the best wind turbine modification with reducedamount of noise. Among all regression models, cubic-correlation furnished the best result with an R-squared magnitude of 85.90 %. It suggested a solid relationship between the aerodynamic performance of the wind turbines (lift/drag) and noise reduction.

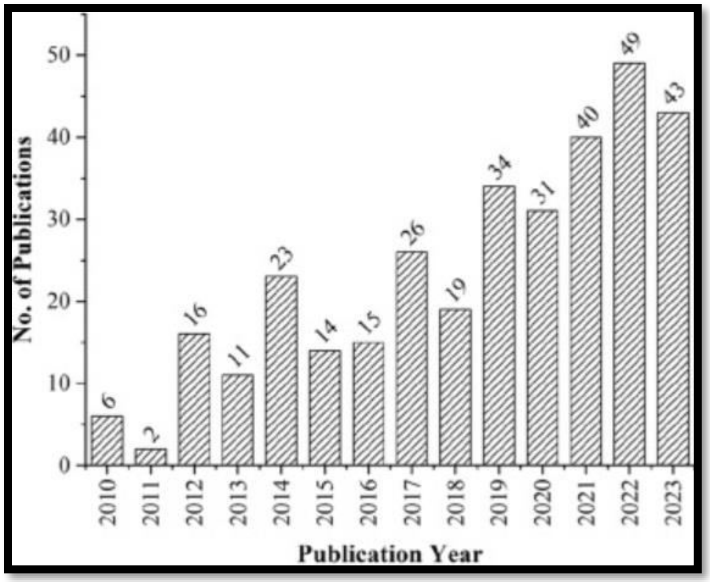

Figure 3. Trend of publications which used the keyword 'noise reduction of wind turbines' either in abstract or title from 2010 to 2023 (Ahmed et. al. 2025)

The regression model also predicted that the sinusoidal TE can lessen the lift-to-drag ratio by 5.10 %. In contrast, TE serration and semi-cylindrical rings were expected to improve the lift-to-drag ratio by 0.41 % and 1.70 %, respectively. In overall, a combination of ANC and TE serration was found expected to provide the best outcome in terms of noise lessening and related aerodynamic performance.Ahmed et al. (2025) had claimed that a lot of research-work has been done to reduce the noise of wind turbines. The authors compared various noise-reducing techniques used so fat. They found a best wind turbine modification that can reduce noise. It was found that cubic-correlation model can give best result with a R-square magnitude of 85.90%. It also showed a strong relationship between aerodynamic performance and noise reduction. The study also showed that a combination of ANC and TE serrations would give the best results in reducing noise as well as improving aerodynamic performance. This research can help improve the design of wind turbines.

Rabiei and Paraskivioiu (2024) studied the effects of installing a Savonius turbine on a forward-facing step, in different scenarios. They claimed that in earlier studies, the Savonius turbine had shown promising performance under uniform wind speed conditions. A potential application of the research was found in urban areas, where there are factors that can impede the uniformity of wind speed. By averaging the rotations of 50 cycles, it was found that the average power coefficient is almost equal to that of the turbine installed on a flat surface. However, despite of the average power coefficient being similar, a significant variation in the cyclic average power coefficient was also found. Finally, the effect of blade number and shape on turbine performance was also studied. In the results, it was found that the semicircular 2-bladed Savonius turbine was the most effective configuration.

Yan et. al. (2024) investigated the performance of Savonius rotor in the vortex flow fields which was generated by solar vortex engines. The study emphasized the potential ofperformance Savonius rotors and also offered insights for turbine design-optimization. This was confirmed by both experiments and computational fluid dynamics (CFD) to analyze the energy conversion accompanied with losses. After analysis it was found that, there is energy gainas well as loss. Turbines with an Aspect ratio of 1.5 and a twist angle of 270° showed an optimal performance, with a maximum power coefficient (Cp) of 29.25%. Additionally, optimizing the GR indicated that plummeting the surface area of turbine blade within the vortex flows can absurdly increase energy output. They claimed that this may be due to a higher density of energy in high-speed zones.

Yan et al. (2024) investigated the performance of the Savonius rotor in vortex flow fields generated by a solar vortex engine. The aim of this study was to evaluate the performance potential of Savonius rotors and provide insights for turbine design-optimization. The study analyzed energy conversion as well as losses using both experiments and computational fluid dynamics (CFD). The results showed that there are energy gains as well as losses. To optimize the turbine performance, the researchers studied various design parameters, including aspect ratio and twist angle. The results showed that turbines with an aspect ratio of 1.5 and a twist angle of 270 degrees showed an optimal performance with a maximum power coefficient (CP) of 29.25%. Additionally, the researchers found that reducing the surface area of the turbine blades within the vortex flow could increase energy production. This discovery could be important for improving the design of Savonius rotors and increasing their efficiency. The results of this study could be important for improving the performance of Savonius rotors and increasing the efficiency of solar vortex engines. In addition, this study could contribute to promoting the development and use of renewable energy sources, which is important for solving climate change and energy security issues.

Kaya et. al. (2024) presented a Taguchi-optimization study which was to at enhance the efficiency of a two bladed Savonius wind turbine. It was conducted by optimizing the inner blade parameters. An L9 orthogonal design was formed. A one-way analysis of variance (ANOVA) was also applied to assess the impact of each parameter, on the performance of wind turbine. By the research, optimal blades configuration was determined using Taguchi method. Furthermore, a MATLAB – Simulink model was also developed to simulate a hydrogen-production system based on an alkaline electrolyte. The electrical energy was produced by the optimized wind turbine to run the set-up. Wind speed data was collected for yearly based simulations from Vieste(Aasmalltown South of Italy). By the analysis it was found that the most effective parameter on the performance of the optimized turbine was the inner blade angle by 91.85 % and the least important parameter was calculated as the number of inner blades, by 0.98 %.

Kaya et al. (2024) presented a Taguchi-optimization study to increase the efficiency of a Savonius wind turbine. The aim of the study was to increase the efficiency of a two-bladed Savonius wind turbine. This was achieved by optimizing the internal blade parameters. An L9 orthogonal design was created. The effect of each parameter was assessed by ANOVA analysis. The optimal blade configuration was determined using the Taguchi method. A MATLAB-Simulink model was also developed. The most effective parameter on the performance of the optimized turbine was the internal blade angle. Wind speed data was collected from Vieste for annual based simulation.Ali et. al. (2023) proposed a simple design of sliding-mode triboelectric nanogenerator (TENG) by adopting Savonius-type vertical axis wind turbine (Figure 4). It was a unique low-cost and high-performance Savonius Turbine. The fabricated Savonius -TENG was found one of the promising solutions to drive small electronic devices and can be operated on very low wind velocities.

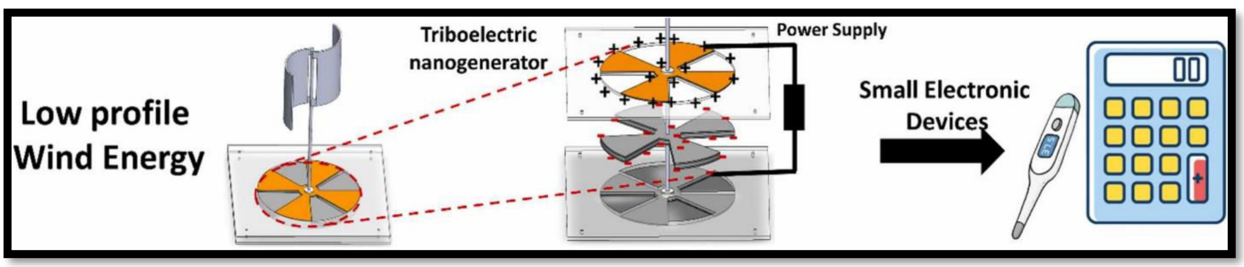

Figure 4. Simple design of sliding-mode triboelectric nanogenerator (TENG) Ali et. al. (2023)

Prabowoputra and Prabowo (2022) had studied the effect of the Phase-Shift Angle (PSA) on staged vertical axis Savonius wind turbine.

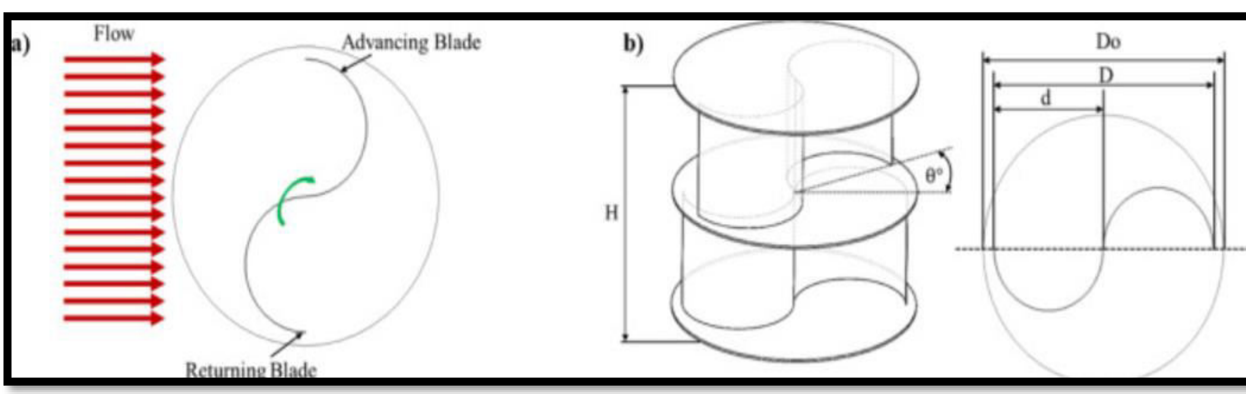

Figure 5. (a) Analyzed Savonius rotor in this work; (b) Savonius design principal parameters.

Phase-shift angles of 0°, 30°, 60°, and 90° were used on a two-stage Savonius wind turbine. The study used computational fluid dynamics (CFD). An SST (shear stress transport) turbulence model was also applied. Factorial design was used. The results indicated that PSA has an effect on the performance of the Savonius turbine. 30° phase shift was found to be the optimal PSA. This study may help improve the performance of the Savonius wind turbine. This study shows that PSA is an important factor that affects the performance of the Savonius wind turbine. The connected attributes, in the field of straight bladed Savonius turbine.

Table 1.Summary of recent researches on Straight Bladed Savonius turbine

S. No.	Authors	Year	Modification/Research brief	Chief Outcomes
1.	Le et. al.	2025	Numerically investigated the effect of a novel cylindrical deflector systems on the AEP of the a Savonius rotor by utilizing 2D URANS simulation in CFD	The highest increment of Cp was found up to 133% by using BA3 conf. at wide flow scenarios
2.	Cui et. al.	2025	Research by applying a new composite FB (Floating breaker) by combining Savonius hydrodynamic turbines (SHT) with a double-pontoon FB	FB with integrated SHT enhances the wave elimination performance by 20% and the wave resistance in surge, pitch and heave by 34%, 17%, and 15%, respectively
3.	Ahmed et. al.	2025	Systematic comparison of different noise reduction techniques of wind turbines to find the best wind turbine.	A combination of ANC and TE serration is expected to provide the best outcome in terms of noise lessening and related aerodynamic performance.
4.	Redchyts et. al.	2024	Comparison of aerodynamics of vertical-axis wind turbine against single and combined Savonius and Darrieus rotor.	The rise in torque coefficient was 14 %.
5.	Rabiei et.	202	Investigated the effects of	The conventional

	al.	4	installing a Savonius turbine on a forwards-facing step under various scenarios	semicircular two-bladed Savonius turbine was found as the most effective configuration, for the step configuration.
6.	Yan et. al.	2024	Investigated the performance of Savonius turbines, within the vortex flow fields were generated by solar vortex engines	Turbines with an Aspect ratio of 1.5 and a twist angle of 270° showed an optimal performance, with a maximum power coefficient (Cp) of 29.25%
7.	Kaya et. al	2024	Taguchi optimization study aimed to at enhance the efficiency of a two bladed Savonius wind turbine, by optimizing the inner blade parameters	The most effective parameter on the performance of the optimized turbine was the inner blade angle by 91.85 % and the least important parameter was calculated as the number of inner blades, by 0.98 %.
8.	Ali et. al.	2023	Proposed a simple design of sliding-mode triboelectric nanogenerator (TENG) by adopting savonius-type vertical axis wind turbine	The fabricated Savonius TENG was found one of the promising solutions to drive small electronic devices and can be operated on very low wind velocities
9.	Khani et. al	2023	Studied different soft computing methods ANN, CatBoost etc. with LR to predict the Cp (power coefficient) of	The authors recommended CatBoost to forecast a Savonius

			Savonius hydrokinetic turbines	hydrokinetic turbine's performance considering the multi-input variables.
10.	Prabowoputr et. al.	2023	Studied the effect of the Phase-Shift Angle on the vertical axis Savonius wind turbine performance as a renewable-energyharvesting instrument	The results indicated that PSA has influence on Savonius turbine's performance and 30° Phase shift was found being the optimal PSA.

Savonius wind turbine (Helical)

The helical Savonius turbine is a type of vertical-axis wind turbine (VAWT) in which the blades are shaped in a helical configuration along the axis of turbine as shown in Figure 6. Helical design improves the turbine's efficiency and performance compared straight bladed Savonius turbines.

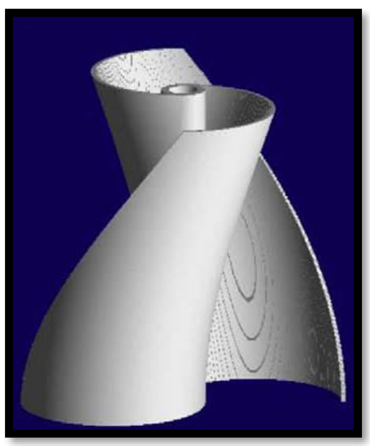

Figure 6. Helical Savonius turbine (Kamoji et. al. 2009)

The helical shape of blades allows smooth airflow and reducing the drag. This also helps to harness wind energy more effectively in turbulent conditions. These turbines can perform well at low wind speeds, making them appropriate for areas with less consistent wind.

Wind tunnel tests were conducted by Sun et. al. (2025) to systematically compare the aerodynamic performance of H-rotor and helical vertical axis wind turbines (VAWTs). The experiment was conducted in smooth and turbulent flows. The chief findings were, Self-starting performance of helical rotor was found to be improved by using NACA4418. References for the design of VAWTs in built environments were provided. Furthermore, they found that turbulence canculminate to serious fatigue issues for H-rotor turbines.(Gadakh, Jawale and Pardeshi 2024)performedresearch on development of Helical Type Wind Turbine. They claimed that the helical-type Savonius wind turbine is a form of vertical-axis wind turbine (VAWT) that beats a conventional straight-blade Savonius design. The authors claimed that helical wind turbines are becoming more and more popular in the field of wind energy harnessing due to their distinguishing design, which may deliver benefits above conventional horizontal- and vertical-axis wind turbines.

Lajnef et. al. (2024) emphasized on the helical Savonius wind rotor (HSWR) to find the impact of selecting the numerical model parameters on the performance characteristics. Experimental tests were performed on a 3D printed HSWR, in a wind tunnel. Good agreement was obtained by validating with numerical model with an error around 5%. The highest power coefficient was found 0.124 at a tip speed ratio of 0.73 and 0.1224 at a TSR of 0.69. It was performed by both numerically and experimentally.Ayadi et. al. (2023) presented a numerical study of a helical Savonius turbine equipped with a deflector. With the implementation of an optimized configuration for the new deflector system, the maximum power coefficient was improved to 0.168 at a tip-speed ratio of 0.7 compared to that of 0.1247 (without deflector). The performance was found to be increased by 34% compared to the same configuration without deflector. (Debnath and Gandhiranjan2023) performed a comprehensive study on design and development analysis as well as blade material selection of helical Savonius rotor. They found that selection of blade material is a significant parameter to enhance the starting torque of the rotor. In this regard,the aim was to study the detail experimental, numerical, and analytical review on HSR as well as selection of blade material with minimum production cost.

Bagade et. al. (2023) performed a numerical investigation on aerodynamic performance of a helical Savonius rotor encouraged by natural Shapes. They explored the possibilities in improving performance of VAWT in low wind speed terrains. The results suggested that, for low wind speed terrains, there is a requirement to find the combination of lift and drag type of profiles for blades. They learnt that naturally inspired shapes (profiles),can be a possible solution of combined lift and drag type wind turbines at low speeds. The blade shape for such collective lift and drag type wind rotor were deduced by literature survey. (Thomai, Sivamani and Venkatesan 2022) performed an experimental and numerical investigation to assess the Performance of Helical Bach vertical axis wind turbine(HB-VAWT), at low wind speeds. The experiments were conducted in natural wind at Wind Turbine Research Station, Kayathar, Tamil Nadu. 3D steady-state numerical investigations was performed. It is found that the numerical results were in accordance with the experimental data. It was also found that helical Bach models have higher overall performance compared to the conventional Bach models as well as conventional helical Savonius model.

(Kothe, Möller and Petry 2020) conductedresearch to test the aerodynamic-performance of a helical Savonius rotor model with a twist of 180°. They did it numerically and confirmed it experimentally. They also evaluated the results with a two-stagedSavonius rotor, with the same parameters. The experiment was carried out in the aerodynamic wind tunnel of Prof. Debi Pada Sadhu,in Fluid Mechanics Laboratory of UFRGS. Despite having a more complex manufacturing process than the two-stage turbine, the helical turbine presented a stable torque and highpower-coefficient. The maximum power-coefficient of the rotor was obtained for 0.65 λ for both cases. Furthermore, the numerical simulation and experimental results presented differences between 2.34% and 12.5% in the C_t and C_p values.

Zadeh et. al. (2021)performed an assessment and optimization of a helical Savonius wind turbine by changing the Bach's section.

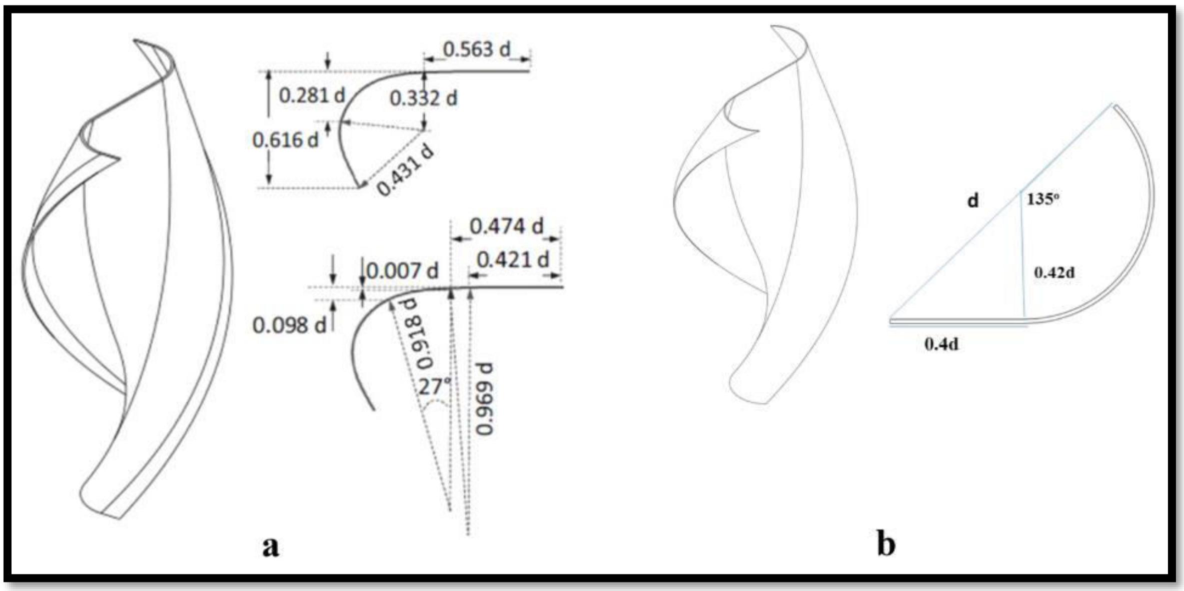

Figure7.A Schematic of the improved Bach model; b Schematic of the Bach model (Zadeh et. al. 2021)

Seralathan et. al. (2020) performed a simulation-study to analyze the static mechanical properties of a helical Savonius vertical axis wind turbine blade. The various static mechanical properties were observed to be maximum, at a wind-load of 15 N. The outer edges of the helical Savonius vertical axis wind turbine blade was also observed. It was found that with a maximum total deformation value prolonged use of the helical Savonius wind turbine blade could lead to damage along the outer-edges of the turbine blade. Helical Savonius turbines have their own advantages over regular straight blades Savonius turbine. Helical design improves the turbine's efficiency and performance compared to that of traditional ordinary, Savonius turbines. The ordinary Savonius turbine consists of simple two- or three-blade configuration. By learning through number of recent and significant researches, it can be concluded that the researchers have enthusiasm to enhance the performance of helical Savonius turbine. Table 2. Represents the summary of various researches in the direction of Helical Savonius rotor.

Table 2.*Summary of recent researches on Helical Savonius Turbine*

S. No.	Authors	Year	Modification/Research brief	Chief Outcomes
1.	Gadakh et. al.	2024	development of Helical Type Savonius turbine, compared with straight bladed.	The authors claimed that helical wind turbines are becoming more and more popular in the field of wind energy harnessing due to their distinguishing design
2.	Lajnef et. al	2024	Emphasized on the helical Savonius wind rotor (HSWR) in which the basic objective was to find the impact of selecting the numerical model parameters on its performance characteristics	The highest power coefficient was found 0.124 at a tip speed ratio of 0.73 and 0.1224 at a TSR of 0.69 both numerically and experimentally
3.	Ayadi et. al.	2023	Investigation of a helical Savonius turbine with a deflector system	The performance was found to be increased by 34% compared to the same configuration without deflector
4.	Debnath et. al	2023	Design and development analysis as well as blade material selection of helical Savonius rotor	Found that selection of blade material is a significant parameter to enhance the starting torque of

				the rotor
5.	Bagade et. al.	2023	Numerical investigation on aerodynamic performance of a helical Savonius rotor encouraged by natural Shapes	They learnt that naturally inspired shapes (profiles) were can be a possible solution of combined lift and drag type wind turbines at low speeds
6.	Sun et. al.	2023	Did experiments to systematically assess the aerodynamic performance of both H-rotor and helical vertical axis wind turbines (VAWTs)	The Self-starting performance of VAWTs was found to be improved by using NACA4418
7.	Thomai et al.	2022	Performed an experimental and numerical investigation to assess the Performance of Helical Bach (VAWT) at low wind speeds	It was found that helical Bach models have a growth in overall performance compared to the conventional Bach models as well as helical Savonius model
8.	Zadeh et. al.	2021	Performed an assessment and optimization of a helical Savonius wind turbine by changing the Bach's section	Compared with the basic model, the Bach-developed model rendered 18.3% performance improvement in the maximum power coefficient
9.	Kothe et. al.	2020	Conducted research to test the aerodynamic performance of a helical Savonius rotor model with	The maximum power coefficient of the rotor was obtained for 0.65 λ

			180° twisted blades numerically as well as experimentally	in both cases. The numerical simulation and experimental results present differences between 2.34% and 12.5% in the Ct and Cp values
10.	Seralathan et. al.	2020	Performed a Simulation study to analyze the static mechanical properties of a helical Savonius vertical axis wind turbine blade	The various static mechanical properties were observed to be the maximum for a wind load of 15 N. The prolonged use of the helical Savonius wind turbine blade could lead to damage along the outer edges of the turbine blade

Researches for Darrius wind turbine(Lift based VAWT)

Darrius wind turbine is the one in which the blades are of airfoil shape and the force is developed on the blades by lift principle. Basically, there are two types of Darrius turbine i.e., egg beater and H rotor. The egg beater bears a symmetrical airfoil blade which can move in a circular path the top andbottom of the blade attached to the central shaft.

Figure 8. Savonius Rotor combined with Darrius rotor (Redchyts et. al. 2024)

The starting torque of this configuration was very high which require higher wind velocity to get running smoothly. The stability of the turbine requires proper firmness of the shaft. The H-rotor also called as Giromill shape has straight vertical airfoil blades which are attached to the central shaft by the help of horizontal supports. The perpendicular blades replace the long egg beater blades of the original Darrieus design. Redchyts et. al. (2024) did a comparison study of vertical-axis wind turbine against single and combined Darrieus - Savonius rotors as shown in figure 8. It was found an improvement in the aerodynamic features of the Darrieus rotor without augmenting it with Savonius rotor. The torque-coefficient was also found better (14% more) for wind turbine with only Darrieus rotor.

(Eltayeb and Somlal 2024) had done research for performance-enhancement of a Darrieus wind turbines by using novel Plain Flap (PF) and Gurney Flap(GF) configurations. The study systematically evaluated different types of PF and GF configurations on NACA 0015 aero foils to increase the performance of Darrieus-type wind turbines. By using CFD simulations withSST k-ω turbulence model andURANS simulations it was found that PF (Plain Flap) and GF (Gurney Flap) modifications can improve Darrieus VAWT performance at low Reynolds number conditions. Davari et. al. (2024) compared four modes of VAWT operation by using the NACA0015 airfoil and modified NACA0015 airfoil for both straight-bladed as well as embossed-bladed VAWTs (figure 9).

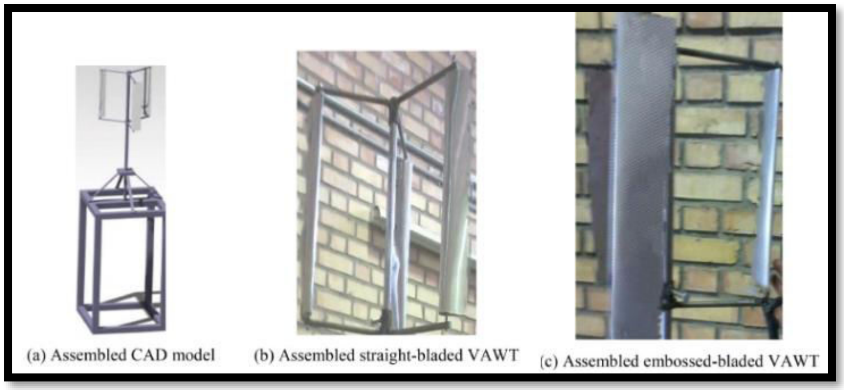

Figure 9.(a) Assembled CAD model (b) Assembled straight-bladed VAWT (c) Assembled embossed bladed VAWT (Davari et. al. (2024))

The results showed that both the cofigurations exhibited the better self-starting capability and rotation at a wind velocity ranging between 1 to 9 m/s. It was also found that by application of embossed material, self-starting force was lower than that of by straight-bladed VAWTs.

Sun et. al. (2023) Developed a small-scale H-type Darrieus vertical axis wind turbine by carbon fiber reinforced composites (CFRC) and investigated its performance by numerical study with experimental validation. For numerical investigation, a 2-dimensional numerical computational model was developed using a multiple reference system model. Wind tunnel experimentations were conducted to confirm the numerical observations. The effect of different parameters of different materials on the power output of the wind turbine were also analyzed. It was found that the maximum power of the wind turbine equipped with CFRP blades was up to 14 times greater than that of the traditional wind turbine. Furthermore, the turbines equipped with carbon fiber blades were able to self-start in light breezes and operate stably, even at the TSR below one.

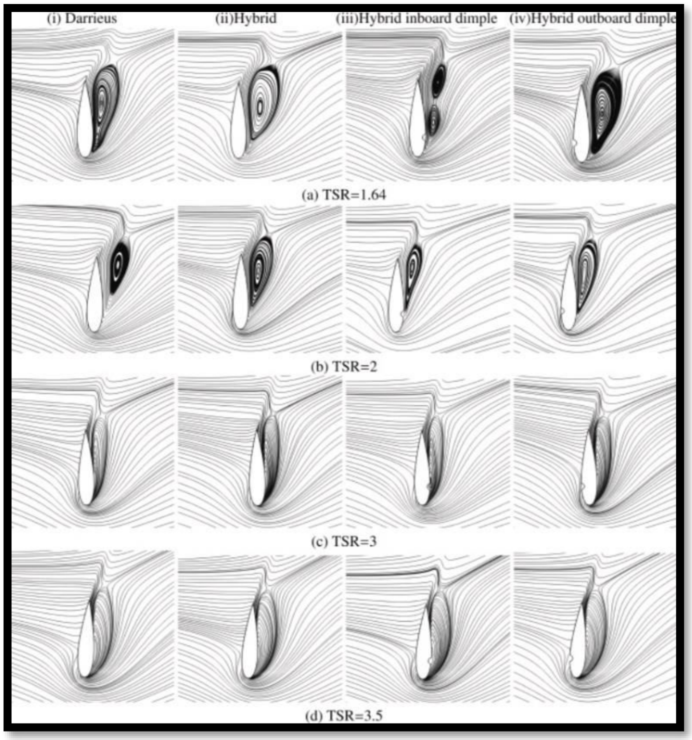

Figure 10. Streamlines on one of the Darrius rotor airfoils at Azimuth angle for the different configurations for the cases of 3 blades Darrius rotor, diameter ratio 0.2 and attachment angle(Re 4.3); at different TSR corresponding to (a) AOA 31^0 (b) AOA 26^0 (c) AOA 18^0 (d) AOA^0 (Eltayesh et. al. 2023)

Hijazi et. al. (2024) developed a H-Darrieus turbine using flexible blades and performed a numerical investigation. A CFD study, coupled with design of experiments (DOE) approach was employed to optimize the flexible blade geometry. The accuracy of using 2D CFD simulations to optimize the blade geometry was also demonstrated. It was found that maximum power coefficient attained by the optimized flexible blade turbine shows a 32% improvement as compared to the one which was not optimized. Eltayesh et. al. (2023) found innovative solutions for improving the performance of Darrieus turbine as depicted in figure 10.

Chegini et. al. (2023) developed a combination of 3-bladed Darrieus and 2-bladed Savonius hybrid wind turbines and studied numerically. It was found that the proposed hybrid wind turbine increased the Cp at $\lambda = 1.45$ by 26.91% compared to the ordinary Darrieus turbine. To optimize hybrid turbine performance, 3 deflectors were placed in front, next to the turbine, The application of deflectors resulted in significant increase of maximum Cp of the hybrid turbine. The double-deflector improved Cp at $\lambda = 2.6$ by 19.75%, showcasing optimal configuration. The investigations were conducted through numerical and other engineering approaches. The investigated interventions included hybridization of the rotor by using an inner Savonius rotor section for improving the machine's start-up and application of dimples for improving the NACA 0021 airfoil performances of outer section. The best enhancement was found by the inboard dimple configuration with hybrid rotor of 3 blades, a diameter ratio of 0.2 and attachment angle of 450. The enhancement of Cp with respect to the ordinary Darrieus turbine was found 47.5% at a low TSR (1.68) 6.2%.

To investigate the power generation capacity of 3-bladed H-Darrieus vertical axis wind turbines (HDWT), by Singh et. al. (2023), a 3-dimensional numerical study was conducted. It was by solving the unsteady Reynolds Averaged Navier Stokes equations with shear stress transport (SST). It was done by using S-1046 airfoil under accelerated wind conditions of a cooling tower exhaust system (Figure 11)

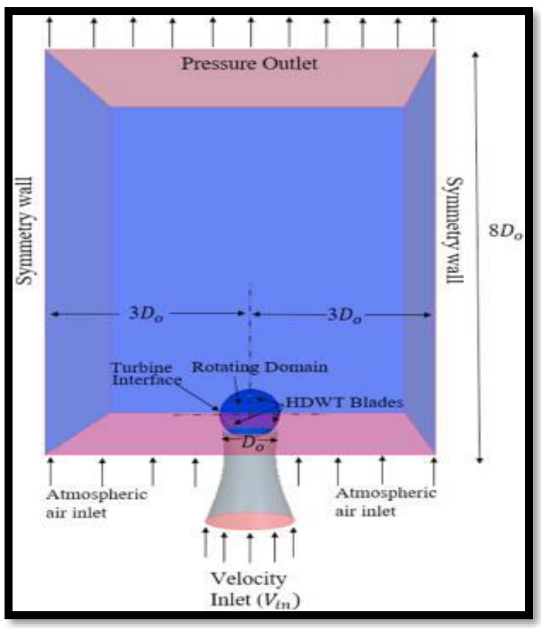

Figure 11. Three-dimensional computational domain (Singh et. al. 2023)

The results showed that the HDWT with a smaller aspect ratio (AR) (0.44) give a better coefficient of power i.e., 0.294 at TSR 2.5 as compared to other testing conditions. Further, a detailed flow field analysis around the HDWT for different ARs and TSRs was provided to discuss the turbine's performance. Furthermore, by performing a comparative study with the free-stream flow condition it was found that HDWT provides 58.5% lower performance than the flow in the exhaust system at a lower AR, which indicates a positive guided flow effect on the turbine performance under exhaust flow systems.

Zidane et. al. (2023) aimed to enhance the performance of H-Darrieus Vertical Axis Wind Turbine (VAWT) by introducing upstream deflectors. The impact of this addition was investigated and analyzed through different deflector configurations (Figure 12). The turbine performance before and after modifications was compared.

Results showed that the presence of a single deflector can increase the maximum moment-coefficient compared to bare configuration by 24%, while two defectors increase the same by 22%.

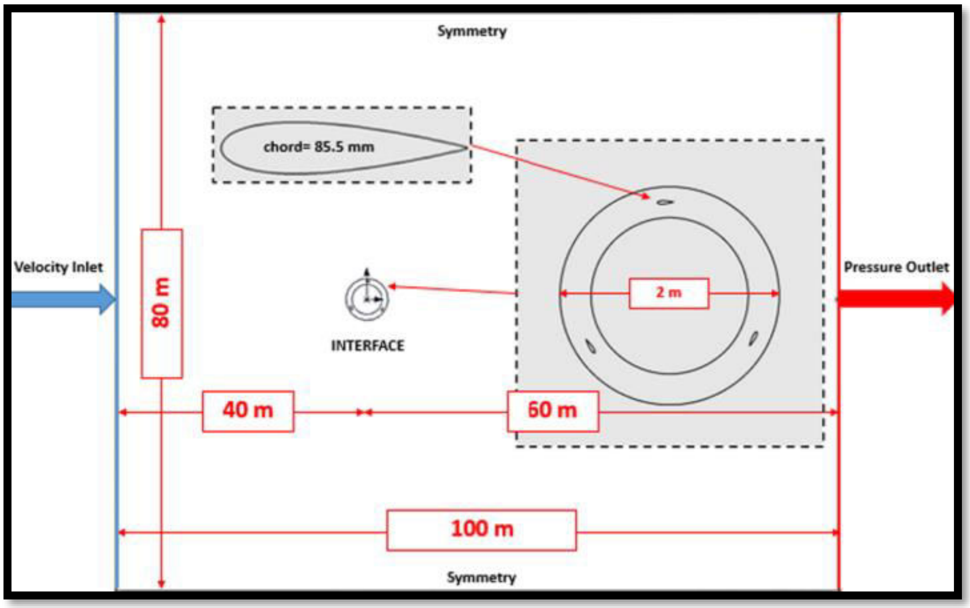

Figure 12. Computational domain (Zidane et. al. 2023)

(Ahmad and Zafar 2023) aimed to investigate the effect of leading-edge tubercles (LET) on the performance of a hybrid vertical axis wind turbine (VAWT). The study involved both of the experimental and computational analysis of an innovative hybrid VAWT configuration. The proposed VAWT design was found furnishing high power coefficient and self-starting capability. A comparison analysis was done with an existing hybrid VAWT without tubercles and a conventional Darrieus design. The findings indicate that the proposed hybrid VAWT attained the highest power coefficient of 0.475 at a tip speed ratio(TSR) of 3.

Sengupta et. al. (2022) investigated to improve the performance of H-Darrieus wind turbine for low wind speed. The effect of circular cavity on aerodynamic performance of the rotor was also investigated by using a subsonic wind tunnel. It was to check which side cavity on the airfoil (inner or outer side) is helpful in terms of the rotor's static and dynamic performances. For this, S1046 and NACA 0021 airfoil blades were considered at various low wind speeds of 5, 6 and 7 m/s for different rotor aspect ratios. A CFD analysis was also performed. Results showed that inner surface cavity on both the blades improved their self-starting ability at 5 m/s wind speed compared to that NACA 0021 blade without cavity, which performed better at 7 m/s. Again, NACA 0021 blade without cavity exhibits the highest performance out of all blade shapes, for which the highest power coefficient of 0.15

was achieved at a tip speed ratio of 1.25 and wind speed 6 m/s. At wind speed 7 m/s, the NACA 0021 blade rotor having outside cavity was found with maximum power coefficient. CFD results showed that H-Darrieus rotor consisting of NACA 0021 blades at 30° azimuthal-angle with circular cavity at 1/4th chord distance from its leading edge, located at its internal surface, can generate higher amount of lift force. Mohammed (2021) in his research claimed that vertical axis wind turbines (VAWTs) are suitable for harnessing wind energy in remote areas. Aerodynamic noise is a notable problem in the use of VAWTs. The author presented a new design of VAWTs with 3 small rotors, instead of the usual single rotor design. A CFD simulation was used to evaluate the aero-acoustics of the proposed design. A combination of sound and turbulence models were solved. The effects of the direction of rotation of the rotor and the distance between the rotors were also investigated. They found an optimized configuration where the aero-acoustics (sound pressure level) of the standard turbine was reduced by 43%.

***Table 3**. Recent research works on Darrieus Wind turbine*

S. No.	Authors	Year	Modification/Research brief	Chief Outcomes
1.	Sun et. al.	2025	Developed a small-scale H-type Darrieus vertical axis wind turbine by carbon fiber reinforced composites (CFRC), investigated its performance by numerical study and experimental validation.	It was found that the maximum power of the wind turbine equipped with CFRP blades was up to 14 times greater than that of the traditional wind turbine
2.	Eltayeb and Somlal	2024	Performance enhancement of a Darrieus wind turbines by using Plain Flap (PF) and Gurney Flap (GF) configurations	URANS simulations showed that PF (Plain Flap) and GF (Gurney Flap) modifications can improve Darrieus VAWT performance under varying wind and low Reynolds number conditions.
3.	Davari et. al.	2024	Compared four modes of VAWT operation by using the NACA0015 airfoil and modified NACA0015	The modified NACA0015 airfoil for embossed-bladed VAWTs exhibited the

			airfoil for both straight-bladed as well as embossed-bladed	better self-starting capability and rotation at a wind velocity ranging between 1 to 9 m/s
4.	Hijazi et. al.	2024	Developed a H-Darrieus turbine using flexible blades and numerically investigated	Maximum power coefficient attained by the optimized flexible blade turbine shows a 32% improvement as compared to the one which was not optimized
5.	Chegini et. al.	2023	Developed a combination of 3-bladed Darrieus and 2-bladed Savonius hybrid wind turbines and studied numerically	The double-deflector improved Cp at λ = 2.6 by 19.75% rendering optimal configuration
6.	Eltayesh et. al.	2023	Hybridization of the rotor by using an inner Savonius rotor section for improving the machine's start-up and application of dimples for improving the NACA 0021 airfoil performances of outer section	The enhancement of Cp with respect to the ordinary Darrieus turbine was found 47.5% at a low TSR (1.68) 6.2%
7.	Singh et. al.	2023	3-dimensional numerical study was conducted by solving the unsteady Reynolds Averaged Navier Stokes equations with shear stress transport (SST) k-omega turbulence model to investigate the power production capability of 3-bladed H-Darrieus wind turbines	HDWT with a smaller aspect ratio (AR) (0.44) gives a better coefficient of power i.e., 0.294 at TSR 2.5 as compared to other testing conditions
8.	Zidane et. al.	2023	Aimed to enhance the	Results showed that

			performance of H-Darrieus Vertical Axis Wind Turbine (VAWT) by introducing upstream deflectors	the presence of a single deflector can increase the maximum moment coefficient of the bare configuration by 24%, while two defectors increase the same by 22%
9.	Sengupta et. al.	2022	Investigated to improve the performance of H-Darrieus wind turbine for low wind speed.	CFD results showed that H-Darrieus rotor consisting of NACA 0021 blades at 30° azimuthal angle with circular cavity at 1/4th chord distance from its leading edge, located at its internal surface, can generate higher amount of lift force.
10.	Mohamed	2021	Introduced a novel design of Vertical Axis Wind Turbines (VAWTs) with 3 small rotors in place of the ordinary single rotor design to reduce noise.	They found an optimized configuration where the aeroacoustics (sound pressure level) of the standard turbine was reduced by 43%.
11.	Redchyts et. al.	2024	Comparison of aerodynamics of vertical-axis wind turbine against single and combined Savonius and Darrieus rotor.	The rise in torque coefficient was 14 %.

Conclusion

By going through number of research papers on chief types of VAWTs it can be concluded that, For Straight bladed Savonius a Floating Breaker (FB) concept was applied and it was found that FB with integrated SHT enhances the wave elimination performance by 20% and the wave resistance in surge, pitch and heave by 34%, 17%, and 15%, respectively. Significant research in the direction of noise reduction techniques, A combination of ANC and TE serration was found efficient in noise reduction. A forwards-facing step was applied under various scenarios and it was found that the conventional semicircular 2-bladed Savonius turbine as the most effective configuration. Taguchi optimization study aimed to at enhance the efficiency Savonius turbine, by optimizing the inner blade parameters. The most effective parameter was found was the inner blade angle by 91.85 %. By application of various software to forecast the performance of Savonius hydrokinetic turbine's, CatBoost was found the best for forecasting. Research was conducted to find the best Phase Shift Angle (PSA) and it was found to be 30°. By recent significant researches conducted on helical Savonius turbine it was found that, the highest power coefficient of 0.124. Experiments by application of deflector yielded that the performance is increased by 34% by application of deflector compared to ordinary helical turbine.

For helical Savonius turbine, selection of blade material is a significant parameter to enhance the starting torque. It was found that naturally inspired shapes (profiles) were can be a possible solution to boost the performance of combined lift and drag type wind turbines at low speeds. It was found that helical Bach models have a growth in overall performance compared to the conventional Bach models as well as helical Savonius model. the Bach-developed model rendered 18.3% performance improvement in the maximum power coefficient. Savonius rotor model with 180° twisted blades numerically as well as experimentally. The maximum power coefficient of the rotor was obtained for 0.65 λ in both cases. Performed a Simulation study to analyze the static mechanical properties of a helical Savonius vertical axis wind turbine blade. The prolonged use of the helical Savonius wind turbine blade could lead to damage along the outer edges of the turbine blade.

For Darrieus turbine It was found that the maximum power of the wind turbine equipped with CFRP blades was up to 14 times greater than that of ordinary wind turbine. Similarly, use of single deflector on Darrius rotor can increase the moment coefficient up to 24%.Use of double-deflector on the turbine improved Cp at $\lambda = 2.6$ by 19.75%. The Maximum coefficient of power attained by the optimized flexible blade turbine showed a 32% improvement as compared to unoptimized one. The wind turbine noise is also an addressable issue. It can be solved by keeping multi-rotors in an optimized geometrical fashion. Introduction of leading-edge tubercles can enhance the performance of the turbine.

Discussion

Use of Vertical Axis Wind Turbines (VAWTs) is a promising option in renewable energy harnessing due to its unique advantages and benefits. However purposeful use in rural areas exists in different parts of world (Burton and Stern 1993; Vishwakarma 1999), Till date proper commercialization of VAWTs are not rendered because of their poor efficiency compared to that of HAWTs. However,good research and enthusiasm can make their commercialization viable. The greatest advantage with VAWTs is, they do not need any sophisticated blade profile can even be developed by unskilled labor at a much lower cost or by scrap materials. They can be developed of any size so decentralized power production potential is there with VAWTs. Proper research and advancements.

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