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Review

Enhancing the Performance of Savonius Wind Turbines: A Review of Advances Using Multiple Parameters

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Abstract: The need to globalize and implement the fourth industrial revolution has led to increased interest in research on renewable energy harvesting equipment. Wind and solar have been the fastest growing sources of energy and have been used to reduce our dependency on fossil fuels for energy. The Savonius wind turbine is an attractive option for regions with high turbulence intensity and low wind speeds due to its advantages over other small-scale vertical-axis wind turbines. These advantages include its simple design, satisfactory performance at lower speeds, and ability to turn independent of the wind flow direction. However, Savonius wind turbines face several challenges. The most significant one being the negative torque generated during operation. This negative torque is caused by the interaction between the exhaust air and the returning blade, thus reducing efficiency, as the turbine has to overcome this additional force. To improve on the efficiency, various assessments and optimization techniques have been employed. These focus on the geometric parameters of the Savonius wind turbine as well as installation augmentation techniques. This article reviews and reports on several combinations of parametric performance-influencing adjustments and power augmentation techniques applied to Savonius wind turbines. The article concludes by proposing future research directions.

Keywords: savonius; parameters; renewable

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Citation: Chitura, A.G.; Mukumba, P.; Lethole, N. Enhancing the Performance of Savonius Wind Turbines: A Review of Advances Using Multiple Parameters. *Energies* **2024**, *17*, 3708. https://doi.org/10.3390/en17153708

Academic Editor: Davide Astolfi

Received: 2 June 2024
Revised: 18 July 2024
Accepted: 19 July 2024
Published: 27 July 2024

1. Introduction

With the already progressing swing of the fourth revolution and the need to control climate change, mankind has found the need to increase electricity production in a clean fashion. The conversion of the kinetic energy present in wind into an electrical form of energy is an example of such methods. As a country seeks to achieve its climate change goals, the use of renewable resources becomes even more relevant. Wind energy is an example of such sources which have been attracting much attention. This energy source has been explored since time immemorial and has mostly found use in agriculture and water wells. The industrial revolution fostered a temporary pause on the use of wind as a form of energy, but it later resumed as the demand for energy increased. Figure 1 shows that only 2% of the total energy distribution in South Africa was being sourced from wind as of 2021.

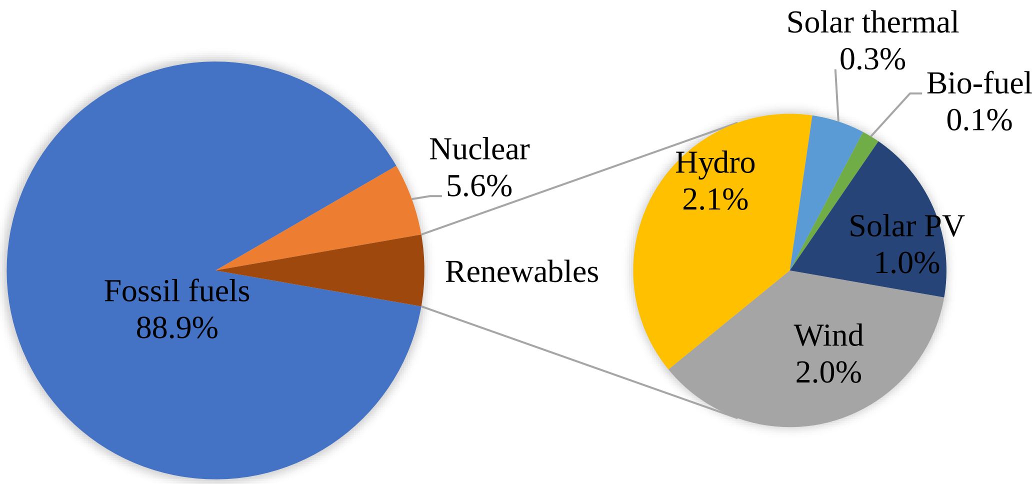

Figure 1. The energy pie of South Africa [1].

To date, wind power is among the fast-growing forms of energy in terms of utilization. The South African Renewable Energy Resource Database (SARERD) in 2001 and, later on, the South African Wind Energy Project (SAWEP) went on to formulate a Wind Atlas for South Africa (WASA) [2,3]. In this atlas, moderate mean wind speeds of 6 m/s have been projected along the coastal stretch and some areas that lie inland. A high wind energy potential lies in the Western Cape, Northern Cape, Eastern Cape, and KwaZulu-Natal provinces, with the Eastern Cape hosting most of the wind farms installed to date [1].

Most passages through which moderate breeze winds (5.5 m/s–7.9 m/s) flow are located near the coastal regions, and mostly in places which are not inhabited by humans [4]. The inhabited areas are characterized by high turbulence intensity, slow-moving wind as a result of human shelter, and other wind flow obstructions. As such, a wind turbine with a very low cut-in wind speed, which is not sensitive to high turbulence intensity, and which can cooperate despite sudden changes in the wind direction would be most suited for such areas. The Savonius wind turbine fits this description well based on its simplicity in construction, easy self-starting capabilities, low operational complexity, as well as its lower running wind speeds.

The main advantages of this kind of turbine are in its simple structure, making it easy to construct and modify. Besides the ability to function independent of the incident wind direction, this turbine ensures a low-noise operation due to its low speed of rotation compared to other vertical-axis wind turbines [5]. The Savonius wind turbine's simple construction involves two semicircular surfaces on opposite sides of each other. These semicircles, as shown in Figure 2, are divided into the advancing and retuning blades. On each blade, the surfaces are further divided into concave and convex shapes. When faced with incident wind, the concave surface creates more drag compared to the convex side of the returning blade. This difference facilitates the rotation of the turbine, and because wind also causes limited drag on the convex side of the turbine, the overlap speeds of the turbine are limited, leading to less-efficient operation [6].

Over the years, the performance of the Savonius wind turbine (SWT) in terms of the peak power coefficient has been gradually increasing. Many studies have focused on the optimization of the blade profile and the placing of a deflector system in the vicinity of the SWT system to bar air to the convex blade surface. Blade profiles have been modified over 18 times, all the while improving the Cp from about 0.12 to 0.33. Typical blade profiles include the batch, semicircular, Benesh, twisted, and Bronsinus. Various other authors have focused on the deflectors, which were studied in many forms, thus improving the Cp from 0.38 to 0.52 [7].

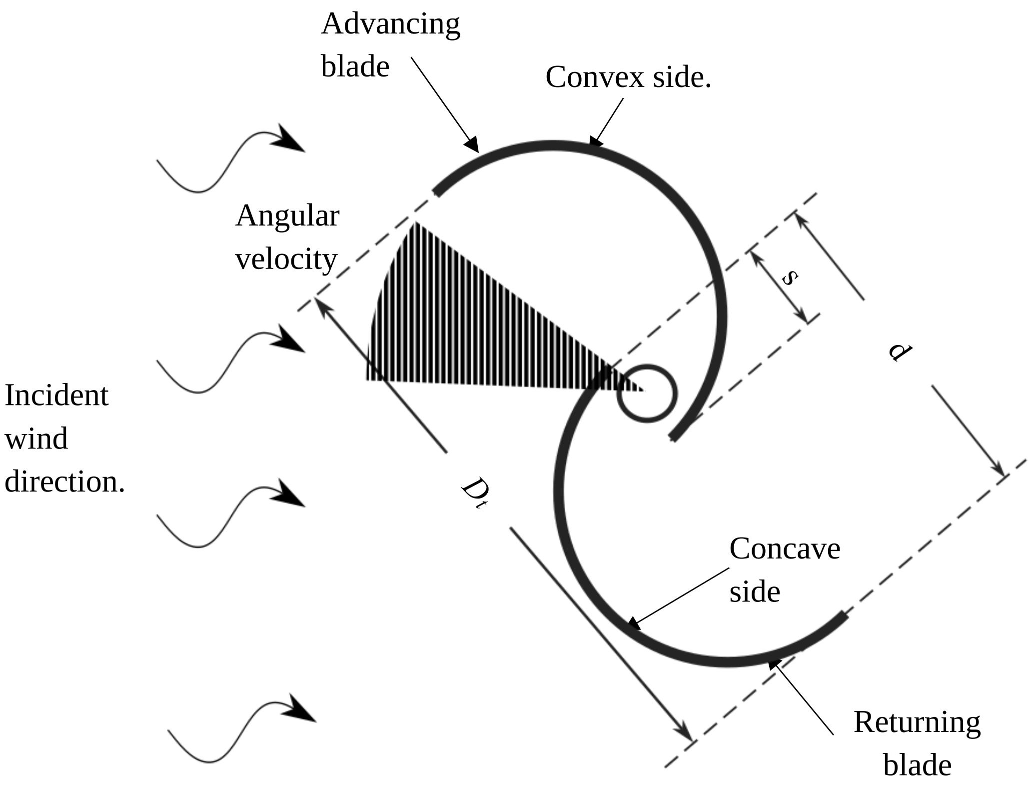

Figure 2. The Savonius wind turbine (adapted from [8]).

This study seeks to review the enhancements on the Savonius wind turbine and how they affect the application of the turbine within turbulent low-moving winds that characterize residential environments. The Savonius wind turbine is suited for such environments due to its ability to move at a generally slower tip-speed ratio; however, aside from the improvement in the Cp, the self-starting ability, operational fluctuations, and angular static torque have not been widely investigated.

2. Drag-Based Wind Turbines

Wind turbines can be classified using the mechanism that they use for the conversion of kinetic energy present in moving wind into the rotational mechanical form of energy. Such converters have been divided over centuries into lift machines and drag-based systems. Lift machines utilize the lift forces generated on their airfoil-shaped blades as the interaction with incident air streams. Drag machines, on the other hand, use the drag forces that are resultant from the interaction of turbine blades with incident airflow.

Drag-based machines, when placed in a stream of flowing air, generate a velocity which is relative to the power-producing surfaces of the turbine. The resultant drag force can be expressed as Equation (1), as follows:

$$FD = CD(\frac{1}{2}\rho[U - \Omega r])2A \tag{1}$$

where FD is the drag force, CD is the drag coefficient, ρ is the acceleration due to gravity, U is the wind speed, Ωr is the blade surface speed, and A is the blade surface area. The power that can then be generated by such drag forces can then be expressed as Equation (2), as follows:

$$P = CD\left(\frac{1}{2}\gamma[U - \Omega r]^2\right)\Omega r = \gamma AU3(\frac{1}{2}CD\lambda[1 - \lambda]) \tag{2}$$

where λ represents the tip-speed ratio (TSR), which is the power can be expressed as the product of the TSR and the torque because of some drag forces that act on the turbine. This yields the power coefficient and is expressed as Equation (3), as follows:

$$Cp = \frac{Pturbine}{Pavailable} = \frac{T\Omega}{\frac{1}{2}AV3\gamma} = (\frac{1}{2}CD\lambda[1-\lambda])^2 \quad (3)$$

where T represents the torque generated; Cp (the power coefficient) takes the value of zero when the TSR is either zero or one (which is the speed when the free-stream air speed is equal to the turbine speed). The power coefficient is the highest when the TSR, equal to $\frac{1}{3}$, yields eight-hundredths. When compared to Betz limits, it can be seen that drag-based machines have a lower perform than lift-based machines. Unlike drag-based systems, where the relative turbine velocity cannot exceed the free-stream wind velocity since the TSR has to take the value between zero and one, lift-based turbine blades can move at higher velocities than the free-wind velocity.

However, such systems fare well in residential situations where there is high turbulence intensity as well as a low wind speed due to obstructions to the free flow of wind. Their low relative blade velocity and high torque facilitates low noise, less vibration, and better starting capabilities than their lift-based counterparts. The drag-based Savonius wind turbine is the most commonly used small-scale wind turbine, mainly because of its simplicity.

The basic idea behind the operating principle of a Savonius wind turbine is that, as the rotor blades rotate perpendicular to the vertical shaft, there exists a difference in the drag force between the concave and convex surfaces. As a result, drag acts as the Savonius rotor's main propulsion source [9].

3. Geometric Properties

3.1. The Aspect (AR) and Overlap (OR) Ratios

The aspect and overlap ratios contribute to a large extent to the structural integrity of the Savonius wind turbine. Increasing the aspect ratio results in a tall turbine structure, i.e., the distance between the end-plates of the rotor with respect to the rotor diameter [10–12]. The result is an increased drag on the concave side of the rotor blades, leading to an increased generation of torque. The increase in the aspect ratio from one to one and five-tenths yields a 10% increase in the power coefficient for turbines with an overlap ratio of one-tenth. For turbines with an overlap ratio of 0 and beyond 0.15, the aspect ratio has not been found to bring about any increase in the power coefficient. For those with a zero overlap ratio, the best blade profile came from a batch-type rotor, which produced the highest Cp at an aspect ratio of seven-tenths [13,14]. A further increase in the aspect ratio led to the instability of the turbine structure; as a result, most of the aspect ratios used in SWTs are below one and five-tenths.

Higher values of aspect ratios have been investigated in the early years, and a trend of high power coefficients have been reported by [15]. Additionally, while there exists a limit beyond which a higher AR value leads to an unstable turbine setup, there has not been much research covering an extensive range of ARs within the same SWT setup. Moreover, more research can be caried out with different setups as opposed to the conventional structure of the SWT. The aspect ratio also changes with multistage Savonius wind turbines, as in the case of [16]. While further increasing the aspect ratio beyond eight-tenths resulted in a decreased Cp in the case of the multistage setup, the reduced torque fluctuations led to an increase beyond this AR limit. The structural integrity was also improved by the additional multistage, though some minor instability may arise at a high TSR [16]. Therefore, modifications to the Savonius turbine may offset this stability limit faced by the traditional Savonius wind turbine, and thus allow for AR values beyond eight-tenths.

The overlap ratio (OR) of a Savonius turbine is also an important geometric parameter in elevating the performance. It can be expressed as the ratio of the overlap distance between the SWT blades and its diameter [17]. An SWT with an amount of overlap creates a flow between the concave and convex sides of the SWT. Part of the wind incident on the concave face is channeled to the back face of the convex blade, thus reducing the effects of the negative torque on the overall turbine. This improves the starting abilities compared to the ones without overlap [18]. Besides the increase in the power coefficient caused by the overlap, a large overlap tends to the reduce the torque due to the formation of a vortex in the overlap region. Various studies have been performed on the topic which have failed to reach an agreement on the optimum OR.

Another study examining changing the inward as well as outward overlap ratios was conducted. Three wind speeds were considered, 3, 5, and 7 m/s, and calculations were performed using a variety of overlap ratios, such as G/d = 0, 0.1, 0.2, and 0.3. The findings demonstrate that, for all of the wind speeds taken into account, the greatest power coefficient was reached at an inward overlap ratio equal to two-tenths, and was reduced by an increase or decrease in the overlap ratio. Two-dimensional numerical simulations were performed involving the use of URANS equations. The simulations were based on the conventional Savonius rotor. The results obtained after evaluating a large range of ORs showed that an OR of 0.15 proved to be the optimum for better results [19]. However, the best OR for a Savonius wind turbine was dependent on the blade profile. Thus the optimum OR will always differ, and hence can be used as a design parameter [20]. Figure 3 gives a summary of the results from several studies, as discussed above.

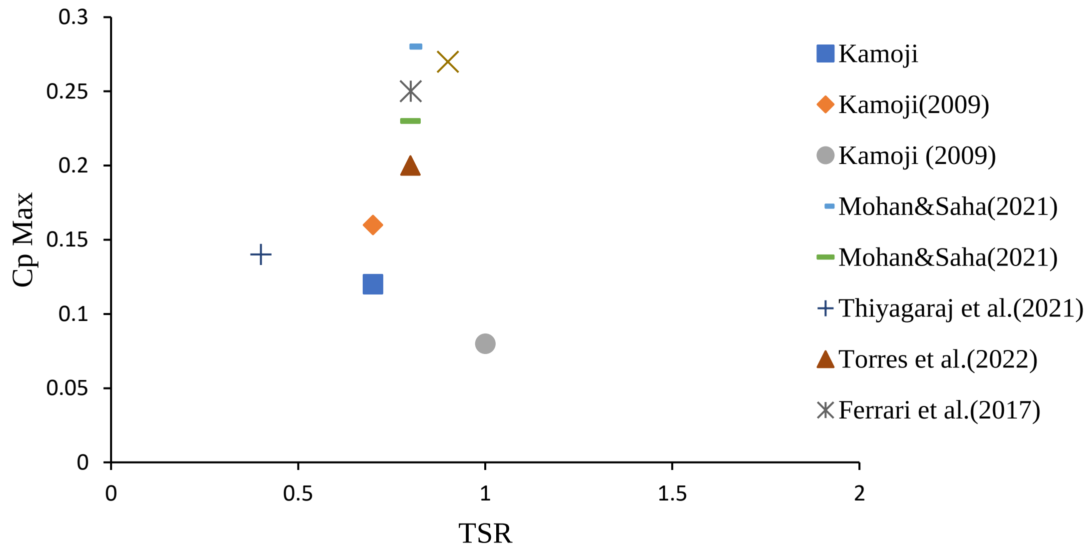

Figure 3. The effect of aspect and overlap ratios on the performance of the Savonius wind turbine.

3.2. Blade Profiles

In general, the conventional SWT suffers from low efficiency. Therefore, it is essential to improve the performance of the turbine either by implementing augmentation techniques or by changing the blade shape. One of the main drawbacks of the Savonius wind turbine is the formation of negative torque on the returning blade's convex side [21]. This happens because the convex side of the returning blade faces the incident wind, therefore creating drag forces on it. This diminishes the momentum gathered by the concave side of the advancing blade. A twisted blade, also known as a helical blade, improves on these characteristics as well as boosts its self-starting capabilities. Because the transitions from each blade are smoother, low fluctuations are experienced, which is the case demonstrated by multistage turbines. The twisted Savonius wind turbine has been described as having a long arm, which contributes to a high net positive torque [13].

In a study to investigate the effect of using twisted blades on a Savonius wind turbine, [22] found that the optimum twist angle was 45°. The study was performed by conducting experiments as well as numerical investigations on the helical SWT. This value agreed with studies performed later on by [23]. A twist angle greater than 45° was used in a study in which the traditional Savonius wind turbine was compared to a twisted blade profile. The study was conducted by [24], who analyzed the effects of twisting the blade on the self-starting ability and the extent of the positive torque fluctuations on the turbine during operation. The findings of the investigation showed that, at angles from 0° to 40°, the spiral lower part did not obtain enough energy from incident wind, which changed for angles greater than 40°. The study set a benchmark for which the future developments to the starting torque of modified Savonius wind turbines can be compared.

Geometric as well as blade profile investigations were carried out by applying optimization techniques to improve the blade profiles. These were followed by experimental as well as 2D simulations to explore how different blade shapes affected the performance of a Savonius wind turbine. In their studies, four different blades were investigated. Among the semicircular, Benesh, modified Bach, and elliptical profiles, the elliptical profile resulted in the highest power coefficient [25]. In a similar study, Ref. [26] numerically studied six Savonius wind turbines based on different profiles. In their findings, the Sivasegaram-built blade profile outperformed the other profiles, resulting in a 7.2% improvement in the torque coefficient at a TSR = 0.59. In another study by [27], experimental investigations as well as 3D computations were performed by comparing five V-shaped profiles. They maintained a fixed V-angle profile of 90° whilst varying the V-edge. Figure 4 shows a summary of the geometric properties on the Savonius wind turbine performance.

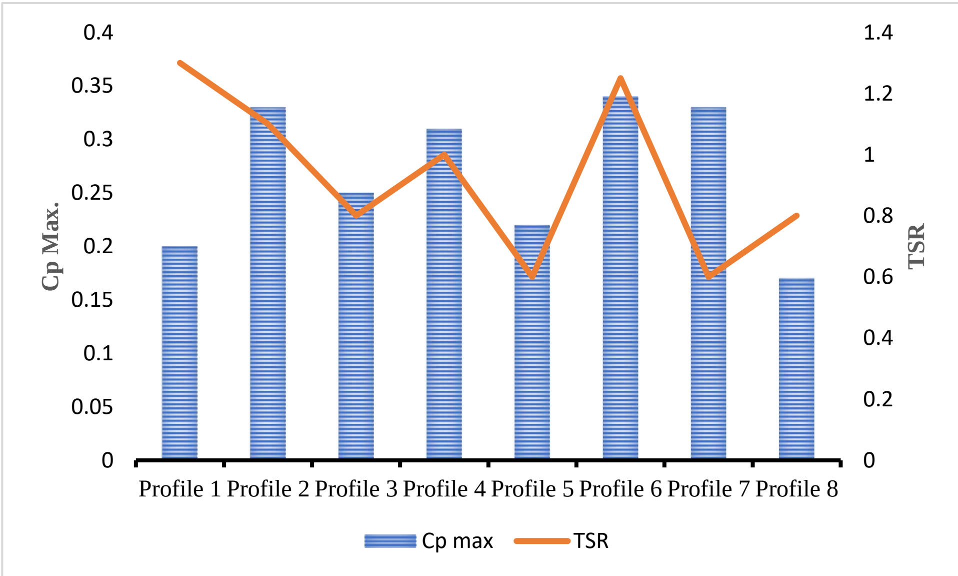

Figure 4. The effect of blade profiles on the performance of the Savonius wind turbine.

3.3. Blade Arc

The angle between the endpoints on a conventional semicircular rotor of the Savonius wind turbine can be referred to as the blade arc. Studies performed by [28] aimed at predicting the best blade arc angle that could be utilized on an SWT. They used the RNG k-ϵ turbulence model and discovered that a blade arc angle of 160° resulted in an increment of 8.37% in the power coefficient compared to the traditional circular blade with 180 degrees. Recent studies by [29] focused on the inner and outer blade arc angles to establish the optimum angles. Their findings stated that 160° for the inner and 20° for the outer arc angles produced the highest power coefficient. In their investigations, they concluded that an increased positive pressure was exerted on the concave side of that blade, whist the vortical formation was diminished with the increase in the blade arc angle. Another study used artificial neural networks for the optimization of the blade arc angle. The results obtained showed that an angle of 166° gave the best power coefficient. Blade arc angles from 0° to 90° can be used for design purposes, but angles beyond 90° will need optimization to obtain the best arc angle for that particular design [30]. More research is required to be able to optimize the different versions of the blade profiles of the conventional Savonius wind turbine. Table 1 shows a summary of the geometric properties of the Savonius wind turbine performance.

Table 1. Summary of the effects of the enhancements on the operation of the Savonius wind turbine.

Reference	Description	Self-Starting Ability	Enhancement	Gap
[19]	Inward and outward overlaps	Not tested	The Cp improved by 3.7% and 7.5% for the horizontal and vertical overlaps, respectively.	Investigation of tensile forces on the rotor.
[13]	A novel SWT design method	Not tested	Max. peak power of 0.21.	Validation of results obtained.
[18]	OR effect on the performance	Not tested	A Cp of 0.263 and 0.293 for SR3345 and SR5050, respectively.	-
[17]	Aerodynamic performance investigation	Not tested	An 80% increase in the power coefficient.	Validation and wake analysis.
[22]	Twisted blade profile	Not tested	Max. peak power of 0.22.	-
[27]	V-shaped rotor	Not tested	A 19% increase in the power coefficient.	Validation of the results experimentally.
[29]	Blade arc	Not tested	A 12.9% increase in the power coefficient.	Further optimization of the design variables.
[30]	Blade optimization using AI	Not tested	Max. peak power of 0.194.	Encouragement for future studies to use AI as another optimization tool.

4. Performance Enhancement Techniques

4.1. Blade Profile Optimization for Improved Performance in Operation

Various researchers have come up with improved blade designs in a bid to diminish the drawbacks of the classic Savonius wind turbine. Among the profiles evaluated by [31], the Bach-type design was found to achieve the highest peak power coefficient of approximately 10% better than the traditional Savonius, with an OR of one-tenth. It is from this profile that a new novel profile was designed; the result of the study was an optimized scooplet-based design. Single objective function maximization was performed to optimize the selected blade profiles with a goal of maximizing the power coefficient. The result was the scooplet-based design, which, when compared with the traditional design, exhibited a 39% improvement in the power coefficient. The major contribution to this improvement is the scooplet, which creates a pressure gradient directed towards the scoop, thus benefiting from an instantaneous torque coefficient. When compared to the modified batch design, the scooplet-based design performed better by a margin of 27% [31].

With the Savonius wind turbine being a drag-based wind turbine, any increase in drag would result in an increase in the power coefficient. Surface roughness was utilized in a study which sought to establish the effect of a zig-zag profile on the concave side of the SWT blades. The design was made to have a taller outside, with the angle of reflection focused on the overlap. Wind through the overlap would then help disrupt the vacuum on the returned blade and thus diminish negative torque formation. The zig-zag profiles, which were 3D printed onto the concave surface, indicated a significant boost in the peak power of 16% when compared to a Savonius wind turbine without a rough surface. This result was obtained at a wind speed of 6m/s and a tip-speed ratio of 0.55. The model highlighted how the drag can be focused on the concave part and less on the overlap part. The enhanced disparity in the drag forces on the blades improved the efficiency of the Savonius wind turbine [32]. More roughness patterns can be experimented with and more efficiency can be obtained from the simple SWT as opposed to the expensive and complicated blade profile designs [33].

In another study, a new blade profile was optimized to produce the best-performing blade profile, which was then tested experimentally to validate the simulations. A design of experiments approach was implemented to optimize the profile using a number of blade profile geometrical properties. A wind tunnel experiment was then conducted using the optimized blade to validate the simulations as well as to gain an understanding of the aerodynamic flow properties of the resultant blade profile. The ultimate blade profile was the result of a selection from 10 different models, choosing the one generating the most power. After a number of numerical analyses at a TSR = 1, an elliptical blade profile, which had an inner wavy area with an OR of 0.109, produced the highest power coefficient. The research established that increasing the overlap distance led to a reduction in the efficiency. This is because of the returning flow, which becomes turbulent. Due to this, compromises have to be considered between the gap guide swirling flow and the impact blockage ratio. These characteristics are a result of the reduced channel width because of the extension of the blade tip length [34]. More research is essential to determine the gap guide's flow angle fluctuation in order to further improve the model. A focus on the development of hybrid wind turbine systems which combine different types of systems to attempt to complement the strengths and weaknesses could guide future research to an increased power output.

Another study was conducted for a batch rotor with a large shape factor. A computational analysis was performed by varying the overlap ratio when an axisymmetric omnidirectional deflector was coupled to it. The effect of the deflector on the batch rotor was investigated for use in areas with high wind direction fluctuations. The model was also used on a conventional Savonius wind turbine, and the results showed that the batch rotor with a shape factor of 0.58 and an overlap ratio of two-tenths resulted in an improved peak power coefficient. A 15.23% rise in the power coefficient was observed when compared to a batch with no overlap. For a batch rotor with a tip-speed ratio of one and three-tenths, an increment of 52.1% was recorded at an overlap ratio of two-tenths.

When compared to a batch rotor with an overlap ratio of five-hundredths, the average performance resulting from the addition of the axisymmetric deflector was 8.78%. Due to the formation of an amplified high-pressure zone on the concave curve, as well as a low-pressure region on the convex curve of the oncoming blade, the performance of the system was improved. The value of the power coefficient produced by the axisymmetric omnidirectional deflector was constant for tip-speed ratios greater than six-tenths, leading to a constant efficiency even at variable wind speeds. The study stresses the need to check the periodic steady-state condition at a range of tip-speed ratios in order to obtain reliable results [35]. Future research needs to be focused on varying the outer diameter of the axisymmetric omnidirectional deflector, as well as to conduct static torque analyses, and thus to analyze the self-starting nature of the turbines at different angles. In essence, the blade profile can be changed to enhance or diminish certain properties of the rotor, and hence it is the most researched method to improve the performance of the Savonius wind turbine [7].

In a recent study, an airfoil high-lift, low-speed FX74-CL5-140 blade was used to optimize the performance of the Savonius rotor. The main attraction of this airfoil blade was the ability to perform well at high TSR values in urban areas. The results produced a high peak power of 0.25, which was higher than the original setup. The natural thickness of the airfoil blade limited the overlap region, thus forming a jet flow at the overlap region and increasing the momentum energy around the rotor. This suppressed vortical formation while strengthening the shear strain on the blade. The resultant wake showed a faster recovery time compared to the original Savonius rotor. The airfoil blade naturally has multiple curves, which changes the normal force direction on the blade surface. This change in the origin position of the force makes the blade able to exhibit more torque on the rotor [36]. Figure 5 below shows the trend of blade profile modifications for the studied period.

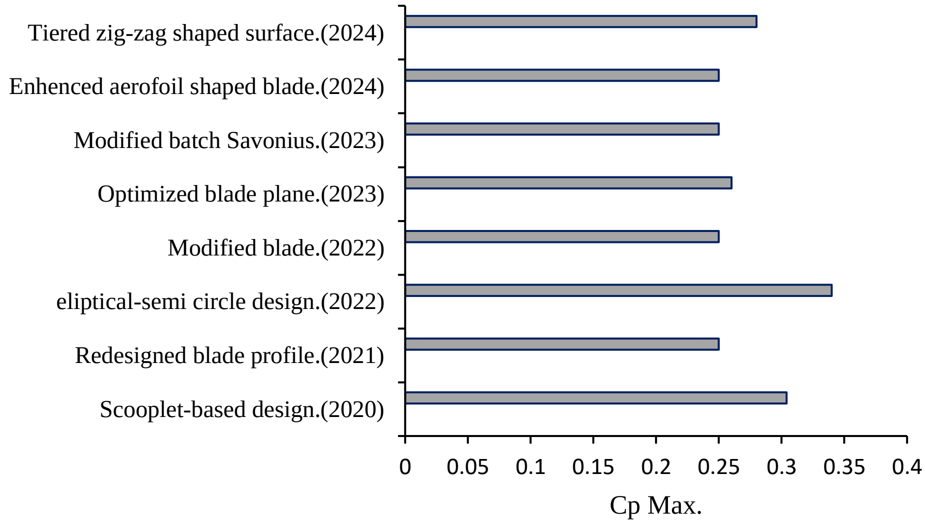

Figure 5. The trend in blade profile modifications and the performance of the Savonius wind turbine.

4.2. Installation Effects

Given the diverse use of the Savonius vertical axis rotor, there is the need to understand the wind profile disturbances when multiple turbines are installed in clusters. Inasmuch as a lot of focus has been given to the efficiency improvement of the Savonius rotor, the torque fluctuation amplitude remains vital, especially in Savonius wind turbine cluster arrangements. High-torque fluctuations affect the service length of the Savonius rotor setup [37]. Wind farm arrangements can be used to amplify wind harvesting to precisely meet the energy demand. Studies have been performed to investigate the effects of clustered wind turbine configurations on the performance of individual rotors. In a study by [38], the interactions of Savonius wind turbines arranged in a cluster were studied. The study followed three distinctive arrangements which were tested numerically at particular tip-speed ratios. The arrangements considered included three turbines arranged in a triangle, in parallel, aligned together, as well as in an oblique setup. At a tip-speed ratio of eight-tenths, and after considering different gaps in-between them, the aligned setup managed to produce a peak power coefficient of 41.7% higher than an isolated Savonius wind turbine at a gap of 4D. Under the same tip-speed ratios and varying distances, the parallel arrangement achieved a peak power value of 32% higher than the isolated scenario. However, it only grew with a distance of 0.2–0.5 between them, and thereafter started dropping. The Magnus effect affected the backward oblique arrangement, while the forward arrangement demonstrated an improvement in peak power compared to an isolated turbine.

Two contra-rotating Savonius wind turbine rotors were examined numerically to evaluate the impacts of the distance as well as the positional difference in azimuth angles between them. In this study, the rotors were separated by a distance of 0 to 1.5D. The results showed aerodynamic improvements compared to an isolated traditional Savonius wind turbine configuration. The distance which resulted in the highest peak power coefficient was equal to the diameter of a single rotor. However, the angle between them did not produce any improvement in performance [39]. In a similar arrangement, [8] investigated the addition of a diffuser onto two Savonius wind turbine arrangements. A numerical approach was again used to evaluate the operational and geometric parameters within the wind lens arrangement. The results of their study proved that the wind lens system improved single- and twin-Savonius-rotor systems by 64% and 114%, respectively, compared to the isolated turbine. The highest performance of the twin-rotor system was obtained when the rotors were counter-rotating. Furthermore, counter-rotating Savonius rotors where also investigated by [40]. The study evaluated the geometric properties of a triangular plate placed in front of two counter-rotating Savonius wind turbines. The triangular plate blocked the air from interacting with the returning blades of the Savonius wind turbines, and thus reducing the negative toque. The results of the study report an optimal power coefficient of 0.22, which, when compared to the traditional Savonius wind turbine setup, represented a 30% gain.

A low-cost and stable Savonius rotor design was sought by [41]. In their study, the turbine stability was prioritized such that, when faced with any disturbance, the power generation efficiency of the rotor could only be minimally affected. In cases where a higher electrical demand existed, multiple small Savonius wind turbines would need to be installed; thus, their study examined the cluster rotor arrangement interactions. The results produced showed that, for two rotors in a cluster, the downstream rotor could benefit from the vortex formed by the upstream rotor if it was close enough. For the three-turbine setup, the two turbines downstream had to place the convex side of their returning blades in the low-velocity wake regions for the increased total power generation of the cluster. However, this setup could be disrupted by a change in the wind direction, and thus future studies will have to research a low-cost yaw mechanism to maintain this arrangement even when wind direction changes.

4.3. The Use of Deflectors in Reducing Negative Torque

The Savonius rotor suffers mostly from negative torque generated on the returning blade. Augmentation techniques have been used to reduce the effect of this phenomenon whilst consequently improving the performance of the Savonius wind turbine. A deflector system was used in most augmentation studies, with the general use being to guide the incident wind away from the returning blade whilst focusing it onto the concave side of the incoming blade surface. A study was conducted to improve the Savonius rotor's efficiency by altering its typical profile and adding guiding blades to its vicinity. For the purpose of choosing the guide blades and forecasting the turbine performance, a computational fluid dynamic (CFD) analysis was carried out.

The recommended improvements to the turbine were tested experimentally, and the findings of the CFD analysis were confirmed. The investigation yielded a maximum power coefficient of 28%. According to the study, guiding vanes aided in reducing the negative torque, thus increasing the efficiency. Even in areas with low wind speeds and heavy turbulence, the modified turbines can be employed [42].

A simple truncated cone was used as a deflector for a Savonius wind turbine setup in order to increase the incident airflow. The study sought to create a simple axisymmetric deflector system which does not need any yaw mechanism while at the same time augmenting airflow to the turbine. A response surface method was used to optimize the parameters of the deflector to ensure the highest performances. The results reported an increased airflow towards the wind turbine, which produced a peak power higher than the conventional Savonius wind turbine structure. A 25% increase in the power coefficient was recorded for this easy-to-manufacture deflector system [43].

Mohamed et al. utilized a shield as an obstruction at the front of the returning blade as they worked on the three- and two-bladed Savonius-type wind turbines. In all of the positions, the barrier plate enhanced the turbine's capacity for self-starting. For a Savonius rotor with two and three blades, the coefficient of power was found to be 0.25 and 0.21, respectively. The deflector's maximum Cp was attained when it was angled at 37°. A porous deflector was used instead of a solid one to reduce the negative impacts of the wake zone brought on by a solid deflector [44]. A numerical analysis was performed to determine the impact of various geometrical factors, such as the porosity, the height, the angle, as well as the distance from the rotor. The outcome showed that, when the wind passed the porous deflector, the wake zone generated behind it broke down into smaller vortices, and the flow field showed reduced variability. For the best configuration, the output power coefficient was improved by 10% with a TSR of one [45].

In a complementary study, a rotating cylinder was then considered for vortical shedding and to avoid the devastating effects of the rotor's wake. The wake from most of the solid stationary deflector systems interacted with the return blade, thus reducing the efficiency of the rotor [46,47]. The results reported that the rotating cylinders used obtained the highest power coefficient when placed at 1.4D and 0.5D in the x and y axes, respectively. The optimum diameter of 0.75 was observed, resulting in better performance compared to the stationary deflecting cylinder for all of the TSRs.

An improvement in the peak power of 33% was realized when using the rotating cylinder. The Savonius rotor with a deflector system was found to produce up to 50% more torque than the traditional Savonius rotor. However, this amount of torque improvement was only realized when the deflector operated at an angular speed of 3 rads as opposed to the 40 rads [48]. In a later study, the authors studied the use of wake-controlling splinters. Their geometric properties as well as the novel middle splinter were adjusted to produce the highest performance on a Savonius wind turbine system. The result was a system with a deflecting cylinder and two attached wake splitter plates, which managed to direct the incident wind away from the returning blade, thus improving the negative torque, especially in the zones from 0° to 90° and from 180° to 360°. The cylinder deflector alone was able to direct wind towards the incoming blade but created flow separation, which interacted with the returning blade. This phenomenon was disrupted by the addition of wake splitter plates, as discussed above [49].

In another follow-up study, a different setup on the cylinder deflector was studied. The use of a structured surface roughness approach to managing the wake on the deflector was studied using a CFD approach. This passive wake control strategy employed a grooved surface to improve the performance of a Savonius wind turbine system. The results of the study managed the wake of the cylindrical deflector and improved the peak power coefficient by 23.2% when compared to a rotor without a deflector. Key to the reduction in the negative torque was the recirculation zone between the deflector and the returning blade [50].

Additionally, an active control strategy was used to control the flaps (vented blades) within the blades of the Savonius wind turbine in order to reduce the effects of the negative torque. The study established the optimum performance parameters of the opening and closing angles as well as the length of the flaps. The result of the study was an optimized elliptical Savonius wind turbine with vented blades. The setup achieved a power coefficient improvement of 21% compared to a bare turbine. Even though the vented wind turbine system required a minimum amount of energy to actuate the vents, it still maintained the omnidirectional property whilst reducing the negative torque significantly [51]. An airfoil deflector was chosen for another study to improve the performance of a Savonius rotor. The deflector with the best performance was made up of eight channel guide vane setups with eight airfoils which injected air into the buckets of the Savonius rotor. Another advantage of using an airfoil deflector system is that it interrupts the formation of a wake zone and reduces turbulence, which are normally created by flat plate deflectors [52].

The airfoil-based deflector not only improved the peak power by 140% compared to the traditional system but also improved the range of operation of the rotor system. An installation angle of 45° was found to yield the best results when using the NACA0018 airfoil deflector. Future studies on this deflector should be guided towards the experimental application of such a deflector in high-rise buildings and even highways [53].In Figure 6, the effects of deflector systems on the performance of the SWT are presented.

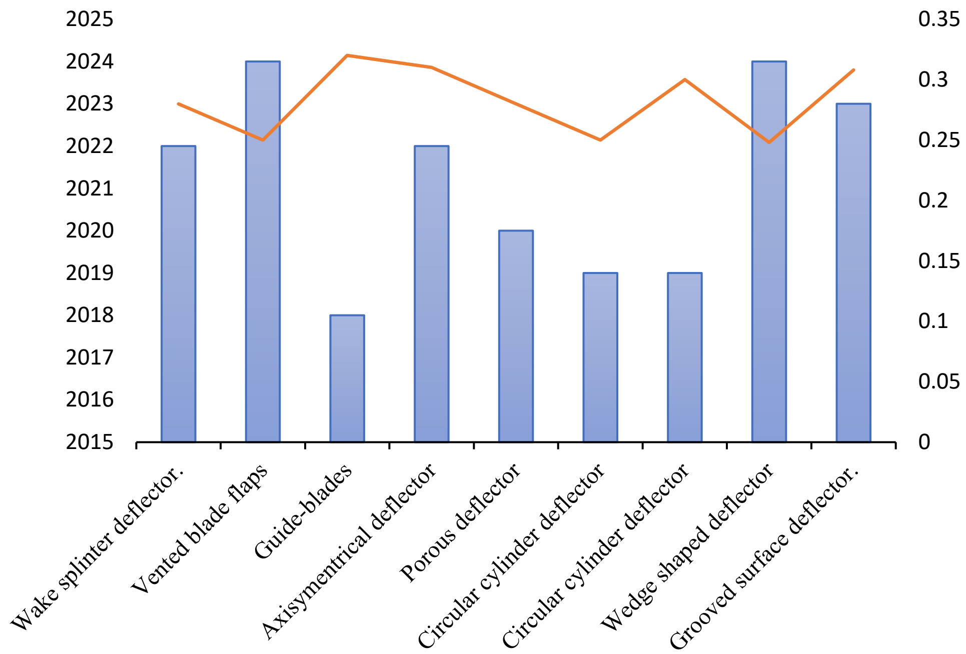

Figure 6. Effects of wind deflector systems on the performance of the Savonius wind turbine.

4.4. Multistage Savonius System

Multistage Savonius wind turbine systems employ a unique arrangement by using a number of turbines stacked on top of one another. The advantages of such a setup are that the fluctuations that arise from the repeated switch over of the two rotor blades during operation are reduced [23]. In a study, a two-stage Savonius-type wind turbine was used to investigate the effect of a phase-shift to the general efficiency of the Savonius turbine. Using phase-shift angles (PSAs) of 0°, 30°, 60°, and 90°, simulations were conducted in an ANSYS (version 2021) Student edition software's Solver CFX environment. The simulations were performed using a steady-state SST (shear stress transport) turbulence model, and the outcomes showed that the phase-shift angle (PSA) had an impact on the Savonius turbine's efficiency, with 30 degrees being the ideal PSA [5].

To follow-up on this study, an investigation of various phase angles and stage ratio effects on the performance of a twin-rotor Savonius wind turbine was conducted. In the study, several two-stage ratios were tested within TSR arrangements. The 2:1 ratio performed the best at a 30° phase angle, thus reaching a peak Cp of two-tenths [54]. Twin-rotor Savonius wind turbines with elliptical rotors were also studied to find out the effect of multiple stages on the performance of a Savonius wind turbine system with elliptical blades. In their study, Ref. [55] investigated a two-stage elliptical rotor setup utilizing the SST k-ω turbulence model in the numerical investigations. The two-stage rotor managed to achieve a peak power coefficient of 0.21, and therefore a 39.4% improvement when compared to a single-stage elliptical rotor setup. The multistage setup also recorded improved lift and drag at elevated TSRs, which was better when compared to the traditional elliptically bladed Savonius wind turbine. The 90° phased-angle twin stages solved the negative torque situation by focusing the transverse flow from the first stage to the second stage at a specific point of rotation. An application of a multistage design was performed by [56] by employing a multistage Savonius rotor design as a wind barrier for bullet trains. In their simulations, the study confirmed that a multistage rotor system reduced fluctuations and improved the Cp compared to the traditional Savonius system.

A helical blade setup has the capacity to improve the effects of negative torque in almost the same way as a multistage semicircular wind turbine can. In a study, a helical wind turbine setup with a twist angle of 180° was investigated and compared to a twin-stage helical wind angle with a twisted angle of 180°. The study compared the numerical results to the experimental results, which were in good agreement. The results reported a minor improvement in the performance after producing the complicated multistage twisted helical rotor [57].

The effect of multistage Savonius wind turbines on the starting capabilities of the Savonius wind turbines was studied by [16]. They tested experimentally the two stages using variable methods to investigate the effects of negative torque, static torque, and dynamic torque variations due to the addition of another stage. The addition of another secondary stage phased at 90° to the primary stage reduced the torque variations, resulting in better momentum generation by the turbine, thus canceling out the effects of the increased AR and reducing the positive peak torque at different blade angles of a single-stage rotor. The self-starting capabilities were enhanced in the twin-stage rotor because of the phased secondary stage, which ensured peak positive torque at all angles of the rotor [16]. Table 2 shows a summary of the geometric properties of the Savonius wind turbine performance.

Table 2. Summary of the effects of the enhancements to the operation of the Savonius wind turbine.

Reference	Description.	Self-Starting Ability.	Enhancement.	Gap for Future Work.
[31]	Novel scooplet blade design	Not tested	Peak power is 39% higher than the classical SWT.	Enhancement and testing of the self-starting capacity.
[32]	Tiered zig-zag pattern on the concave side of the SWT	Not tested	A 16% increase in the power coefficient.	Testing of more patterns on the concave blade of the SWT.
[34]	Blade profile modification	Not tested	A 22.8% increase in the power coefficient.	Development of hybrid systems with other blade profiles or VAWTs.
[35]	Number of blades and cowl	Not tested	An 8.78% power coefficient improvement by adding a deflector.	Enhancement and testing of the self-starting capacity.
[38].	Spatial distribution of the SWT	Not tested	Backward oblique setup has 3 times the power coefficient of an isolated rotor.	Evaluating different turbine system setups.
[40]	V-plate deflector	Not tested	A 30% increase in the power coefficient.	Modification of the system for changing the wind direction.
[49]	Wake splitter deflector	Not tested	A 15% increase in the power coefficient.	Enhancement and testing of the self-starting capacity.
[55]	Multistage turbine system	Not tested	A 14.44% increase in the power coefficient.	Investigation of an augmentation device that can be used with this multistage turbine.
[41]	Cluster arrangement	Not tested	A 28% increase in the power coefficient.	A cluster with a yaw mechanism relative to the upstream turbine.
[42]	Rotor guide blades	Not tested	Peak power of 0.32.	-
[44]	Nozzle-augmentation system	Not tested	Peak power of 0.39.	Different augmentation shapes.
[45]	Porous deflector	Doubled the static torque	A 28% increase in the power coefficient.	Include inter-parameter interactions.
[46]	Numerical cylinder deflector	Not tested	A 17.31% increase in the power coefficient.	Smoothing diverted the wind flow.

Table 2. *Cont.*

Reference	Description.	Self-Starting Ability.	Enhancement.	Gap for Future Work.
[21]	Multistage rotor	Not tested	Peak power of 0.29.	Testing of different blade profiles.
[57]	Multistage helical turbine	Positive static torque from 0° to 90°	A 9.25% Cp gain compared to other multistage systems.	Numerical method can be applied in future work.
[16]	Multistage Savonius wind turbine	Positive static torque in all angles; improved self-starting	A 138% increase in the power coefficient.	Establishment of upper limit for turbines.
[51]	Active flap turbine blades	Not tested	A 21% increase in the power coefficient.	Using overset meshing to avoid gaps on the flaps.
[50]	Rotating cylinder deflector	Not tested	A 23.2% increase in the power coefficient.	Use of a U-shaped deflector.
[23]	Twisted blade profile	Positive static torque on all directions	Peak power of 0.31.	Reducing the structural load for a better Cp.
[5]	Multistage Savonius wind turbine	Not tested	Peak power of 0.29.	Investigation of other blade profiles.
[58]	Cluster arrangement	Not tested	-	A cluster with a yaw mechanism.
[47]	Experimental rotating cylinder deflector	Not tested	A 66.193% increase in the power coefficient.	Smoothing diverted the wind flow.

5. Conclusions and Recommendations

It has always been difficult for researchers to create a compact wind turbine with a basic design that has a better efficiency. The goal of this review has been to provide an overview of the modification and evolution of the Savonius wind turbine, keeping the applications in low-wind-speed areas in South Africa in mind. Although the Savonius wind turbine has the potential to contribute to the energy mix, limitations are visible in its self-starting capacity, which is influenced by the static torque, as well as its power coefficient, which is mostly affected by the negative torque. This literature review shows that the performance of the Savonius wind turbine is tied to a number of geometric parameters, which, in turn, gives it character. The multi-parameter interactions of the turbine are yet to be fully investigated and, as such, each modification is unique. Several modifications to the Savonius wind turbine properties were found to considerably improve the efficiency, peak power, magnitude of fluctuation, and, in some cases, the self-staring capability. Of the discussed reviews in Tables 1 and 2, only less than 18% of the studies considered testing the effect of the respective enhancement to the self-starting capability of the turbine. Despite having good self-starting properties, the Savonius wind turbine would struggle to start if installed in most areas in the Eastern Cape, South Africa. A case study of Mthatha in the Eastern Cape can be considered. The wind terrain was investigated for a period of ten years by [59], and the average annual wind speed was 3m/s, which does not reach the cut-in wind speed of most of the shelf turbines. For such a site, the aspect and overlap ratios limit the application, since occasional high wind speeds can be observed, even though the average is low. However, due to some blade profile modifications, the structural integrity can be improved, and thus higher AR and OR values can be utilized, thereby improving the power coefficient. Given the low-speed nature of the area, deflectors such as the wedge deflector, which deflect more air to the turbine, can improve the drag forces on the turbine blades, thus improving the self-starting capability as well as augmenting the incident wind. Augmentation devices which can also act as deflectors can also be considered to interface such low winds with higher cut-in wind speed turbines. While other factors such as multistage effects and blade arcs are not site-specific, cluster arrangements can bring advantages to a wind farm made up of Savonius wind turbines. Future studies could also look into the use of different materials as a way to improve the structure and shed weight simultaneously, thus improving the self-starting ability at all-turbine angles.

As highlighted in the study, recent focus is being directed towards the reduction in operational fluctuations. This is achieved by maintaining a positive torque in all angular positions on the turbine. Another focus area is the smoothening of the flow directed from the returning blade by the use of deflectors, as well as the modification of the blade profiles and the cluster interaction of Savonius wind turbines. Multistage enhancements have been among the studies reporting the highest improvements in the peak power. The reason for this is mainly the reduction in the torque fluctuations and the improved structural integrity. The most mentioned guide for future studies involves the combination of several parameters in order to study their interactional effects. Most methods compared one parameter while holding others constant. This limits the extent of the investigation that can be performed on the operational characteristics of the modified turbine system. This involves the use of hybrid turbines which can combine the strengths and negate the negative aspects of most designs. Cluster arrangements of the Savonius rotor have shown positive interactions which are better than lone setups. The major recommendation is to develop a cluster formation which will not be disrupted by a change in the wind direction.

Author Contributions: A.G.C. contributed towards the conceptualization, writing—original draft preparation, and formal analysis of the manuscript. Writing—review and editing, as well as the funding acquisition and supervision, was performed by P.M. The project administration and provision of resources was performed by N.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Special acknowledgement to RNA: Renewable Energy-wind of GMRDC University of Fort Hare.

Conflicts of Interest: The authors declare no conflicts of interest.

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