

Small Scale Wind Turbines Optimized for Low Wind Speeds

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Abstract

A combination of common vertical axis wind turbines (VAWT) rotors was designed and tested for optimal performance in low wind speeds. The Savonius rotor creates high torque and is self-starting even at low wind speeds, but is relatively low in efficiency rating. The Savonius rotor is used to start the straight bladed Darrieus rotor. The Darrieus rotor is not a self starting rotor, but has much higher efficiency than the Savonius rotor. The combination of rotors increases the total power of the turbine in lower wind speeds.

1. Introduction

The goal of this project was to design a wind turbine specifically for low wind speed sites. The turbine was also to be designed for low cost using simple to manufacture parts. After careful consideration of the existing literature and other wind turbines that are commercially available, a hybrid combination of common vertical axis turbine rotors was chosen. The Savonius rotor is a self-starting, high torque at low speed rotor. It is used to jump start the Darrieus rotor, a non self-starting, but high efficiency rotor. A small model of the wind turbine was built and thoroughly tested in a wind tunnel at wind speeds of 5-13 mph. This combination proved to be an effective design that self-starts and produces more energy at low wind speeds than other options currently available.

Since most of the country has low speed wind available, this turbine would be applicable in many places and there is a growing market for smaller, more compact wind turbine designs that are easy to maintain and are able to generate power in lower wind speeds and in unsteady conditions. An additional benefit of these turbines is that they can be mounted on existing structures, therefore lowering installation costs by reducing or eliminating the need for tower structures. These smaller turbines can also use batteries to store energy, thereby reducing and possibly eliminating the need for grid power. The main objective of this project is to develop a small-scale vertical-axis wind turbine that will be a safe and viable option for many environments and applications.

The proposed design is a hybrid between the standard Savonius rotor and a vertical wing, straight-bladed Darrieus rotor, with both turbines on the same axis. This design combines the advantages of both designs while attempting to reduce the disadvantages. A prototype was built

to be fully adjustable so it can be quickly modified during wind tunnel testing for testing various combinations of design parameters. The data collected from the wind tunnel testing was used to determine the best configurations.



Figure 1. Rendering of the hybrid turbine.

2. Design Decisions

The hybrid wind turbine design for this project was developed through research of current commercial design and a thorough literature survey. The team believed combining the Darrieus and Savonius type rotors on one axis would allow for self-starting as well as speed control by the drag-type Savonius. Many configurations were considered but not chosen for this project including single- or three-stage Savonius, twisted geometry Darrieus blade profiles and convergent nozzles.

The original study by Savonius [1] only considered a single basic rotor design. The classic Savonius rotor does not have any airflow between "buckets" (see Figure 2). In the classical Savonius style, the buckets are connected or a pole is blocking the flow between the buckets.

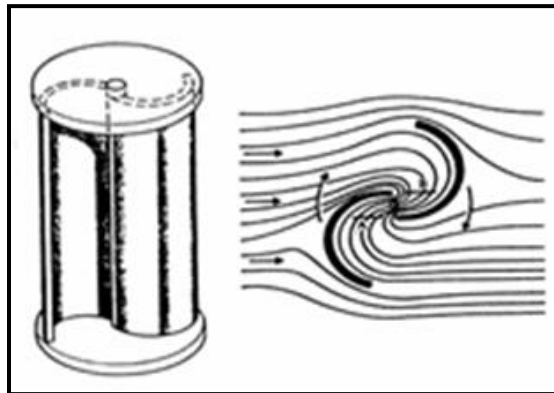


Figure 2. Classic Savonius Rotor with no air flow between buckets.

Subsequent studies by researchers have shown that allowing air to flow between each side of the rotor dramatically improves the efficiency. A simple modification to the original study by Savonius by overlapping the rotors (see Figure 3), and thus allowing air to flow between each of the sides, significantly increased the efficiency. Fujisawa [2] experimented with different numbers of stages and experimentally measured the efficiency of each combination. This study concluded the two stage overlapping Savonius rotor was the most efficient of the combinations tested. This also allowed the turbine to be started with wind from any direction because offsetting the stages will ensure that one "bucket" is always in the direction of the wind.

Twisted blade profiles have also been tested in the literature, but were not used in the current project because they would have been difficult for the team to fabricate with the given time allowed and the efficiency benefit was negligible.

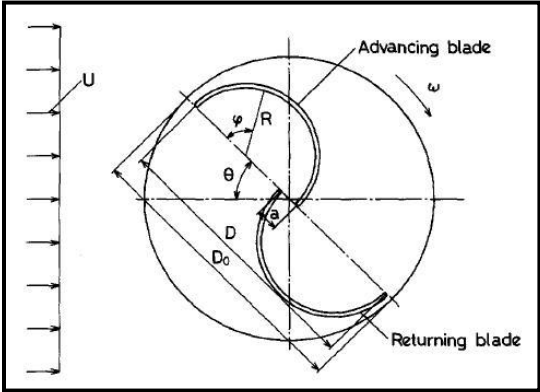


Figure 3. Overlapping Savonius rotors.

A slightly more efficient design (see Figure 4) was studied by Modi [3]. This design, although slightly more efficient, is much more complicated to manufacture and ensure perfect alignment. Ultimately, it was decided that the savings in manufacturing cost and reliability was more important than a small increase in efficiency.

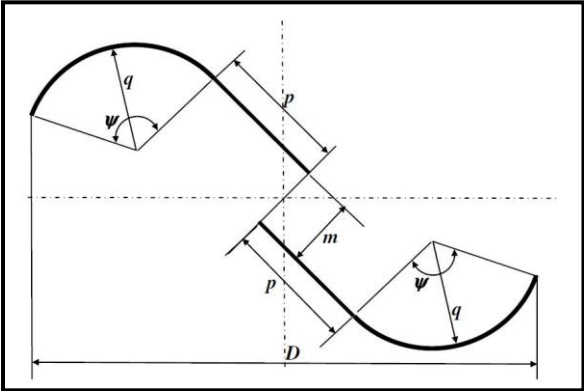


Figure 4. Modified Savonius rotor.

Another method to increase efficiency is to add converging [4]. Converging nozzles (see Figure 5) increase the velocity as it comes into the "torque" side of the rotor and also deflects air from the "anti-torque" side. Although this increases the air speed through the turbine, it changes

the entire design of the turbine because the turbine now has to be rotated in the direction of the wind, eliminating the "accepting wind in any direction" aspect of the design.

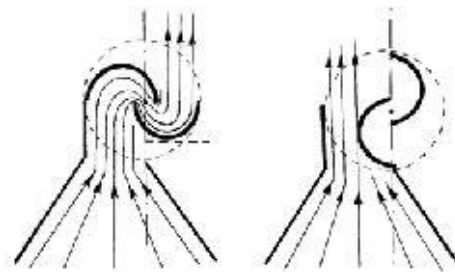


Figure 5. Converging nozzles on Savonius rotor.

The same type of design aspects and decisions had to be made for the design of the Darrieus portion of the design. In reviewing current commercial models of Darrieus rotor turbines, all turbines were optimized for high wind speeds. In addition, the standard design "rules" were also for high wind speeds. This information was taken into consideration when designing the Darrieus portion of our turbine design.

The most common Darrieus blade profiles are the NACA 0012 and NACA 0015 - which are both symmetrical profiles. Guillaume [5] studied the difference between the standard symmetrical profiles and specially designed cambered profiles. This report claimed the S2027 blade profile increased overall energy produced by about 16% over the standard NACA 0015. The group chose to test the two standard symmetrical blade profiles and the S2027 cambered profile to verify these claims.

The number of Darrieus blades was another design parameter. Current commercial Darrieus turbines use between three and nine blades. Some turbines do use a large number of blades, although typically only for large turbines. The group could not find any information on how to choose the number of blades so to reduce costs of manufacturing; the group chose three blades, which was the common number of blades for turbines of similar size.

Chord length was the last design parameter considered. The chord length makes the most impact on the torque produced. The standard design convention for Darrieus turbines is a chord length of about 10-20% of the length of the blade - but this design standard is meant for high wind sites. With lower wind speeds, less torque will be made by each blade. In order to

compensate for some of this torque loss, the group tried increasing the chord length of each blade. This has consequences, such as increased cost to manufacture, increased weight and increased moment of inertia that hinders the turbines ability to increase speed quickly.

Several options were available for measuring the power the turbine produced with varying levels of cost and accuracy. The cheapest and least accurate method was to use a "rope break dynamometer" [9] (see Figure 6). The rope break can be successfully used in large applications, but the group was unsuccessful using this option when the torque being measured was so small. The next option was to use a cantilever beam attached to the resistance motor with a strain gauge mounted on the surface of the beam. In theory, the strain gauge measures the strain in the beam, which is only caused by the torque the wind turbine is producing. In practice, the strain gauge measured other unwanted effects, such as wind and vibrations.

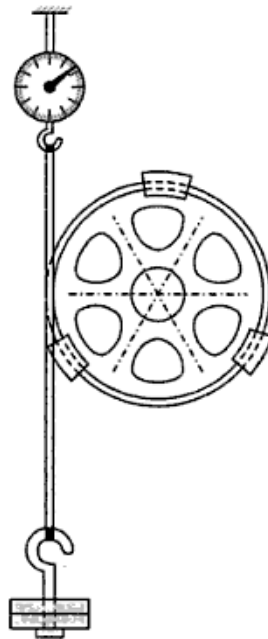


Figure 6. Rope break dynamometer.

The usual way for measuring torque in a wind tunnel is to use a rotary torque sensor. These sensors are very accurate and easy to use. The sensor is connected to the shaft of the turbine on one side and the resistance on the other side. The entire sensor rotates with the turbine. Ideally, this option would be selected, however, these sensors are very expensive, costing anywhere between \$4000 and \$7000. Ultimately, a solution using a reaction torque

sensor was developed. See the "Additional Notes - Power Measurement" section for more details.

3. Wind Tunnel Model and Test Parameters

This hybrid turbine design was intended to be very versatile, excelling in many different environments and applications. The Savonius rotor is a basic rotor that excels in low wind speeds, accepts wind from any direction and provides high torque at low rotational speeds. The Savonius rotor is limited to low rotational speeds and somewhat lower efficiency levels than other rotors. The Darrieus rotor excels in moderate wind speeds, still produces power in low wind speeds, but requires an external source to start the rotation. In the proposed design, the Savonius rotor provides the external assistance needed to jump start the Darrieus rotor. With these ideas in mind, the proposed turbine is an ideal solution for sites with relatively low to moderate wind speeds; sites where large horizontal axis turbines would not be the appropriate solution.

The wind tunnel model was built to have interchangeable parts to test different combinations of design parameters. Two slightly different symmetric airfoil shapes were tested, NACA 0012 and NACA 0015, as well as one cambered profile, S2027 (see Figure 7). Both of the symmetric airfoils were tested with three different chord lengths. These profiles represent the most common airfoil shapes used in previous literature concerning straight-bladed Darrieus rotors. The distance from center to the straight Darrieus blades (Figure 8) and the pitch angle of the Darrieus blades (Figure 9) were also varied.

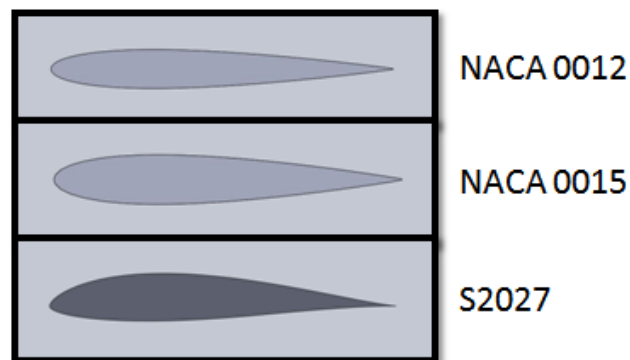


Figure 7. Blade profiles tested.

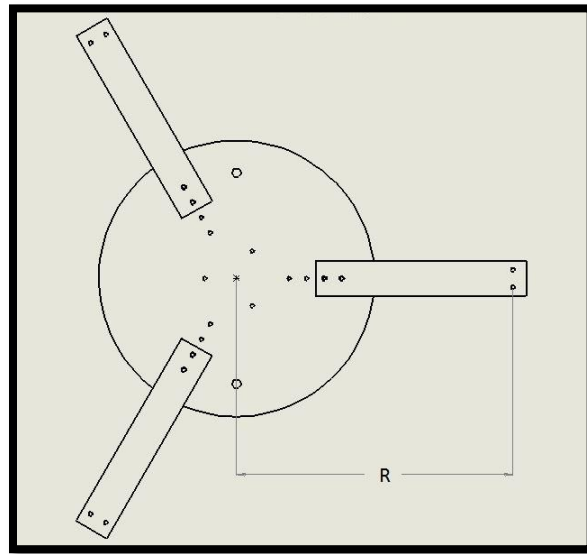


Figure 8. Darrieus blade distance from axis.

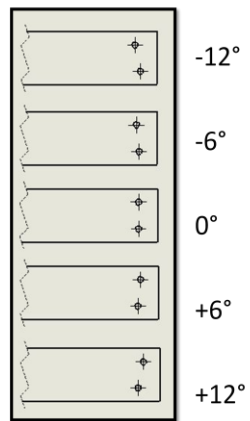


Figure 9. Darrieus blade pitch angles tested.

4.1 Wind Tunnel

The prototype turbine was tested at The Ohio State University Aeronautical and Astronautical Research Laboratory wind tunnel facility. The tunnel is a subsonic Eiffel type open circuit design (shown in Figure 10) with a test section measured at 3' x 5' in area. The prototype was built to be mounted vertically in the contraction section of the wind tunnel. This placement allowed the team to observe the most accurate power results in the lowest wind speeds. A test stand was built to hold the turbine while tested in this section. A cup anemometer was placed within this section to measure the wind speed.



Figure 10. Turbine model in contraction room of wind tunnel during wind tunnel testing.

4.2 Equipment

- RTS Torque Sensor (25 in*oz capacity)
- Omron Rotary Encoder (100 pulses per revolution)
- National Instruments USB 6009 Data Acquisition System
- Labview 8.5 Vishay 2120A Strain Conditioner in a Vishay 2100 Mutli-Channel Amplifier
- Japan Servo AC Induction Motor
- Inspeed Data Logging Wind Speed Anemometer
- Bearings / Couplings / Magnets - more information below
- Custom-built rotors - more info below

4.2.1 Couplings / Bearings-Magnets

Due to misalignment issues between the motor and wind turbine shaft, a few couplings were tested. Flex, Oldham, flexible spider, and Bellows couplings were evaluated to fix the issue of parallel misalignment. It was found that Bellows couplings allowed for some slack and corrected the misalignment, while maintaining some rigidity. The smoothness of the rotation of the shaft was critical for the torque sensor readings.

In order to use low friction roller bearings, the group used the concept of magnetic levitation to support the turbine. With the existing small-scale model, fairly small magnets can be attached around the shaft to hold the turbine. The magnets are neodymium N42, (1.5" OD x 0.75" ID x 0.75" thickness). The magnets are in place at the top of the test stand with approximately an inch and a half gap between the magnets.

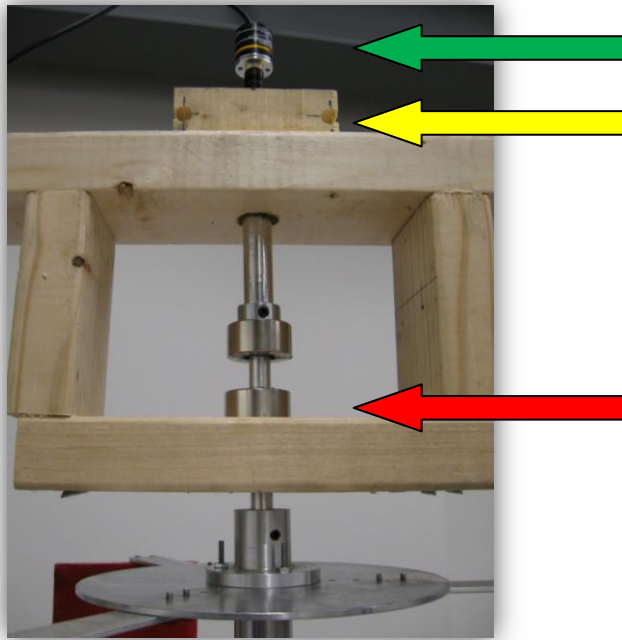


Figure 11. Close up picture of magnetic levitation system (red), bearing block (yellow) and rotary encoder (green).

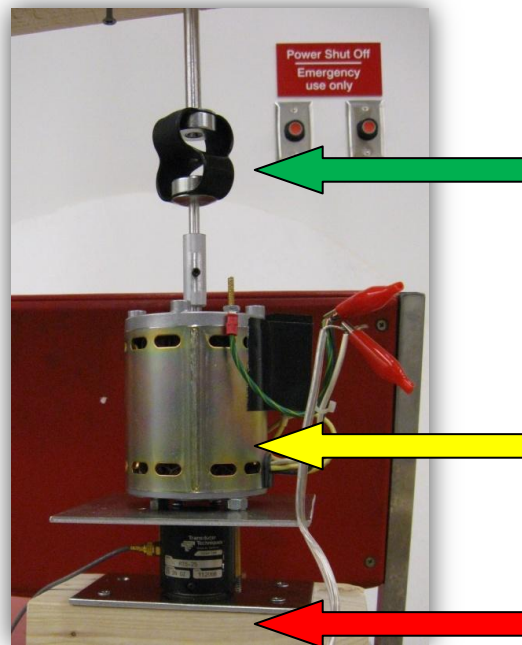


Figure 12. Torque Sensor and resistance motor connected to turbine with flex coupling.

4.2.2 Custom-built rotors

The Savonius blades were constructed from PVC pipe with JB Weld used to attach the blades to the aluminum plates. The Darrieus blades were custom made fiberglass blades.

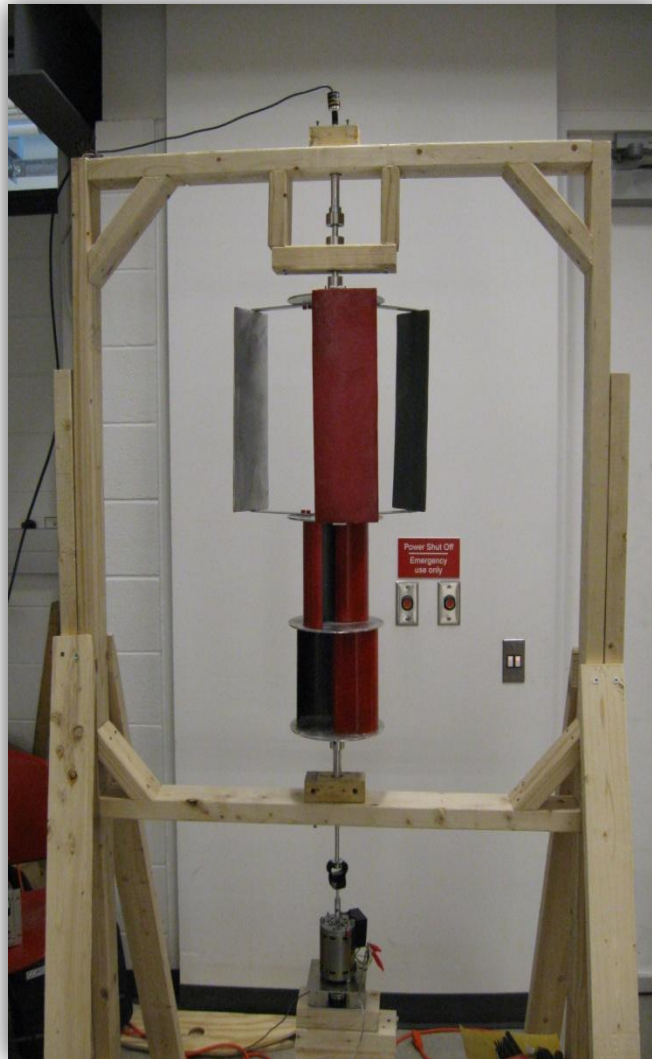


Figure 13. Turbine model mounted in test stand.

5. Power Measurement and Testing Procedure

The procedure for testing the power a wind turbine makes is much like testing an engine in a car. A very low power dynamometer was developed for our testing purposes. A shaft from the turbine was connected to an AC induction motor. When DC power is applied over the AC motor, the motor does not spin, but resists motion at a level corresponding to the power applied. This motor was connected to a reaction torque sensor. The torque sensor measured the amount of resistance the motor was applying to the wind turbine.

The wind tunnel was set to a constant speed (5, 8, 11, 13 mph) and the wind turbine was allowed to spin freely until the turbine reached a maximum rotational speed. Next, a small load was applied to the turbine, which caused it to slow down. When the turbine slows, the energy that was helping to rotate the turbine is converted to an increased torque. Allowing this process to continue until the turbine stops gives a turbine power curve (for example see Figure 14). This process was used to test each combination of design parameters. Because the torque is not constant around the entire revolution, the torque measured around the revolution was averaged over several revolutions.

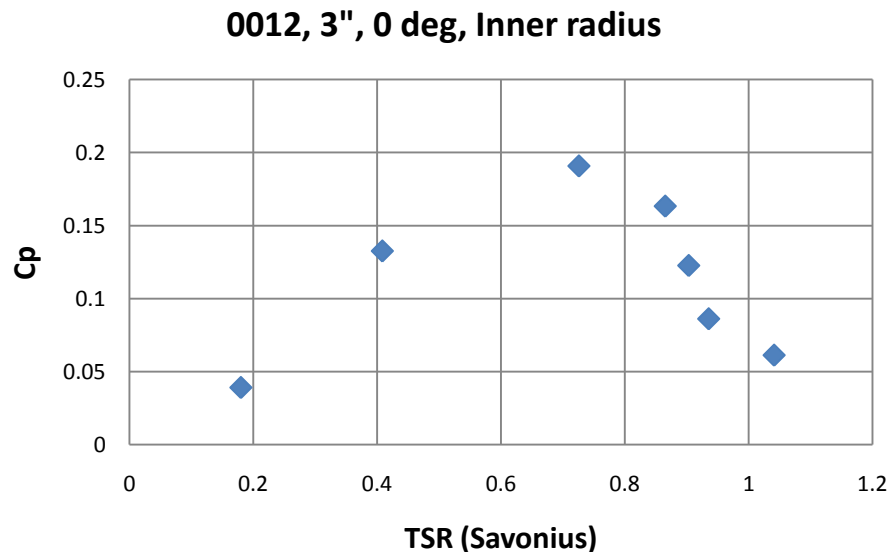


Figure 14. Example test data for NACA 0012, 3" chord length, 0 degree pitch angle, Inner radius Darrieus arm length at 11 mph.

6. Results to Date

In order to test the experimental setup, the Savonius rotor was tested alone and compared to previously published data [2]. From this previously published data, we expected the maximum coefficient of power (C_p) to be 0.18 to 0.20. The maximum C_p found from our experimental setup was 0.18-0.19 (see Figure 15) which is in the expected range. This procedure verified the measurement techniques and procedures.

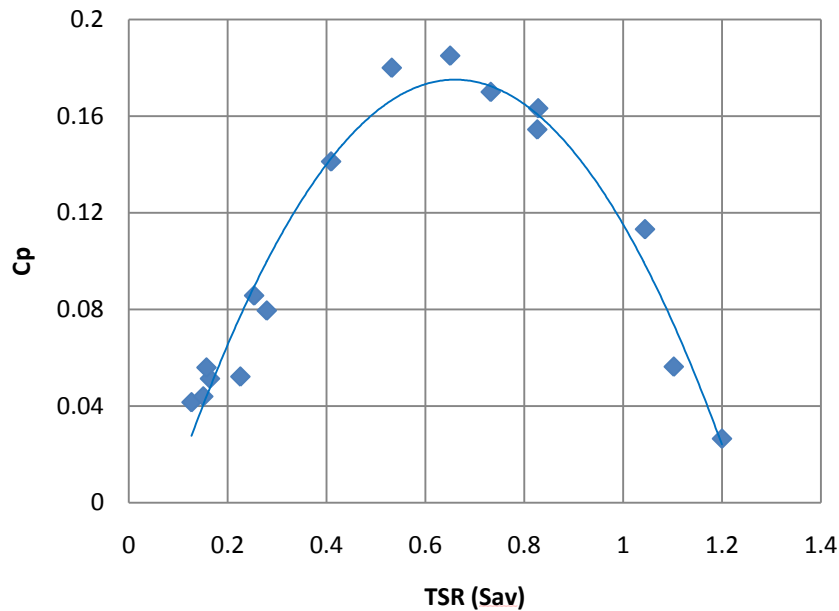


Figure 15. Coefficient of Performace vs Tip Speed Ratio (Savnoius only).

The rest of the turbine configurations were then tested. Figure 16 is a sampling of turbine speeds vs. wind speeds with no load. As shown, the maximum speed was about 525 RPM for the Savonius only at a wind speed of 13 mph. Already at 13 mph, the Savonius was beginning to govern the speed. Although it was not tested, the group believes the turbine would not be able to rotate any faster than 550 RPM. The other lines shown in Figure 16, show two configurations of the turbine using the smallest and lightest blades tested at the outer and inner radius positions. These configurations do not seem to have reached the maximum rotational speed at 13 mph, but are close to their maximum speed.

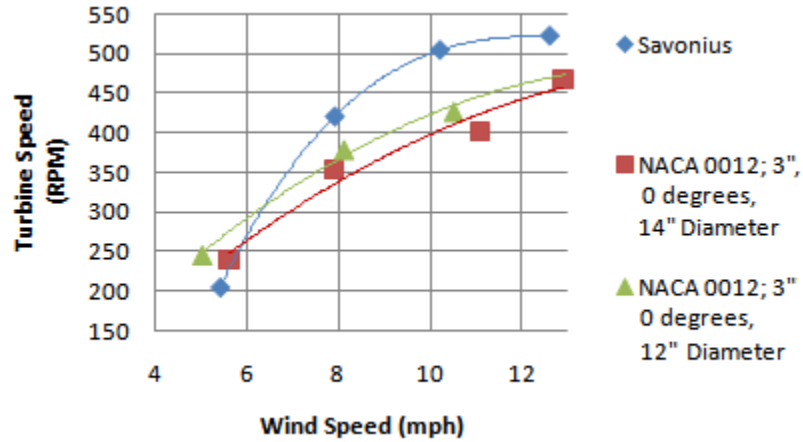


Figure 16. Turbine speed vs wind speed.

The next two figures (Figures 17 and 18) compare the power produced by the Savonius rotor alone (dark blue lines), the estimated power produced if the Savonius rotor was the entire height of the turbine (light blue line) and the hybrid combination of Savonius rotor and Darrieus rotor (all other colors). The legend describes the configuration of the turbine including the profile type, chord length, and pitch angle.

A very important aspect of this design is the ability to self-start. In all cases, except the NACA 0012 and NACA 0015 with 6" chord lengths, the turbine started at 5 mph or less. As shown in Figure 18, the turbine did not self start until 8 mph in the larger chord length configurations. The extra weight of these blades made starting the turbine much more difficult.

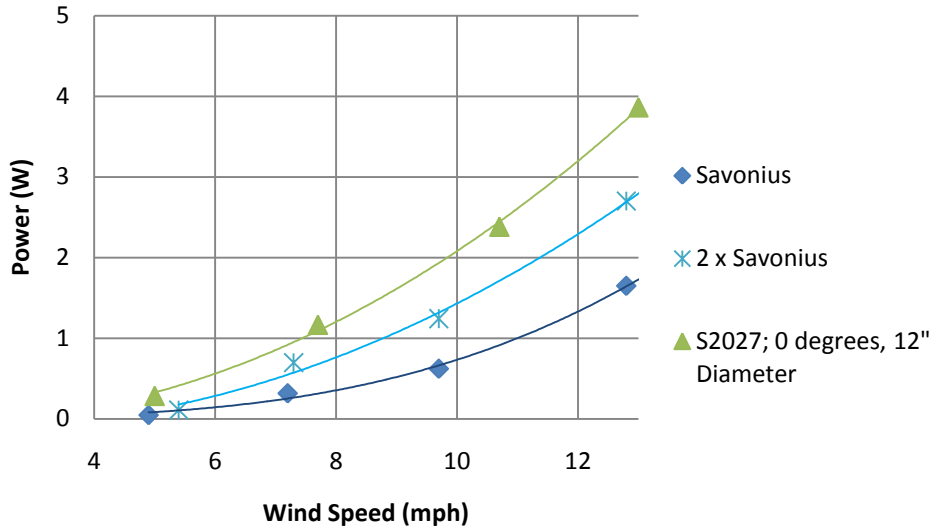


Figure 17. Power vs Wind Speed (S2027; 4.5" Chord, 0° angle, 12" diameter).

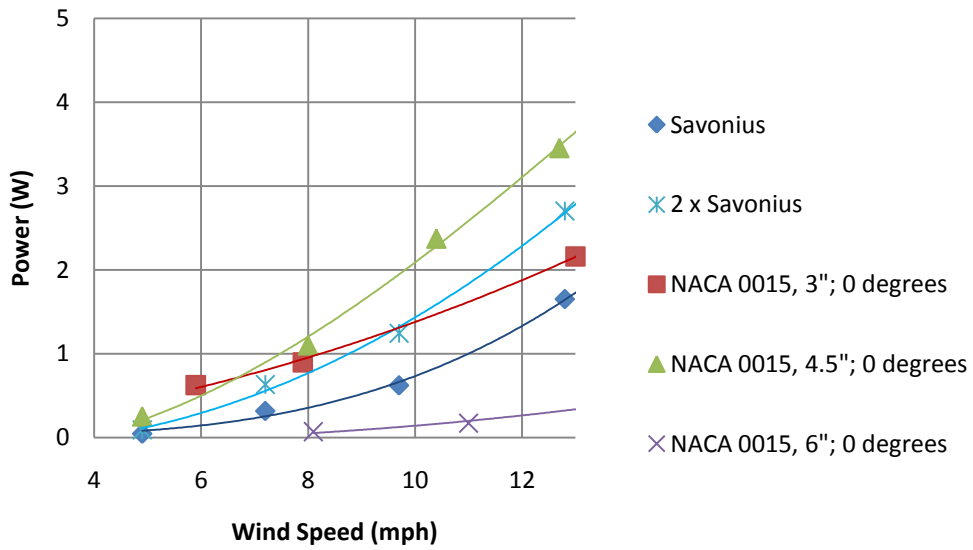


Figure 18. Power vs Wind Speed (NACA 0015; 0 angle, 12" diameter).

7. Analysis

As can be seen in the above figures, the lines are not always parallel and do cross at times. Therefore, it is not possible to simply pick the higher line and conclude that that configuration is better - each configuration must be checked individually. It was determined that the configuration that produced the most energy was the S2027 blade profile, with a 4.5" chord length, 0 degree pitch angle and 12" Darrieus diameter.

Because this project was completed for Westerville Electric Division in Westerville, OH, data were compared using average wind data [8] for several cities in Ohio (see Table 1) to calculate the total amount of energy that could be produced with this turbine design. Several different turbine heights were calculated (10 ft, 12 ft, and 15 ft) while keeping the ratio of diameter to height the same as the model. The resulting estimated energy production can be seen in Table 2.

| City | Jan | Feb | March | April | May | June | July | August | Sep | Oct | Nov | Dec | Average (mph) |
|--------------|------|------|-------|-------|-----|------|------|--------|-----|-----|------|------|---------------|
| Akron, OH | 11.6 | 11.1 | 11.4 | 10.8 | 9.1 | 8.4 | 7.6 | 7.3 | 8 | 9.1 | 10.8 | 11.3 | 9.7 |
| Columbus, OH | 9.8 | 9.6 | 10.1 | 9.6 | 8.1 | 7.2 | 6.5 | 6.2 | 6.4 | 7.4 | 9.1 | 9.4 | 8.28 |
| Dayton, OH | 11.4 | 11.3 | 11.7 | 11.3 | 9.7 | 8.8 | 8.9 | 7.3 | 8.1 | 9 | 11 | 11.1 | 10.05 |
| Toledo, OH | 11 | 10.5 | 11 | 10.9 | 9.5 | 8.4 | 7.5 | 7.1 | 7.7 | 8.8 | 10.2 | 10.4 | 9.4 |

Table 1. Average Wind Speeds throughout Ohio.

| City | Average Wind Speed (mph) | Average Energy Produced per year (kW*hr) | | |
|--------------|--------------------------|--|--------------------------|--------------------------|
| | | Full Size Height – 10 ft | Full Size Height – 12 ft | Full Size Height – 15 ft |
| Akron, OH | 9.7 | 224 | 354 | 554 |
| Columbus, OH | 8.3 | 144 | 226 | 355 |
| Dayton, OH | 10 | 226 | 356 | 558 |
| Toledo, OH | 9.4 | 221 | 349 | 547 |

Table 2. Estimated Energy Production for several turbine sizes.

One of the most common vertical axis residential wind turbines, the Mariah Power Windspire [6] (see Figure 19), has been independently tested by the National Renewable Energy Lab (NREL) [7]. The results of this test allow a fair comparison between the newly designed hybrid turbine and a commercially available turbine. To make a comparison, a hybrid turbine height of 12 ft was chosen to compare to the 20 ft height of the Windspire Turbine. The results are tabulated in Table 3.



Figure 19. Mariah Power - Windspire Turbine.

| City | HYBRID TURBINE | WINDSPIRE | % Increase |
|--------------|---|----------------|------------|
| | Average Energy Produced per year (kW*hr) | | |
| | Full Size Height – 12 ft | Height - 20 ft | |
| Akron, OH | 354 | 163 | 117% |
| Columbus, OH | 226 | 28 | 707% |
| Dayton, OH | 356 | 211 | 69% |
| Toledo, OH | 349 | 126 | 177% |

Table 3. Hybrid comparison to Windspire turbine.

The results demonstrate the effectiveness of the hybrid turbine in low wind speeds. In fact, in locations such as Ohio with low wind speeds, the hybrid turbine could produce much more power than other commercial turbines.

7.1 Applicability

This project is a starting point for what could potentially be an extremely successful wind turbine design. Because most of the country experiences only low wind speeds, wind turbines optimized for high wind speeds are not effective. More research needs to be done in the low wind speed wind turbine area.

This project may be particularly interesting to entities that have new projects that are currently not connected to a power grid and have lower power use. This may be an attractive alternative to constructing power lines to the location or having to provide liquid fuel for a generator. This wind turbine design, in conjunction with a battery pack, could provide enough power for the location.

8. Future Plans

This research project can be taken in three separate directions; Computation Fluid Dynamics (CFD) modeling, generator design and materials/manufacturing process. With the experimental data collected during this project, CFD models can be created and compared to actual data to determine the accuracy of the model. All of the wind turbine modeling is useless without a generator design that can accommodate the aspects of the wind turbine. Also, this project is useless if the actual full size product is not possible to manufacture. Scaling this model to a full size prototype may mean studying advanced composite materials.

References

- [1] Savonius SJ. The S-rotor and its application. *Mech Eng* 53, 1931.
- [2] Fujisawa, N., & Gotoh, F. (1992). Visualization study of the flow in and around a Savonius rotor. *Experiments in Fluids*, 12, 407-412.
- [3] Modi, V.J., Fernando, M.S.U.K., & Roth, N.J. (1990). Aerodynamics of the Savonius rotor: experiments and analysis. *Energy Conversion Engineering Conference, 1990. IECEC-90. Proceedings of the 25th Intersociety*, 213-218.
- [4] Shikha, Bhatti, T.S., & Kothari, D.P. (2003). Wind energy conversion systems as a distributed source of generation. *Journal of Energy Engineering*, 129(3),69-80.
- [5] Guillaume, Algazze, Duc (2009). Economic Feasibility of wind turbines for individual households. *EWEC Proceedings 2009*.
http://www.ewec2009proceedings.info/allfiles2/54_EWEC2009presentation.pdf
- [6] The Windspire: Windspire Wind Turbine by Windspire Energy (Formerly Mariah Power).
<http://windspireenergy.com/windspire/>
- [7] Husky, Bowen, Jager – Wind Turbine Generator System Power Performance Test Report for the Mariah Windspire 1-kW Wind Turbine (NREL). December 2009
- [8] National Climate Data Center. Wind - Average Wind Speeds (mph).
<http://lwf.ncdc.noaa.gov/oa/climate/online/ccd/avgwind.html>
- [9] Ambekar, A., (2007). *Mechanism and Machine Theory*. New York: Simon & Schuster.