Enclosed Vertical Axis Wind Turbines

A Major Qualifying Project Report

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Abstract

This project studies vertical axis wind turbines (VAWT) to be mounted on the roofs of residences and public buildings. Vertical axis wind turbines were tested in the WPI closed circuit wind tunnel with different blade numbers, blade configurations, enclosures, and blade airfoil shapes to determine which variations could improve the performance of the turbine. The desired product of this research is a turbine design that would generate as much energy as possible given normal inland wind conditions. Enclosures were designed and tested with the goal of accelerating the wind through the turbine and blocking wind that would act against the direction of rotation. Wind turbines were made with thin, flat plate blades at angles of 30°, 37.5°, 45°, 52.5°, and 60°. At a blade angle of 45°, turbines were made with 2, 3, 4, 5, 6, 7, and 8 blades. Additionally, two turbines were made with an S1223 airfoil blade shape, having the same chord length as the thin, flat-plate blades. One turbine was made with three airfoil blades and another made with five airfoil blades. All the turbines were tested at wind speeds from 0 to 34.9 mph and their performance was evaluated based on rotor rotational speed, ω. Without an enclosure, the turbines with a higher number of blades had a higher number of rotations per minute (rpms). The 2-bladed turbine with $\omega=90$ rpm was the slowest performance and the fastest rotation was the 8-bladed turbine with $\omega=1254$ rpms. The first enclosure had an outlet approximately 210° after the inlet. With the first enclosure, all turbines increased their rotational velocity by at least 34.9% with the largest increase being 2325%. Turbine with more blades showed a smaller increase in velocity than turbines with fewer blades. The increase shown by the 8-bladed turbine was the least significant and the increase shown by the 3-bladed turbine was the most significant. The second enclosure had the outlet directly across from the inlet. Enclosure 3 was a simple 90° arc blocking wind on the half of rotation that resists the wind. Enclosure 4 consisted of two identical 90° arcs, one on the upstream half blocking the side where the wind resists the rotational speed and one blocking air from exiting directly opposite the inlet and forcing the wind to change direction within the enclosure. These enclosures had similar results to the first enclosure. Based on the performance of these prototype turbines with and without enclosures, it is apparent that enclosures increase the rotational velocity of the vertical axis wind turbines. The turbines with airfoil blades performed worse than the flat-plate blade turbines. The airfoil turbines did not have a linear relationship with the wind speed and in some ranges of wind speed, the rotational speed and wind speed were negatively related.

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1. Introduction

a. Vertical Axis Wind Turbines

This project studies vertical axis wind turbines (VAWT) to be mounted on the roofs of residences and public buildings. Vertical axis wind turbines have several advantages over horizontal axis turbines in the household-scale market. VAWT are commercially appealing due to the generator's close proximity to the ground. The generator at ground level allows easy access to the generator and drive train for the turbine to be serviced and repaired. Additionally, vertical-axis turbines are omnidirectional, which negates the need to compensate for gyroscopic forces induced by a turbine rotating into the wind. VAWT operate at lower tip speeds than HAWT, leading to lower sound emissions. The three most common vertical axis wind turbine types are Savonius, Darrieus, and the giromill
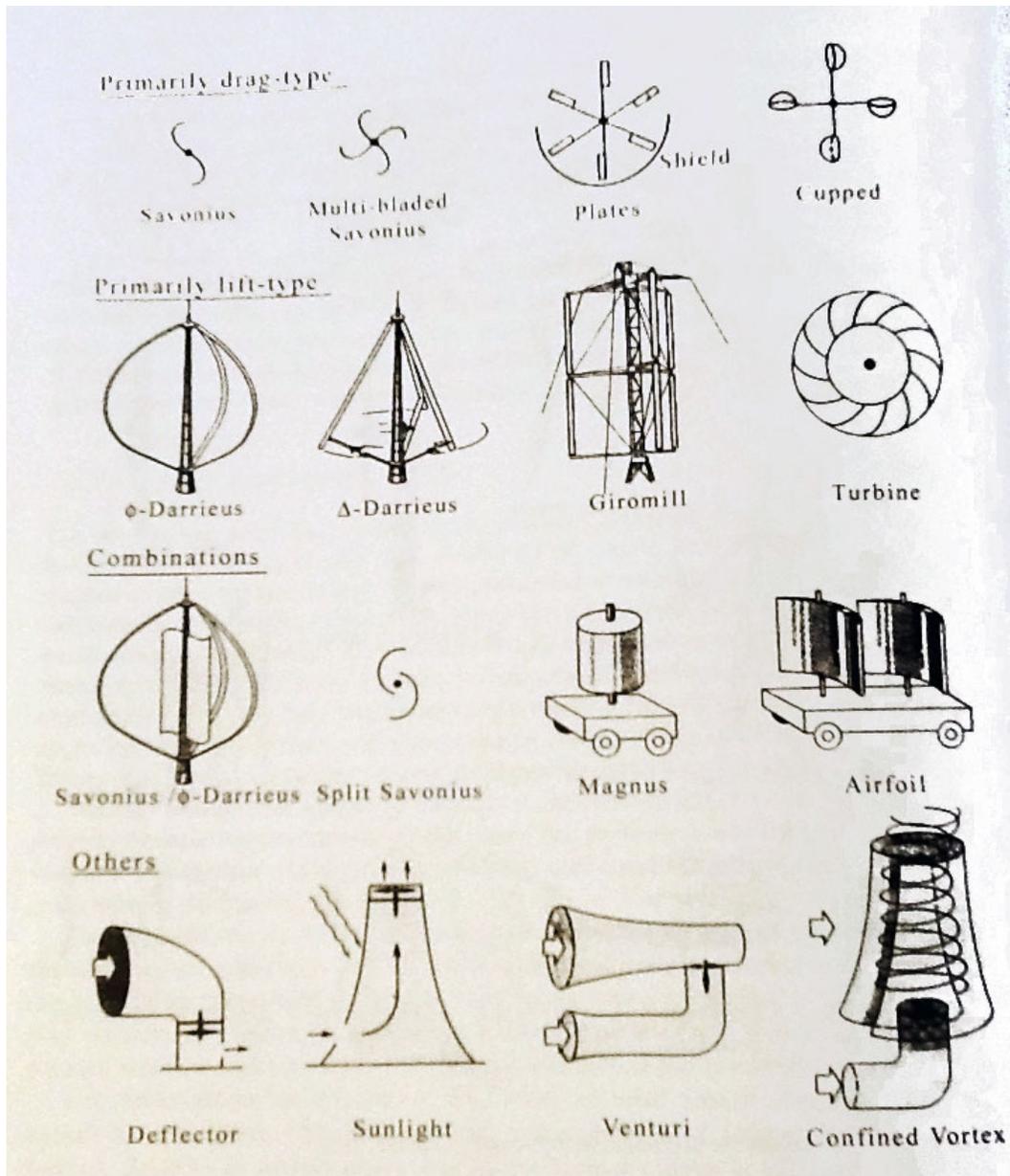
Figure 1. *This chart displays many varieties of VAWT, including the mainstream types: Savonius, Darrieus, and giromill* [1] *from Wind Energy Explained by J.F. Manwell et al.*

The Finnish inventor and engineer Georg Savonius created the Savonius model in 1924.[2] The Savonius rotor is a significant step above basic drag devices, which are only pushed by the wind. A drag device is confined to spinning below the wind speed, as drag due to the wind is the only force acting on the blades. The Savonius turbines begin to introduce a lift force via air circulation. The twin cylindrical halves overlap in the cup direction, while maintaining separation between the two halves. The air that circulates, rather than leaving the device, causes a lift force that allows the turbine's blade speed to exceed the wind speed. This rotor needs little wind to start, but its downfall is its inefficiency. Its modern

popularity is limited to those looking for an easy do-it-yourself turbine to build. One of its few commercial uses is starting a Darrieus turbine.

French engineer George Darrieus invented the Darrieus turbine in 1925. The Darrieus turbine utilizes a curved blade design that disperses the bending stresses throughout the entire blade causing tension instead of bending. Previous models involving straight blades directed all of the bending stress, generated by the centripetal force, into the points of attachment. Materials could withstand much more tension than bending stress, so the Darrieus turbine allows for lighter blades and higher speeds. Despite the advances in durability, Darrieus turbines still have a short working life and are prone to catastrophic failure. At rest, the blades bend under their own weight and, in motion the lift forces reverse every revolution. Both at rest and in motion, the Darrieus blades fatigued their attachments. The guy wires, usually necessary to secure the turbine, can also be a challenge. Advantages such as easily servicing the generator and drive train are less significant given that the guy wire attachments and bearings at the top of the turbine also require servicing. In contrast with the Savonius model, the Darrieus turbine has very little material and can maintain rotation efficiently once started. Despite its ability to maintain rotational velocity, the Darrieus turbine has difficulty starting and often needs a motor or a second turbine, such as the Savonius to start. The swept area for a Darrieus turbine is 2/3 D^2 and it has a small range of tip speed ratios around 6 with a power coefficient just over 0.3. [2]

A giromill has straight rods positioned vertically and equidistant from the axis. The giromill is actually a variation of the Darrieus rotor. The giromill has a greater swept area than a Darrieus turbine of the same height and diameter. The swept area is the height multiplied by the diameter. Furthermore, the giromill, due to its vertical straight blades, can have a variable blade pitch. The variable blade pitch or "articulating" blades allow the giromill to self-start, thus eliminating the need for a startup motor. The curved blades of a Darrieus turbine gave it the advantage of turning the bending moment into tension, allowing for lighter material to withstand higher tip speed ratios. The straight rods of the giromill eliminate those advantages, causing a bending moment in the blades and strong load at the point where the blades attach. The tip speed ratio is variable, but stresses on the points of attachment and bending moments led limited appeal and usability. [2]

Turbines utilizing the Magnus effect never gained popularity, but the concept is eccentric enough to have resulted in several studies. The Magnus effect describes the lift created by a spinning object traveling through the air. Anton Flettner, a German famous for engineering helicopters, was an enthusiastic proponent of experimenting with the Magnus effect. His two massive ventures in 1925 and 1926 included powering both a ship across the Atlantic and the rotor of a horizontal-axis turbine using the Magnus effect. Seven years later, J. Madaras attempted to drive cars around a track using the Magnus effect, but the material cost was too extensive to complete the project.[3]

b. Horizontal Axis Wind Turbines

The demand for renewable energy has resulted in the popularity of wind farms. Ease of mounting, stability, and greater efficiency make horizontal axis wind turbines the most common type used in wind farms. While spacious, flat states lead in wind power capacity, with Texas recorded at 10,085 MW and Iowa following at 3,675 MW, there are 38 states with utility-scale wind installations, including 14 states producing over 1,000 MW.[4] Adding to the appeal of wind farms is its easy integration into utility networks, as reported by two studies across the United States. Another incentive exists in the possibility for expansion into the field of offshore wind farms. While this idea has been successfully implemented in Europe, plans are being developed by Cape Wind near Nantucket Sound, Massachusetts for the first American offshore wind farm.[5] While wind energy is the lowest costing option for renewable energy, it is still twice as expensive as traditional coal sources, which can generate electricity at approximately six cents per kilowatt-hour. The efficiency of wind turbines is below 50% due to air density and wind speeds, but offshore wind may provide greater consistency and velocity, thus increasing efficiency. Improvements in efficiency are limited by Betz's Law, which dictates an inconvenient theoretical maximum power coefficient at 59.3%. The power coefficient is the ratio of total power from the rotor to the power from the wind.[1] Horizontal-axis wind turbines remain the most practical method of harnessing wind power, with current research only furthering the gap.

Cape Wind is a project by Energy Management Inc. on Nantucket Sound with the goal of implementing 130 floating, horizontal axis turbines to harvest wind energy several miles off of the coast. Cape wind predicts that its 130 turbine will generate 420 megawatts of energy, providing three quarters of the cape's energy.[5] The offshore wind that is targeted by these turbines is stronger and less turbulent which will lead to a higher and more consistent rate of energy generation. Offshore wind also deals with the frequent complaints of residents who approve of wind energy, but resist turbine installation in their own neighborhoods. The major issues cited are usually noise and safety, and neither are factors for offshore wind farms.

2. Background

a. Blade Pitch and Stall

       The blade pitch is the angle of the chord line of the blade relative to the blade position that is tangential to the rotational path of the blade. The chordline is defined as the line connecting the leading edge and the trailing edge. The pitch is considered to be positive when the leading edge is rotated outward, away from the axis of rotation and the trailing edge is rotated inward, toward the axis of rotation. Blade pitch, β, is illustrated in Figure 2 from Coton, et al.[6]
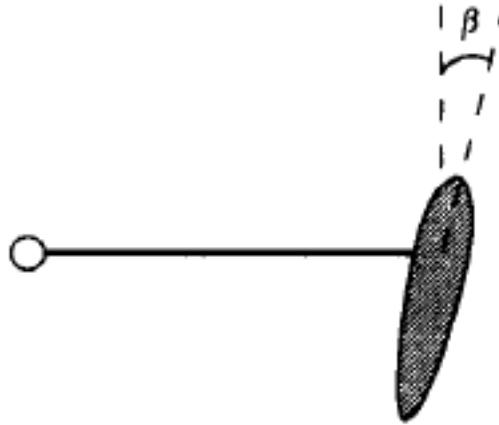
Figure 2. *Blade pitch, β, is defined as the angle between the chordline of the airfoil and the line tangent to the path of rotation. Blade pitch is positive as the leading edge is rotated outwards.* [6]

       Pressure and shear stress on an airfoil result in a force on blade, which can be separated into two perpendicular forces referred to as lift and drag. Lift is the force defined as being perpendicular to the freestream velocity, or wind. Drag is the force defined as being parallel to the freestream velocity.[7] The direction of the effective freestream changes continuously along the path of rotation of the airfoil blade, as shown in Figure 3. At the points referred to as 0° and 180° in Figure 3, the effective freestream velocity is parallel to the freestream velocity and the lift is radially inward while the drag is tangent to the path of rotation and in the opposite direction of the freestream velocity. At other points on the path of rotation, 90° and 270° are shown, the effective freestream velocity is the vector sum of the freestream velocity local to the point and the rotational velocity of the turbine, ω or Ω.
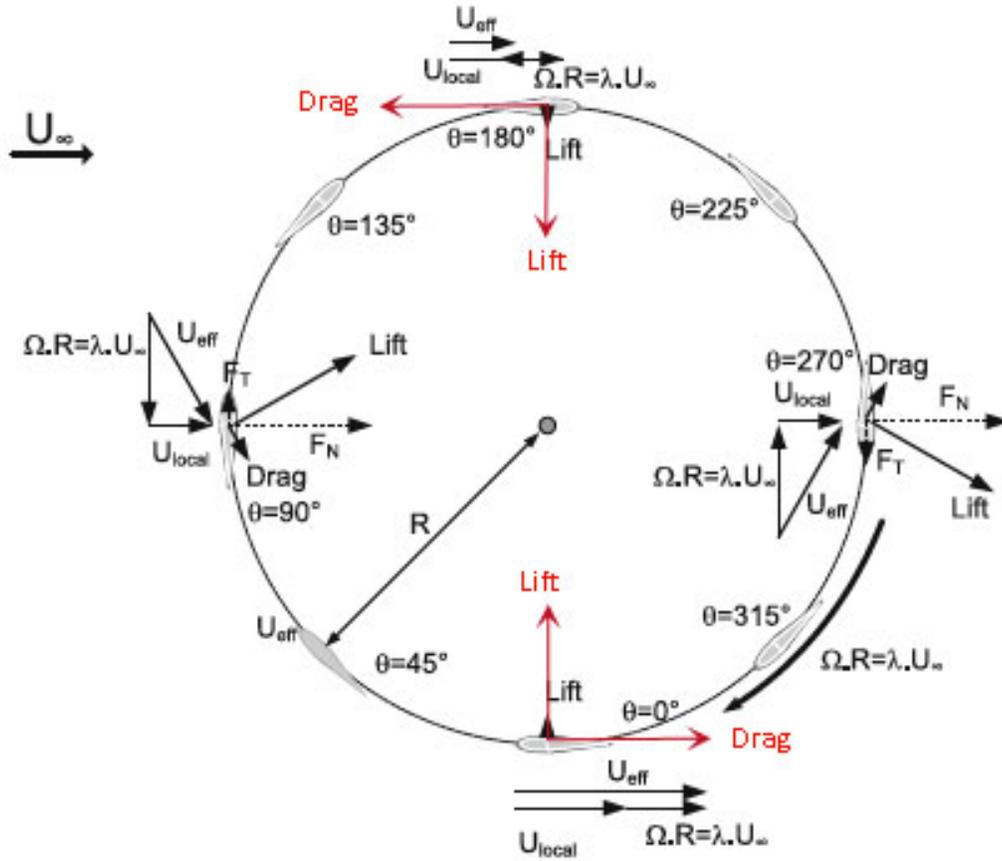
Figure 3. *Lift and drag forces on airfoil blades at four points during the rotation of a VAWT from Ferreira, et al.[8] The red annotations emphasize the directions of lift and drag forces at 0° and 180°, but the lengths of the arrows do not indicate relative magnitude.*

Torque on the shaft, which is the axis about which the blades rotate, is defined as the cross product of the vector from the shaft to the blade and the force on the blade, as shown in equation (5). The force on the blade is the sum of the lift and drag forces. The ultimate goal is the generation of power, $\dot{W}$, which is the product of torque and the angular velocity as shown in equation (6). Through the torque and power equations, it is evident that an increase in the lift force leads to an increase in the power generated by the turbine.

$$\tau = \vec{r} \; x \; \vec{F}$$

(5)

$$\dot{W} = \tau * \omega$$

(6)

Changes in applied pitch are apparent in the timing of the loading patterns. On the upstream pass, there is a single local maxima as the blade is in stall, while the

loading pattern in the downstream pass is characterized by two local maxima. Increases in blade pitch delay stall to a greater azimuth angle, thereby increasing the blade torque. Decreasing the blade pitch causes stall to occur earlier, diminishing the applied blade torque while increasing the magnitude of the bending moment on the cross-arm as shown in Figure 4.[6] (Coton *et al.* 1996)

Figure 4. *The effect of blade pitch on the timing of stall as it occurs in rotation and its effect on the bending moment applied from Coton et al.*[6]

b. Power Output

The hypothetical maximum power, $\dot{W}$ *that* can be obtained by a wind turbine is a function of the air density ρ, the swept area A, and the velocity V of the turbine. The hypothetical maximum power[2] can be calculated using equation (7).

$$\dot{W} = \rho A \frac{V_1^3}{2}$$

(7)

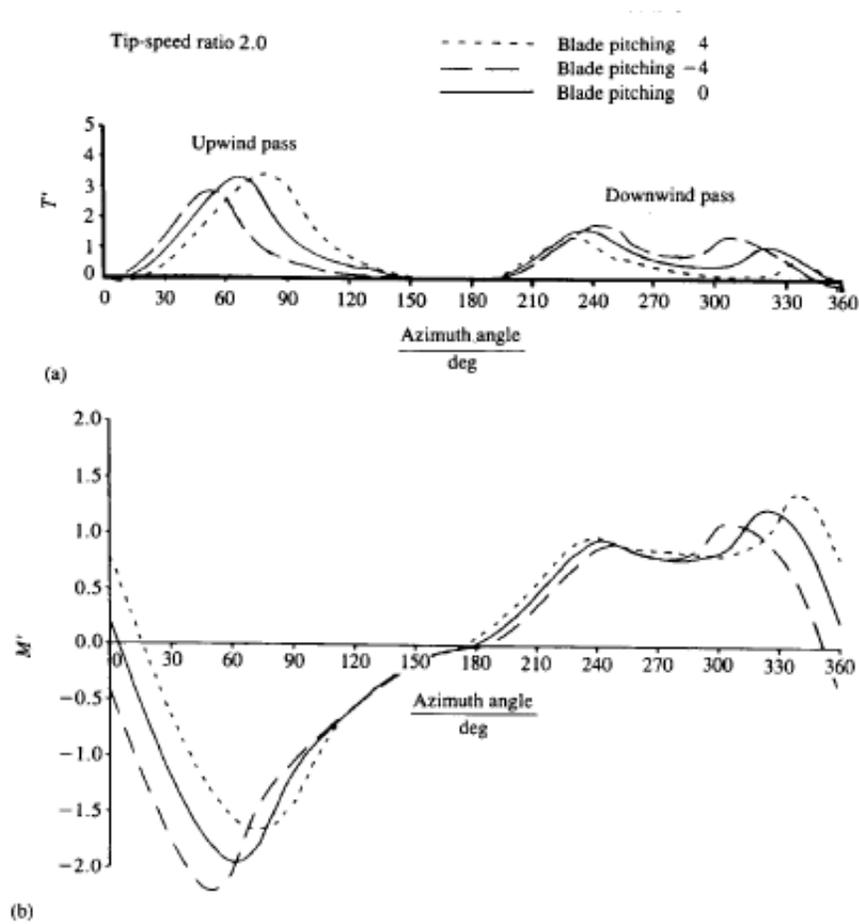Density remains effectively constant for standard tower heights where the fluid is air. Swept area is given by the turbine design. The size and shape of the turbine determine the swept area and once the turbine is created, this value becomes constant. The velocity is determined by the wind speed. The velocity value is cubed, meaning that the productivity can vary significantly with changes in the wind speed. The significance placed on the wind speed means that the same turbine will have substantially different output values depending on the location of the turbine. The geographical roughness is one factor, but tower height is the factor that can be manipulated most easily.

Choosing the height of the tower that a turbine will be mounted on is a balance between wind speed and air density. Air density decreases at higher altitudes while wind speed increases. The air density is approximately 1.225 kilograms per cubic meter at sea level but decreases based on the air pressure and temperature, as well as humidity. Household-scale turbines are less likely to be mounted high enough to be affected by the decreasing air density. Air can be approximated as a combination of ideal gases, and the ideal gas law is manipulated to give an equation for density[2] as in equation (8).

$$\rho = \frac{p}{R \cdot T}$$

(8)

The Greek character ρ is the symbol for air density in kilograms per cubic meter while p is the air pressure in Paschal at the altitude in question. The variable R is the specific gas constant for dry air in Joules/kilogram*Kelvin and the variable T is the temperature given in Kelvin. While changes in air density do affect the power output, but changes in air density are not significant enough to discourage high towers. A 100m tower would only decrease the air density by approximately one percent while the increase in wind speed would be far more substantial.
Wind speed predictions for a potential location are important for evaluating the potential yield. Wind speeds vary significantly by altitude in addition to geographic location and past data is rarely available for the exact location and height of a potential site. When data is unavailable for a particular height, it can be predicted using the wind profile power law or using the log wind profile equation. The wind profile power law, equation (9) relates wind speed, *V* in meters per second, to the altitude, *z* in meters, using the exponent, α. The subscript *ref* denotes that the value is from the reference location. The exponent is based on the stability of the

atmosphere and must be derived empirically for any given location, or, for neutral stability, α has a value of 1/7. If one turbine is at twice the height of an identical turbine, the higher VAWT will experience wind speeds 10.4% greater than the lower VAWT.[2] The 10.4% increase in wind speed leads to a 34.6% increase in the power output due to the cubed velocity term in the power equation, equation (7).

$$V_z = V_{z_{ref}} \left(\frac{z}{z_{ref}} \right)^{\alpha}$$

$$(9)$$

The Rayleigh distribution is the specific form of the Weibull distribution that has the shape factor of 2. Both the Weibull model and the Rayleigh model, by inclusion, are continuous probability distribution curves. The distribution of wind speeds for any given location is often accurately described by a Rayleigh distribution curve. An average wind speed is not enough to predict the wind power that would be available in a particular area as power is a function of velocity cubed. When the average wind speed is the only information known, the power available can be estimated by extrapolating a Rayleigh distribution with the same average for the wind speed.[2]

d. Betz Limit and Efficiency

A German scientist, Albert Betz, mathematically found a theoretical maximum for the percentage of wind energy that can be captured by a wind turbine, or coefficient of power. Equation (10) is a calculation for the coefficient of power. This maximum, known as the Betz Limit, is 16/27 or 59.3% of the wind energy. According to Betz's calculations, the optimal efficiency occurs when the turbine reduces the downstream wind speed to 2/3 of the upstream wind speed. Where the wind velocity upstream of the turbine is V1 and the velocity downstream is V2, the Betz Limit is derived from equation[9] (11). (Angle *et al.*, 2010)

$$C_P = \frac{\left(1 + \frac{V_2}{V_1}\right)\left[1 - \left(\frac{V_2}{V_1}\right)^2\right]}{2}$$

$$(10)$$

$$P = \frac{1}{2}\rho A \left(\frac{V_1 + V_2}{2} \right) (V_1^2 - V_2^2)$$

$$(11)$$

The extractable power available from a particular wind, relative to the overall power available in the wind, can be calculated by substituting the free

stream velocity, V_∞ into Equation (11). The resulting equation is Equation (12)[9].
(Angle *et al.*, 2010)

$$P_{max} = \frac{16}{27}\left(\frac{1}{2}\right)\rho A V_\infty^3$$

(12)

The coefficient of performance, Equation (10) represents the ratio of the power produced from a free stream flow to the maximal power available. While the Betz Limit predicts near 59% efficiency, this limit does not take into account factors such as aerodynamic drag, losses at the blade tip, and losses from the wake, which spins opposite the direction of the rotor. Realistically, the C_P values recorded for turbines are in the 30-50% range. This is only 51-85% of the Betz Limit. Another calculation for power defines efficiency relative to the Betz Limit, as the Betz Limit is the theoretical limit. In this calculation, Equation (13), the power produced is a function of the air density and velocity and the capture area of the turbine and efficiency relative to the Betz Limit as defined above.[9] (Angle *et al.*, 2010)

$$P_\eta = \eta\frac{16}{27}\left(\frac{1}{2}\right)\rho S V_\infty^3$$

(13)

3. Project Objectives

a. Turbine Configurations

- Determine the number and angle of thin, flat-plate blades that increase VAWT performance the most.

    The initial challenge was designing a basic vertical axis turbine that could be created and tested with relative ease. One of the goals for testing was to determine an ideal blade angle and number for the turbine. The constraints for the design were that the blade angle and number must be simple to adjust and the results must reflect the differences in blade configuration. VAWTs were designed with 2, 3, 4, 5, 6, 7, and 8 blades at an angle of 45 degrees and, additionally, 4-bladed turbines were designed with blade angles of 30°, 37.5°, 45°, 52.5°, and 60°. The design work was done in the CAD program Solidworks for all eleven configurations of the prototype. All elements of the design were held constant except for the number and angle of the blades that were purposefully varied for test. Throughout the design process, adjustments were made to the chord length of the blade and the blade positions to allow all of the blade configurations to fit on bases with a constant chord length for all prototypes.
    The prototypes were constructed of several flat pieces of acrylic bonded together, so a laser cutter was the most efficient method of manufacturing the turbines. The prototypes were built of 3/8" thick acrylic and connected using a chemical to melt and bind the pieces together. The enclosures and bases were made of translucent acrylic to allow the blades to be visible. The blades were made from opaque, blue-colored acrylic to be visible while rotating.
    One objective of testing done in this project was to determine whether a particular blade quantity or blade angle would be significantly preferable to the others with respect to efficiency. A secondary goal in this project was to determine if any particular blade quantity or angle produced results that were not consistent with the other configurations. Turbines giving atypical or inconsistent results in the wind tunnel without a enclosure or airfoil would not be expected to give typical and consistent results when tested with different enclosures or airfoils.

b. Enclosures

- Determine whether any enclosures increase performance.
- Determine which configuration of enclosure, including a lack of enclosure, increases VAWT performance the most.

    Testing done on turbines without enclosures will be compared to the tests done with different configurations of enclosures. The enclosure that provides the greatest increase in efficiency compared to testing done without enclosures would

be considered the most effective enclosure of those that were tested. The enclosures vary in specific characteristics such as the portion of the turbine that is enclosed while keeping other variables constant, such as the material that the enclosure is made of, the circumference and curvature of the enclosures, and the thickness of the enclosures. With these variables held constant, it will be possible to attribute the increases in efficiency to the specific characteristics that were purposefully varied. Finding the variables that increase efficiency will make it possible to recommend an optimal enclosure design, which will take advantage of those characteristics which positively effect performance while excluding element that may prove to hinder the performance of the turbine.

c. Airfoil Testing

- Determine whether S1223 shape airfoil blades increase the performance of a flat-plate VAWT.

The majority of testing in this study is to be done using flat plate blades in the turbines in order to simplify evaluations of the results despite the expectation that performance will improve with the use of airfoils. Two turbines will be tested with S1223 shape airfoil blades and be compared with flat plate turbines with the same number of blades. The initial airfoil-blade turbines, built with the S1223 airfoil blades, serve as a foundation for further testing and will be referred to in comparisons with turbines that will be tested in the future. For continuity and accurate comparison to prior and subsequent turbines, the turbine with the S1223 airfoil blades undergoes the same testing protocols as the flat plate turbines.

The S1223 airfoil turbine is mounted on the anemometer shaft without any enclosure initially, and then it is tested with each enclosure in turn. The mounted turbine is then connected to the data acquisition device via the connection at the bottom of the shaft. The turbine, with any enclosure it might have, is inserted into the wind tunnel through the 6-inch porthole located at the bottom of the clear section of the recirculating wind tunnel in Higgins Laboratory. The wind speed in the tunnel is raised by increments of 0.5 Hz at a time from 0 to 17.0 Hz, which converts to about 35 mph. The turbine is not raised an additional increment until it reaches its maximum rotational velocity at that wind speed. The maximum rotational velocity for a particular wind speed is determined to have been reached when the data acquisition device indicates that the turbine has completed an equal number of revolutions in a five second interval as in the previous five second interval. The wind tunnel is shut off and the turbine is allowed to come to a stop after the turbine reaches its maximum rotational velocity with winds at 35 mph.

From the testing of two turbines with S1223 airfoil blades it can be determined whether the turbines behaved as predicted or whether unexpected factors caused the turbines to give different results than predicted. These unexpected factors would then be taken into account for the recommendation of further airfoil testing. Different blade shapes or quantities could be recommended

based on the results. Comparison of the results of the S1223 airfoil turbine with the flat plate turbines will create a benchmark for airfoil efficiency increases. Each subsequent airfoil-based turbine will seek to improve upon the efficiency of the S1223 turbine. There are many different airfoil shapes designed for use at low Reynolds number conditions. Performance improvements based on overall shape characteristics such as camber and thickness can be adjusted to effect the efficiency and blade characteristics such as twist, taper, and pitch can be analyzed to effect the lift forces on the turbine at all points in the rotation.

4. Design and Manufacturing Methods

a. Flat-plate turbines

      The goal of the initial set of vertical axis turbines (VAWTs) with flat plate blades was to empirically determine which blade configuration would perform best and compare VAWTs with enclosures to those without enclosures. It was decided that the wind turbines would be tested in the Higgins closed circuit wind tunnel, shown in Figure 5, and the testing area of the tunnel would be most easily accessible by a circular porthole with a six-inch diameter. It was intended that there would be an enclosure surrounding the turbine as shown in Figure 6, therefore the turbine design with a 5.25-inch diameter accounts for an eighth-inch enclosure, and an eighth-inch clearance between both the turbine and enclosure, and the enclosure and porthole. The interior diameter for the top and bottom bases of each turbine is 3 inches with four supporting spokes connecting to an inner ring that slides over the shaft of the anemometer. An additional keyed ring with the same dimensions as the shaft ring was adhered to the bottom of the turbine to keep the turbine stationary relative to the anemometer shaft. A separate ring is slid down the shaft to the top of the turbine and secured in place by a setscrew to keep the turbine from sliding up the shaft during rotation and displacing the key at the bottom.
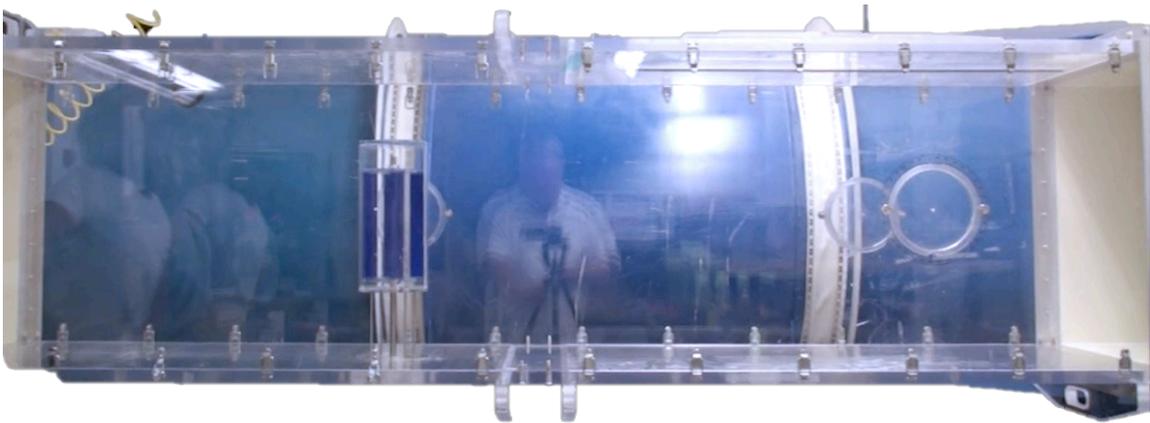

Figure 5. *Higgins closed circuit wind tunnel with the four-bladed flat plate turbine with an angle of attack of 45° in enclosure E1.*

Figure 6. *A detailed view of the four-bladed flat plate turbine with an angle of attack of 45° in enclosure E1. The inlet of the clear acrylic enclosure is demonstrated.*

The blades were designed as flat plates, nine inches in length and with a 1.5-inch chord length. The same blades were used in each variation of the flat plate turbines for consistent comparison. The chord length allowed the blades to fit securely on the turbine bases without protruding outside of the diameter of the base or blocking the airflow through the turbine as shown in Figure 6. Turbines were designed with seven variations of blade number: 2, 3, 4, 5, 6, 7, and 8 blades. All of the blade number variations had the blades at a 45-degree angle from the radial line. Additional turbines were also designed with blade angle variations. Each of the blade angle variations had four blades and the angles tested were 30°, 37.5°, 45°, 52.5°, and 60° from the radial line. All naming conventions are listed in the appendix with pictures, and the naming conventions without pictures are listed below. The Solidworks drawing for the turbine with 4 flat-plate blades, all at a 45° angle, is pictured in Figure 7.

A3	The vertical axis turbine with three S1223 airfoil blades.
A5	The vertical axis turbine with five S1223 airfoil blades.

|	
B2	The vertical axis turbine with 2 thin, flat-plate blades at a 45° angle. The only turbine with two blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.
B3	The vertical axis turbine with 3 thin, flat-plate blades at a 45° angle. The only turbine with three thin, flat-plate blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.
B4	The vertical axis turbine with 4 thin, flat-plate blades at a 45° angle. When only the blade number is specified, the turbine with blades at a 45° angle is indicated.
B4-30°	The vertical axis turbine with 4 thin, flat-plate blades at a 30° angle.
B4-37.5°	The vertical axis turbine with 4 thin, flat-plate blades at a 37.5° angle.
B4-52.5°	The vertical axis turbine with 4 thin, flat-plate blades at a 52.5° angle.
B4-60°	The vertical axis turbine with 4 thin, flat-plate blades at a 60° angle.
B5	The vertical axis turbine with 5 thin, flat-plate blades at a 45° angle. The only turbine with five thin, flat-plate blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.
B6	The vertical axis turbine with 6 thin, flat-plate blades at a 45° angle. The only turbine with six blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.
B7	The vertical axis turbine with 7 thin, flat-plate blades at a 45° angle. The only turbine with seven blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.
B8	The vertical axis turbine with 8 thin, flat-plate blades at a 45° angle. The only turbine with two blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.
E0	E0 or Enclosure 0 refers to the testing condition when no enclosure is being used.
E1	E1 or Enclosure 1 refers to the enclosure with an outlet approximately 210° after the inlet, thereby redirecting the wind vector within the enclosure.
E2	E2 or Enclosure 2 had the outlet directly across from the inlet.
E3	E3 or Enclosure 3 was a simple 90° arc blocking wind on the half of rotation that resists the wind.
E4	E4 or Enclosure 4 consisted of two identical 90° arcs, one on the upstream half blocking the side where the wind resists the rotational speed and one blocking air from exiting directly opposite the inlet and forcing the wind to change direction within the enclosure.
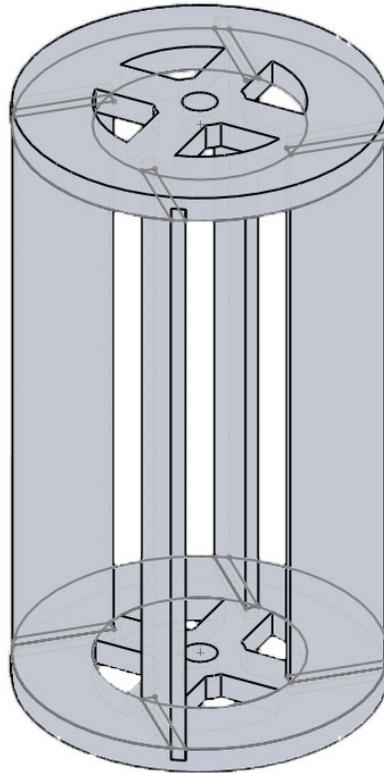
Figure 7. *The Solidworks assembly for a VAWT with four flat-plate blades at a 45° angle of attack.*

b. Enclosures

Several different types of enclosures were designed and tested. The enclosures were cut from acrylic cylinders of an eighth-inch thickness. The internal diameter of the acrylic tubing was 5.5 inches and the external diameter was 5.75 inches. The enclosure inlets and outlets were cut axially using a band saw to avoid deforming the cylinder in the radial direction. The pieces were the adhered to bases with the solvent methylene chloride. The enclosures are designated by numbers from 1-4 with Enclosure 0 being the condition without an enclosure.

c. Airfoils

To create a more efficient turbine, airfoils were created and tested as blades. Drag-type turbines have the limitation that their rotational velocity can never be higher than the wind speed. Lift-type turbines, such as those that use airfoils, can rotate with a higher rotational velocity than the wind velocity. Past research determined that symmetric airfoils are ideal for VAWTs due to half of the rotational path, the negative half, being resisted by the wind. In this project, turbines were to be tested with enclosures that would block or severely limit the amount of wind on the negative half of the rotation, eliminating the need for a symmetric airfoil. The S1223 airfoil had been categorized as a low speed, high lift design with a high lift coefficient. Selig and Guglielmo, the designers of the S1223 airfoil shape give the

maximum lift coefficient, $C_{l, max}$=2.2 and empirical results for the coefficient of drag, C_d, in Figure 8.[10] The frequency with which the S1223 appeared in other research papers gave a guideline for the comparison of experimental values. Based on the performance of the VAWT with S1223 airfoil blades and a comparison to experimental data collected with S1223 airfoils, it is possible to extrapolate and make predictions about the performance of other airfoils. The shape of the S1223 airfoil was provided in the form of eighty-one coordinate points from the University of Illinois airfoil database,[11] which were adjusted for a 1.5-inch chord length and entered into Solidworks to create a model as in Figure 10. The profile was extruded to create a blade nine inches in length. Three blades were printed in ABS plastic on a 3D printer. The same profile shape was used on the turbine base template to create a base for the airfoils as in Figure 9. The base was constructed from acrylic using a Universal Laser Systems laser cutter to cut a disk with the airfoil shapes cut out and a solid disk, which was adhered to the cut disk using the solvent methylene chloride. The complete base then had the airfoil shapes cut halfway through the total thickness of the base. The thickness of each piece of acrylic was 3/16 inches, making the total thickness of the base 3/8 inches.
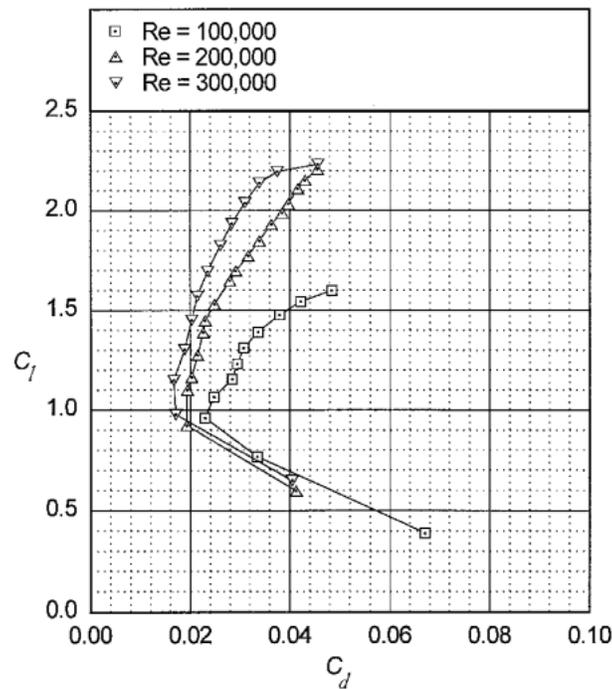
S1223 Airfoil Coefficient of Drag

Figure 8. *The coefficient of drag, C_d, is graphed with respective lift coefficient values, C_l at three different Reynolds numbers.*[10]
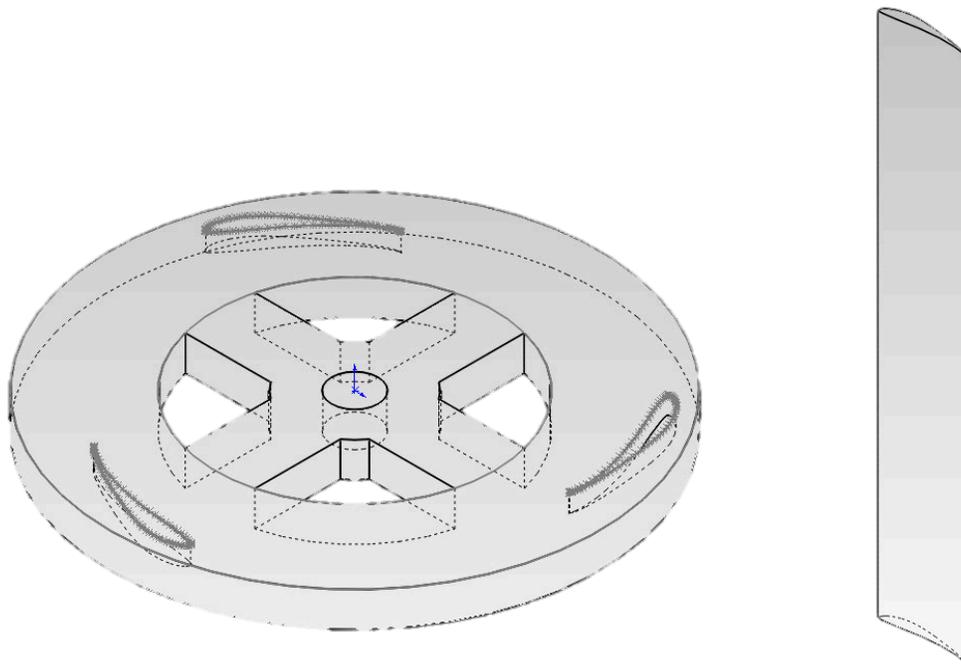

Figure 9. *(left) The base of a turbine designed to fit three airfoils of the S1223 shape.*
Figure 10. *(right) An airfoil, nine inches in length, with a 1.5-inch chord length and the S1223 shape.*

5. Testing

Each flat plate turbine was tested in the Higgins closed circuit wind tunnel pictured in Figure 5 without any enclosure and then with enclosures. This wind tunnel has a 10 foot long test section with a 2 foot by 2 foot cross-section and a maximum wind speed of 55 meters per second. The turbines and enclosures were mounted on an anemometer using the keyed ring and the top ring with a setscrew as shown in Figure 6, which was built into a porthole cover. The rotational speed (RPM) of the turbines was collected every five seconds during testing via a data acquisition device. Turbines were tested in wind speeds up to at least 34.9 mph. The testing procedure started the turbines without any wind and increased by increments of approximately two mph, allowing the rotational velocity of the turbine to stabilize at each increment before the wind speed was increased. This procedure was repeated for each turbine without an enclosure, and then with Enclosure 1, also shown in Figure 6.

Prototype testing at wind speeds up to 34.9 mph is based on the wind speed in the wind tunnel for testing models. Enclosed VAWT that would be mounted outdoors and used for power generation would be significantly larger. Actual dimensions for an enclosed VAWT that would be used outdoors have not been determined, making it impossible to determine what outdoor wind speed corresponds to the tested wind speed. Relating wind speeds over a scaled model to the wind speeds over the actual product requires that the Reynolds number for the flow over the two structures be equal. The Reynolds number, calculated in equation (14), is a non-dimensional number that is the ratio of inertial resistance to viscous resistance for a fluid in motion.[12]

$$Re = \frac{\rho V L}{\mu}$$

(14)

During the first iteration of testing, it was found that significant vibrations occurred at particular wind speeds.   The vibrations decreased the turbines rotational velocity and strained the shaft that the turbine was mounted on. When an enclosure was being used, the turbines would vibrate on the shaft with enough force to be in contact with the enclosure, despite the allotted eighth-inch clearance on either side. An additional support was needed to retain stability throughout testing and, as a consequence, a sleeve was fitted over the top of the shaft and the sleeve freely rotated about a spring-loaded point that fit into a small niche in the top of the wind tunnel. The sleeve effectively eliminated the detrimental vibrations and allowed the turbine to spin with minimal friction influence. The testing without an enclosure and with Enclosure 1 was repeated with the stabilizing plastic sleeve.

Testing of Enclosure 2, Enclosure 3, and Enclosure 4, as well as an additional set of testing without any enclosures were performed by another set of students.

These rounds of testing were conducted from the 20 Hz setting on the wind tunnel downward in increments of 1 Hz, which corresponds to a wind speed of 40.1 mph, decreasing by 2 mph every 30 seconds. These tests were all done with a different stabilizer, which could be secured to the top of the wind tunnel test section on one side and had a freely rotating point, which could be inset into the top of the turbine shaft on the other side. This stabilizer was found to be the most effective in eliminating vibration as can be seen visually during testing and in the increasing linearity of the test result data points.

6. Results

a. Blade Number

Vertical axis turbines were tested with different quantities of thin, flat-plate blades. Turbines were made with 2, 3, 4, 5, 6, 7, and 8 blades with a blade angle of 45°. The performance of the turbines in the controlled wind tunnel testing can be measured by the slopes of VAWT rotational speed, ω, in rpm plotted against the wind speed in the tunnel. The slope of a linear fit for each turbine with each enclosure is given in Figure 11.

Blade Number Slope Comparison

	E0 Slope	E1 Slope	E2 Slope	E3 Slope	E4 Slope
B2	3.138	23.78	46.88	2.566	38.59
B3	2.404	53.98	48.40	44.92	47.17
B4	17.69	51.37	48.40	48.01	44.23
B5	34.29	51.30	48.33	52.72	43.99
B6	35.31	47.29	49.40	51.07	50.65
B7	38.83	51.45	48.62	46.27	
B8	39.00	52.40	49.33	50.35	44.04

Figure 11. *The blade number comparison table compares the slopes of a linear fit line for data of each turbine with each enclosure. The slope ω/V_∞ is the ratio of turbine RPM to wind speed and has units of RPM/MPH.*

The slope that is the ratio of ω, the turbine rotational speed, and V_∞, the wind speed in the wind tunnel is recorded in Figure 9, but it is more readily apparent in the plots in Figures 12, 13, 14, 15, and 16. When tested with enclosures, most of the turbines performed similarly, as shown in Figures 13, 14, 15,and 16, but the performance of the turbines was more varied without an enclosure. In Figure 12, the slopes of the turbines with 2 and 3 blades increase ω at less than one-tenth the rate that the turbines with 5, 6, 7, and 8 blades do. The turbine with 4 blades increases ω at half the rate or less that the turbines with 5, 6, 7, and 8 blades increase ω.
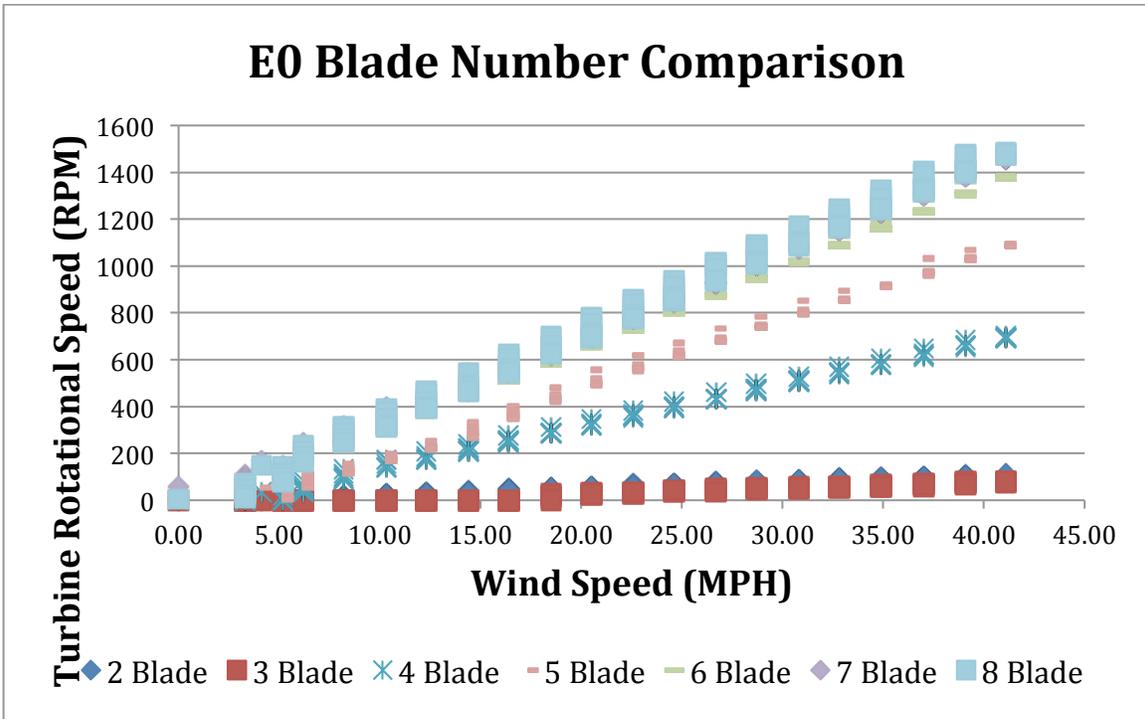
E0 Blade Number Comparison

Figure 12. *The performance of turbines with blade quantities of 2, 3, 4, 5, 6, 7, and 8 in a wind tunnel with no enclosure.*
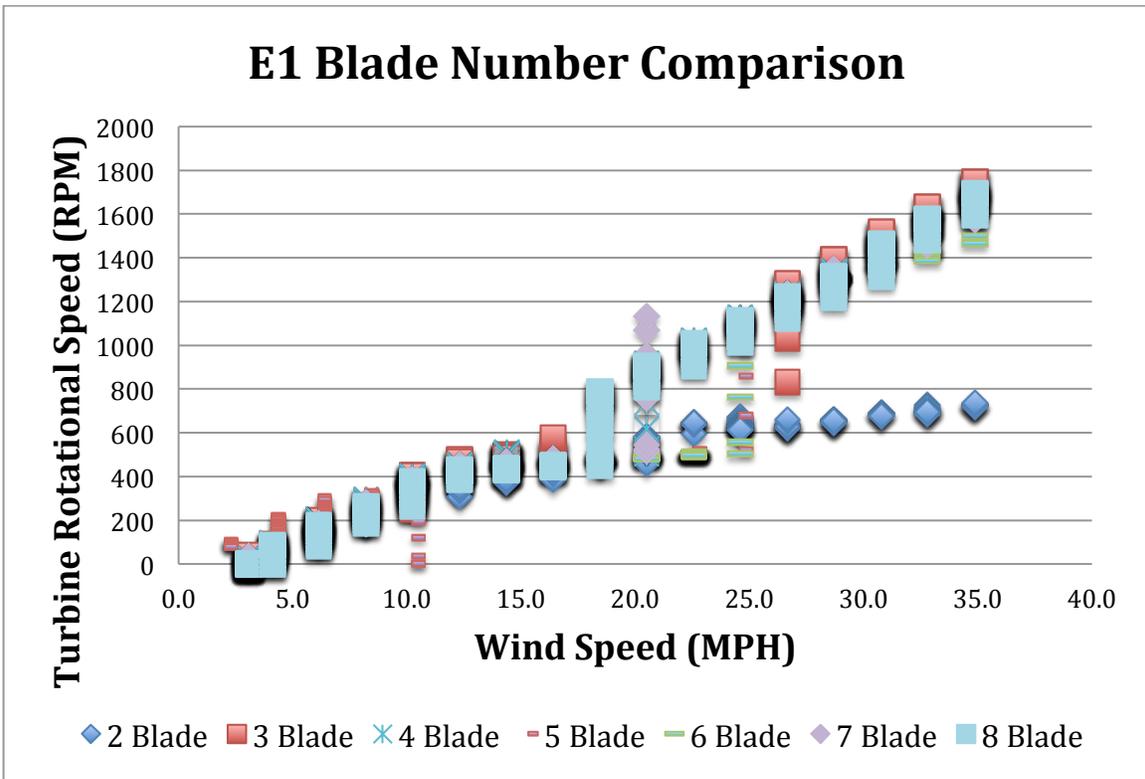
E1 Blade Number Comparison

Figure 13. *The performance of turbines with blade quantities of 2, 3, 4, 5, 6, 7, and 8 in a wind tunnel with Enclosure 1.*

Figure 14. *The performance of turbines with blade quantities of 2, 3, 4, 5, 6, 7, and 8 in a wind tunnel with Enclosure 2.*
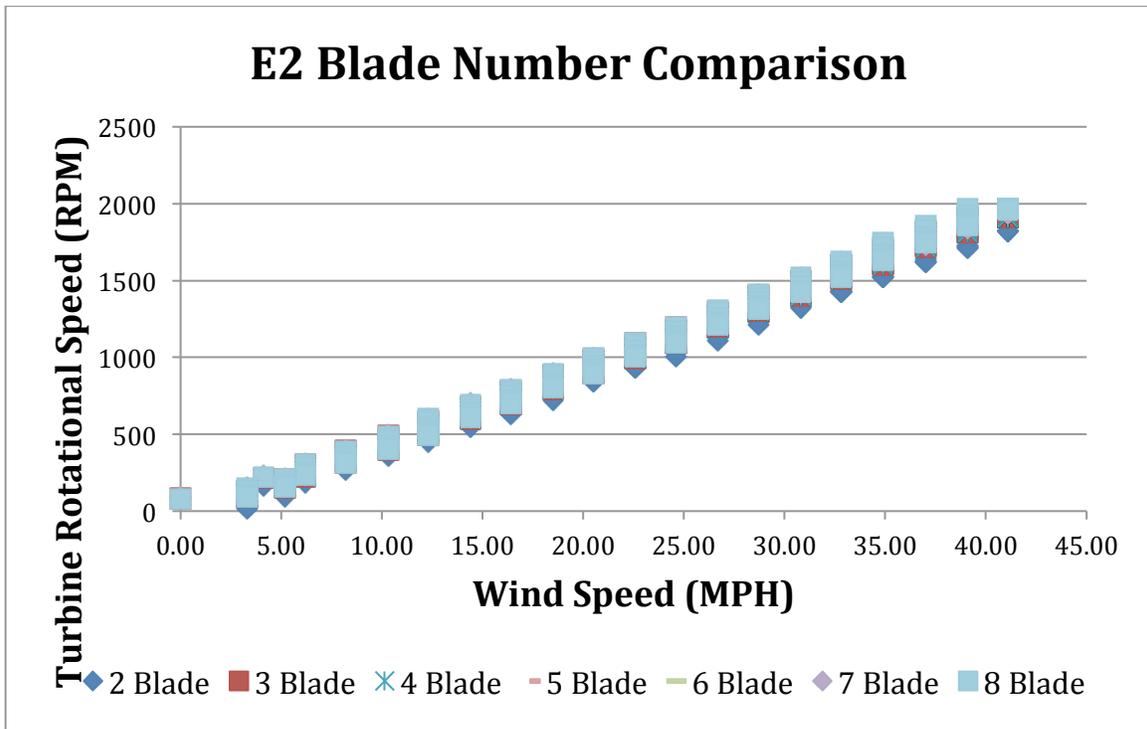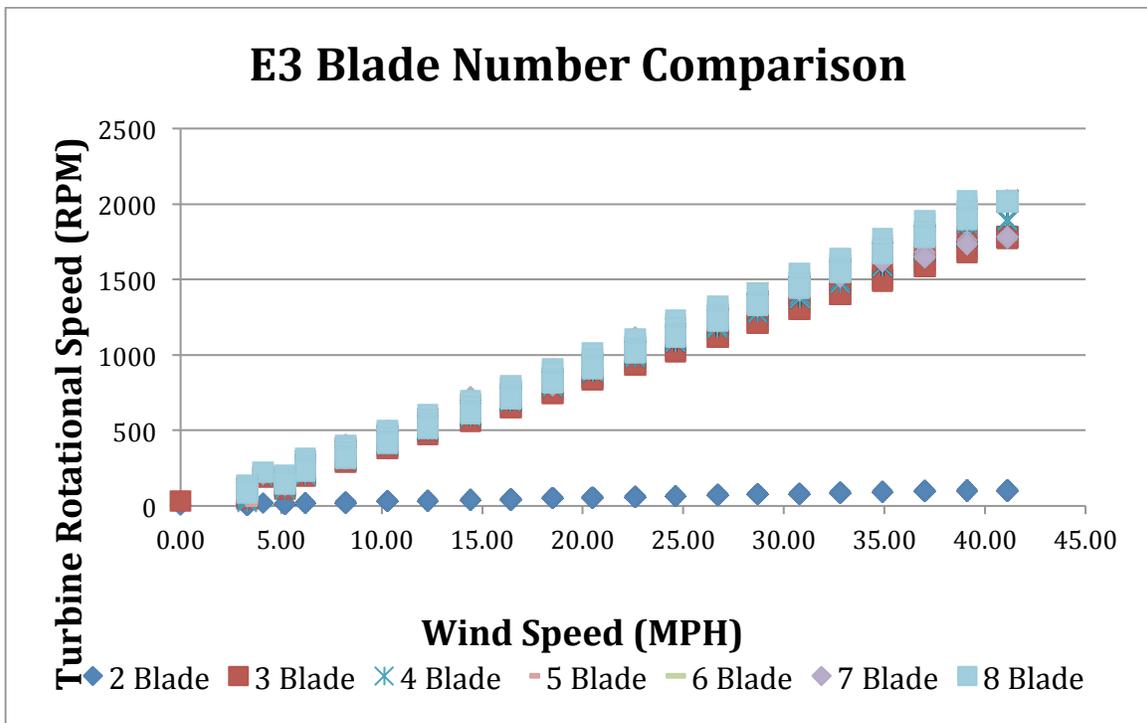

Figure 15. *The performance of turbines with blade quantities of 2, 3, 4, 5, 6, 7, and 8 in a wind tunnel with Enclosure 3.*
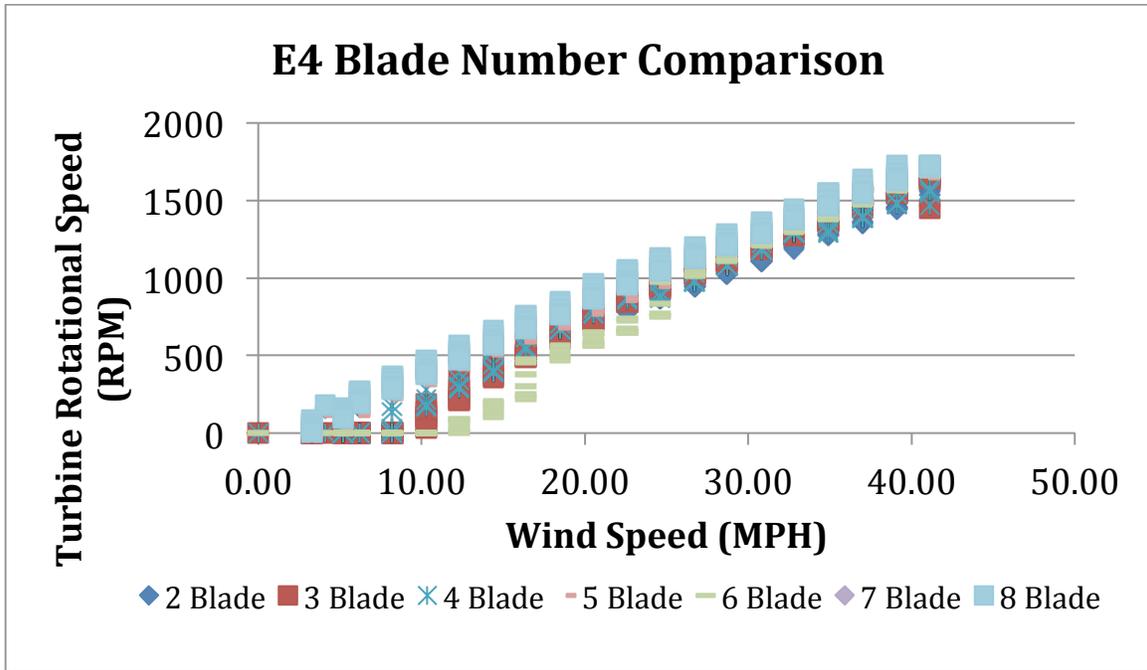
Figure 16. *The performance of turbines with blade quantities of 2, 3, 4, 5, 6, 7, and 8 in a wind tunnel with Enclosure 4.*

The turbine with 2 blades performs lower than average without an enclosure and with all four enclosures, as shown by the red boxes in Figure 17. It performed below quartile 1 in every enclosure and fits the statistical definition of an outlier in the case of Enclosure 1 and Enclosure 3. All of the turbines with 5 blades or less performed below average in at least two of the testing conditions while the turbines with 6 and 8 blades only performed below the average in one enclosure apiece. The turbine with 7 blades did not perform below average in any enclosures, but was not tested with Enclosure 4.

Performance by Blade Number with Respect to Average Performance

	E0 Slope	E1 Slope	E2 Slope	E3 Slope	E4 Slope
Average	24.380	47.368	48.480	42.272	44.778
B2 minus Ave	-21.242	-23.588	-1.600	-39.706	-6.188
B3 minus Ave	-21.976	6.612	-0.080	2.648	2.392
B4 minus Ave	-6.690	4.002	-0.080	5.738	-0.548
B5 minus Ave	9.910	3.936	-0.151	10.446	-0.789
B6 minus Ave	10.930	-0.078	0.920	8.798	5.872
B7 minus Ave	14.450	4.082	0.140	3.998	Not tested
B8 minus Ave	14.620	5.032	0.850	8.078	-0.738

Figure 17. *The performance of each turbine in each enclosure with respect to the average performance in that enclosure. The top row shows the averages to which the turbine performances are compared. The red boxes indicate a below average performance, while the green boxes indicate an above average performance.*

b. Blade Angle

Drag-type turbines with four thin flat plate blades were tested at five blade angles to determine the configuration with the optimal performance. The blade angles tested were 30°, 37.5°, 45°, 52.5°, and 60°. A measure of performance was the slope of the linear fit line comparing the rotational speed of the turbine, ω, in rpm and the wind speed in the wind tunnel in miles per hour. The slope of the linear fit to each test was displayed in Figure 18.

Blade Angle Slope Comparison

	E0 Slope	E1 Slope	E2 Slope	E3 Slope	E4 Slope
B4-30	2.299	39.74	50.15	42.62	42.79
B4-37.5	22.21	54.90	49.79	46.63	49.45
B4-45	17.69	51.37	48.40	48.01	44.23
B4-52.5	19.66	53.30	47.74	49.79	42.77
B4-60	7.980	53.40	47.48	49.68	42.88

Figure 18. *The blade angle comparison table compares the slopes of a linear fit line for data of each turbine with each enclosure. The slope ω/V_∞ is the ratio of turbine RPM to wind speed and has units of RPM/MPH.*

The slope comparison shows that the turbines performed similarly when enclosed. The only instance of a turbine performing significantly better or worse than turbines in the same enclosure with a different angle occurred with the test of the turbine with a blade angle of 30° in enclosure 1. The average slope for enclosure 1 was 50.54 when the slope of the turbine with a 30° blade angle was included and the average was 53.24 when the outlier was neglected. The turbine with a blade angle of 30° falls 13.5 rpm/mph short of the weighted average while the second furthest is the turbine with a blade angle of 45° which falls 1.87 rpm/mph below the weighted average.

The turbines with different angles performed similarly when tested with enclosures, but their slopes were significantly varied when tested without an enclosure. The similitude and variation are apparent when the turbines are graphed by enclosure.
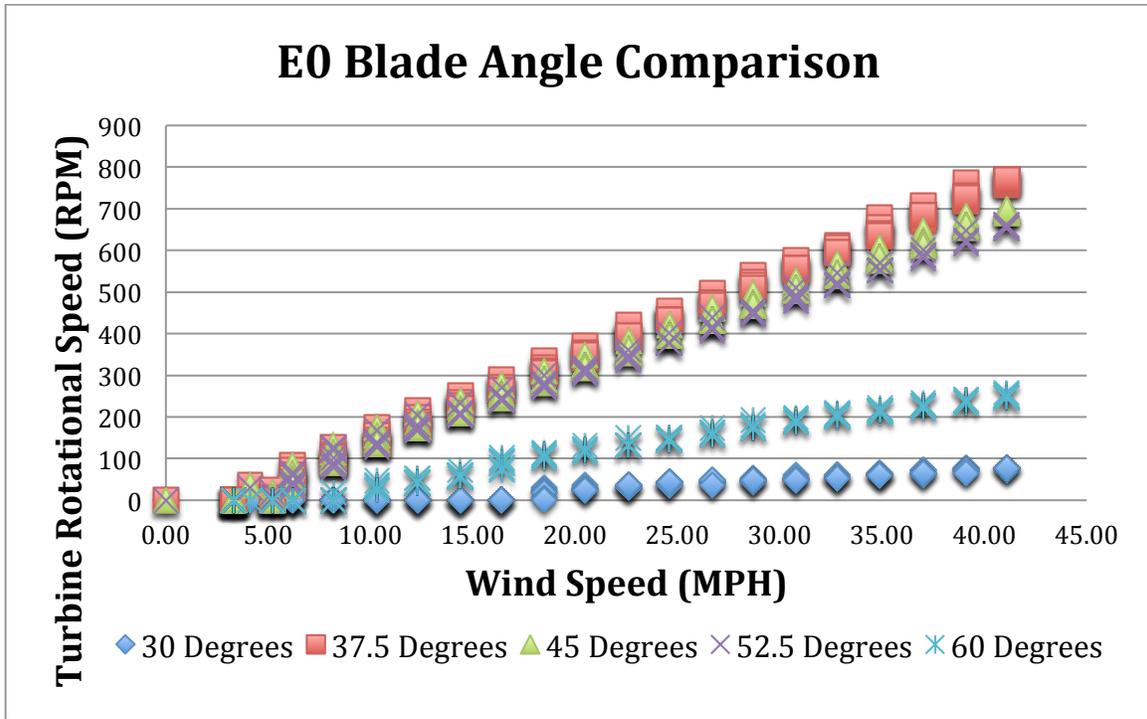
Figure 19. *The performance of turbines with blade angles of 30°, 37.5°, 45°, 52.5°, and 60° in a wind tunnel without an enclosure.*
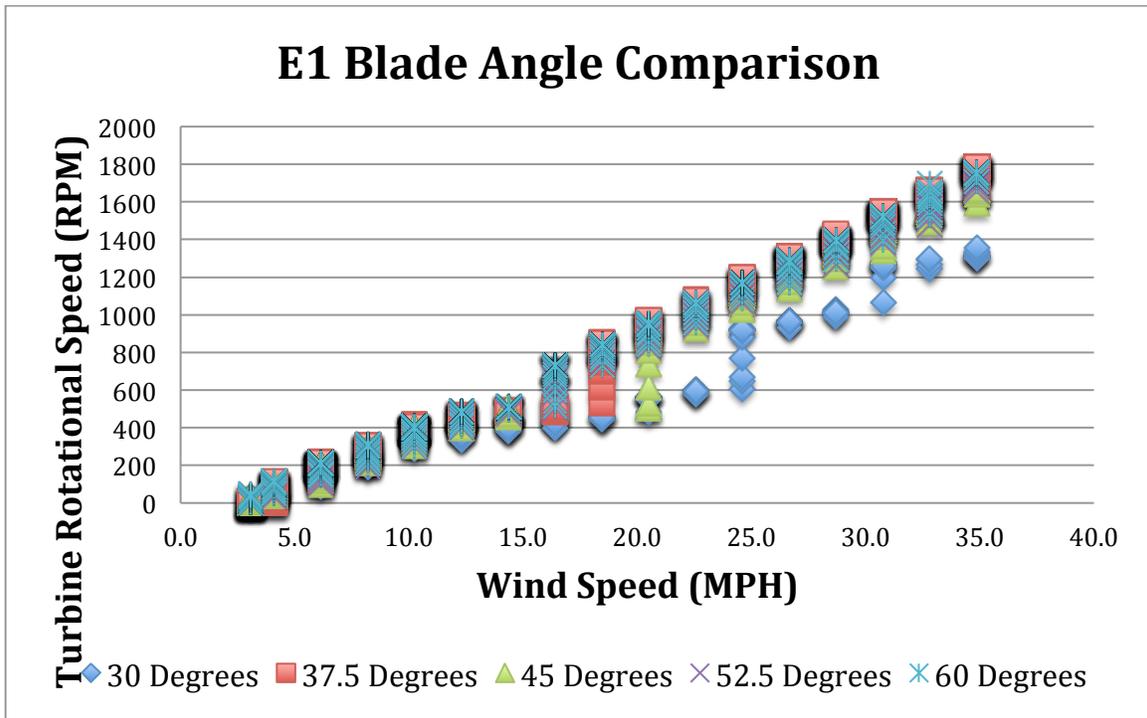

Figure 20. *The performance of turbines with blade angles of 30°, 37.5°, 45°, 52.5°, and 60° in a wind tunnel with Enclosure 1.*
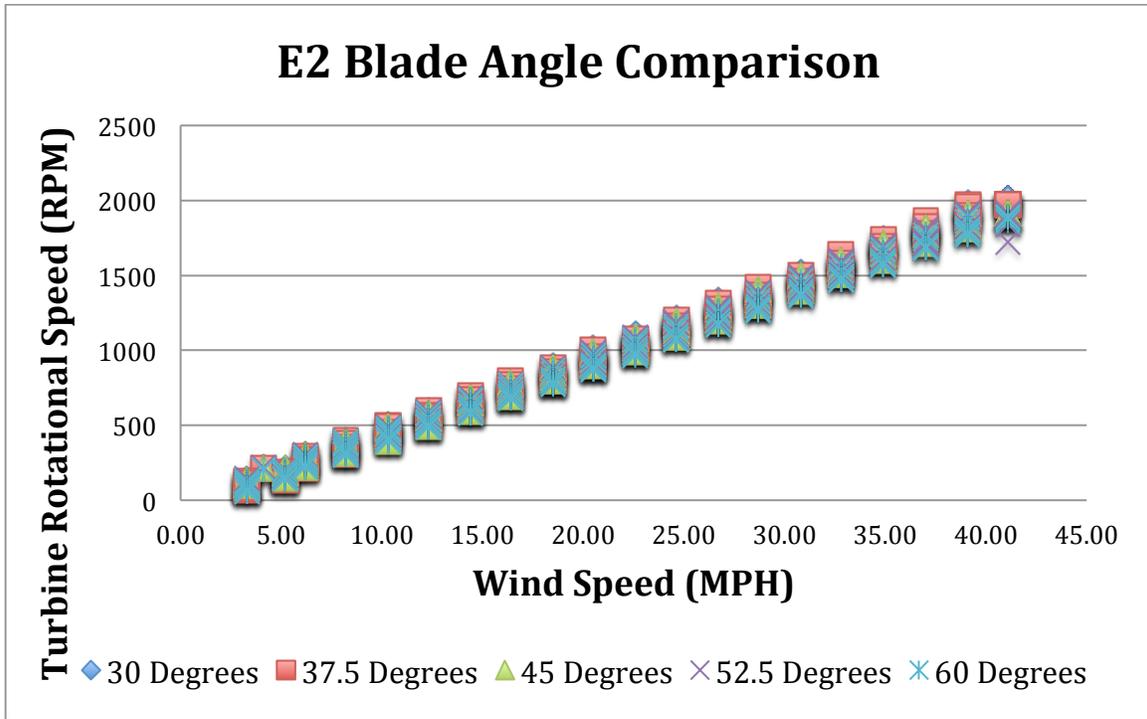
Figure 21. *The performance of turbines with blade angles of 30°, 37.5°, 45°, 52.5°, and 60° in a wind tunnel with Enclosure 2.*
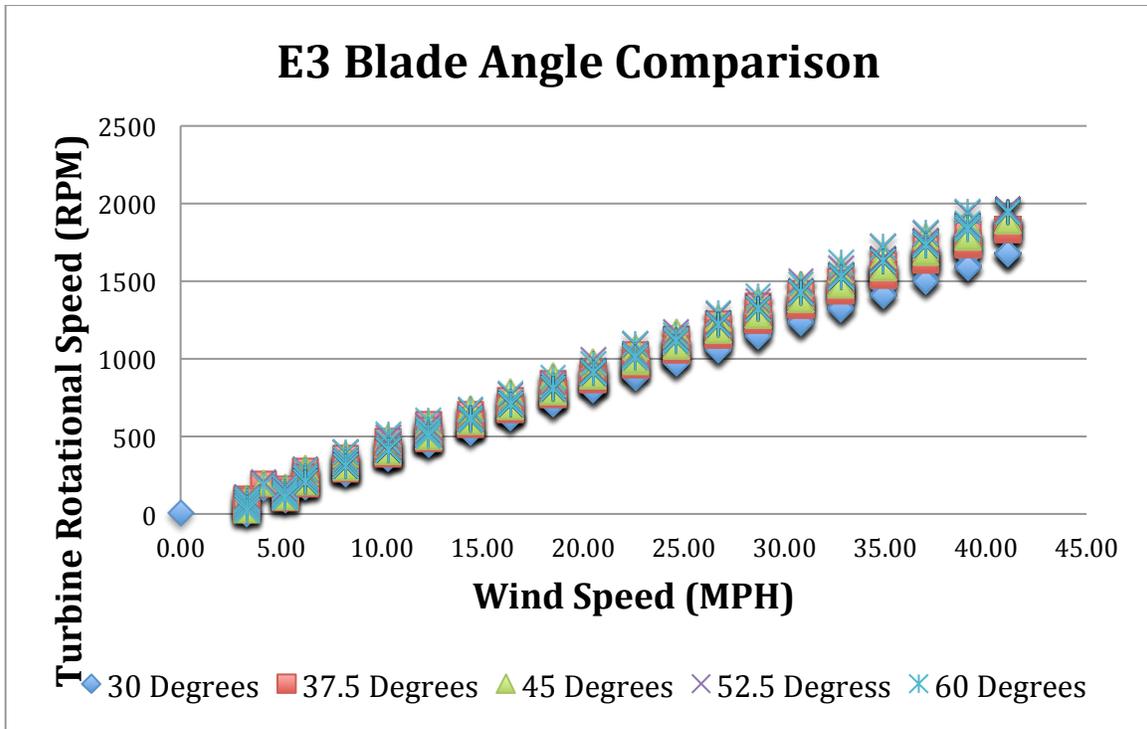

Figure 22. *The performance of turbines with blade angles of 30°, 37.5°, 45°, 52.5°, and 60° in a wind tunnel with Enclosure 3.*
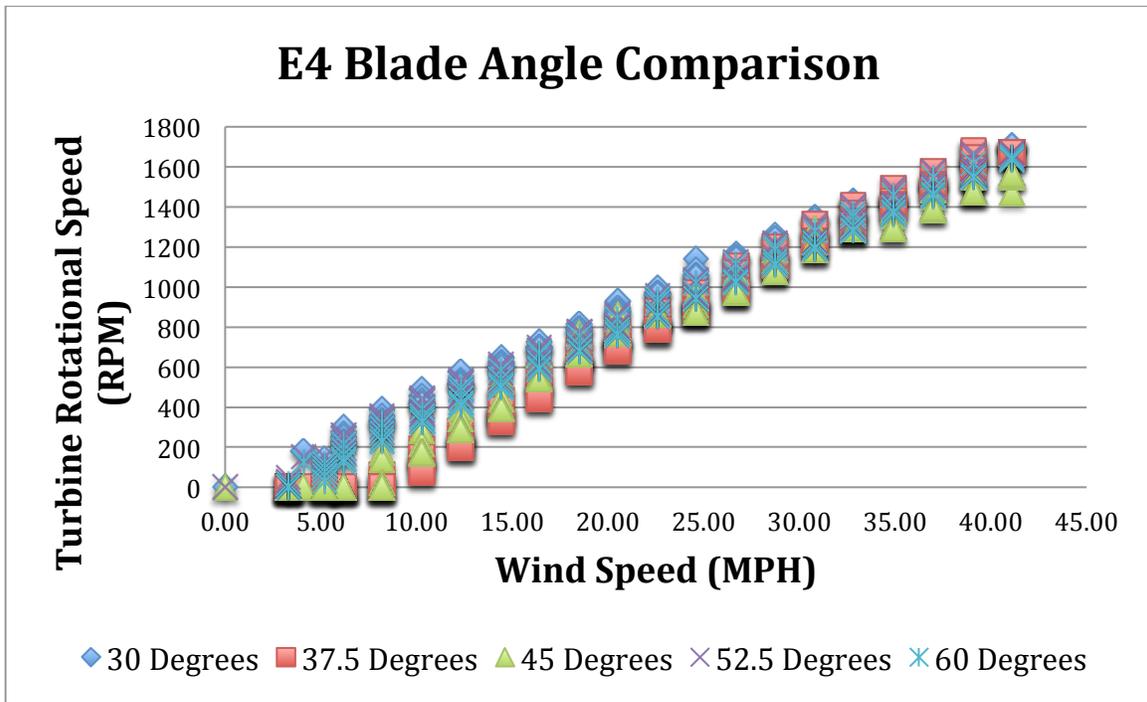
Figure 23. *The performance of turbines with blade angles of 30°, 37.5°, 45°, 52.5°, and 60° in a wind tunnel with Enclosure 4.*

Figures 20, 21, 22, and 23 show the turbines with different blade angles producing similar rates of rotational velocity with respect to wind speed. Performances are similar, but the turbine with a 37.5° blade angle performed above the average for four of the five enclosures and the turbine with a 30° blade angle performed below the average for four of the five enclosures. The average slopes for each enclosure and the performance of each turbine are indicated in Figure 24 with below average performances indicated in red and above average performances indicated in green.

Performance by Blade Angle with Respect to Average Performance

	E0 Slope	E1 Slope	E2 Slope	E3 Slope	E4 Slope
Average	13.9678	50.542	48.712	47.346	44.424
B4-30 minus Ave	-11.6688	-10.802	1.438	-4.726	-1.634
B4-37.5 minus Ave	8.2422	4.358	1.078	-0.716	5.026
B4-45 minus Ave	3.7222	0.828	-0.312	0.664	-0.194
B4-52.5 minus Ave	5.6922	2.758	-0.972	2.444	-1.654
B4-60 minus Ave	-5.988	2.858	-1.232	2.334	-1.544

Figure 24. *The performance of each turbine in each enclosure with respect to the average performance of all of the turbines in that enclosure. The top row shows the averages to which the turbine performances are compared. The red boxes indicate a below average performance, while the green boxes indicate an above average performance.*

c. Enclosures

Each turbine was tested without an enclosure and with four different enclosures. The performance of each enclosure relative to the other enclosures and the performances of the turbines without any enclosure were assessed through plotting the performances of each turbine without any enclosure and with each of the four enclosures. These results are plotted in Figures 25-35.
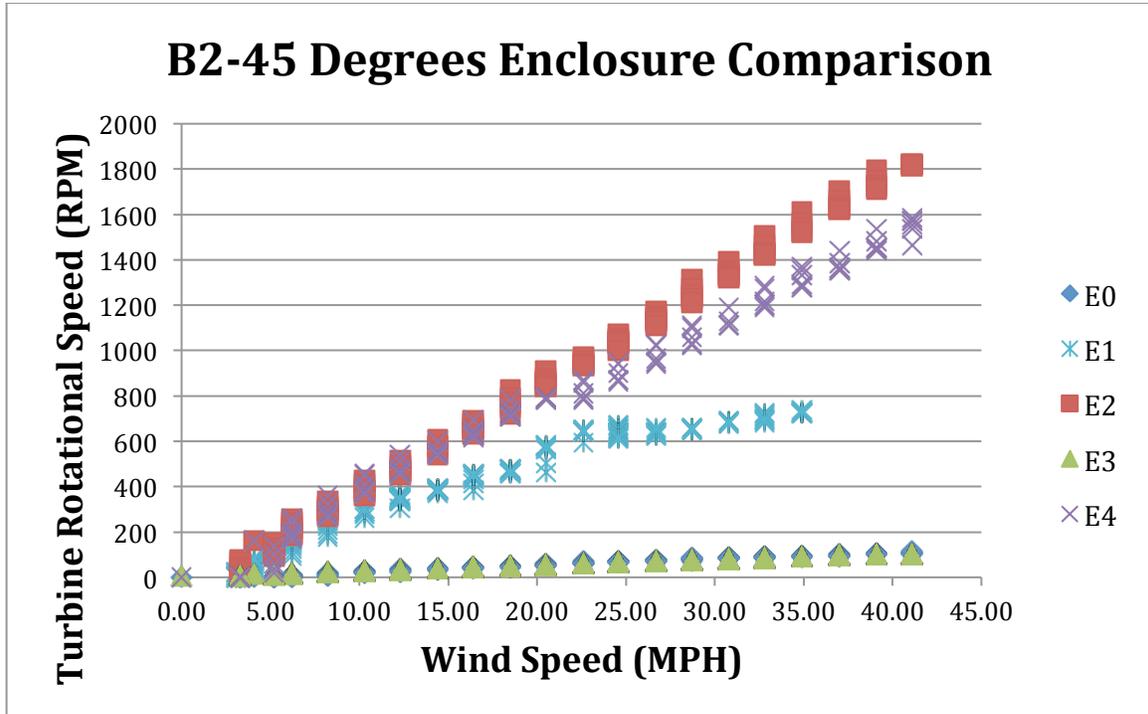

Figure 25. *The turbine with two blades at 45° (B2-45) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*
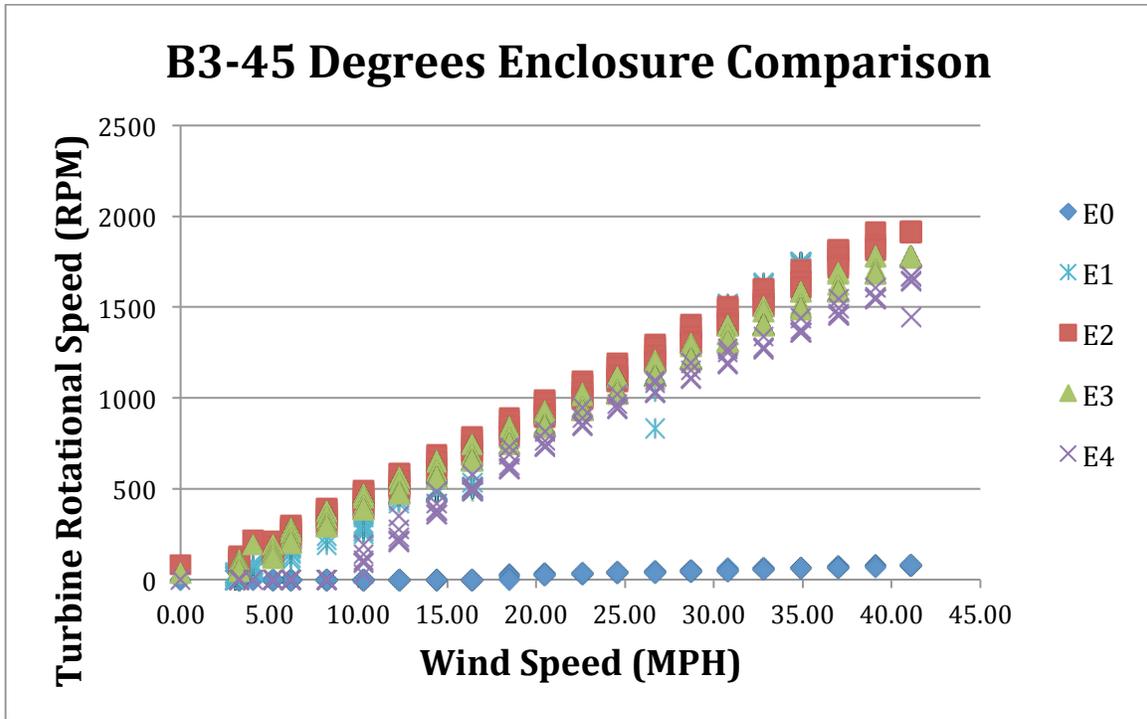
Figure 26. *The turbine with three blades at 45° (B3-45) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*
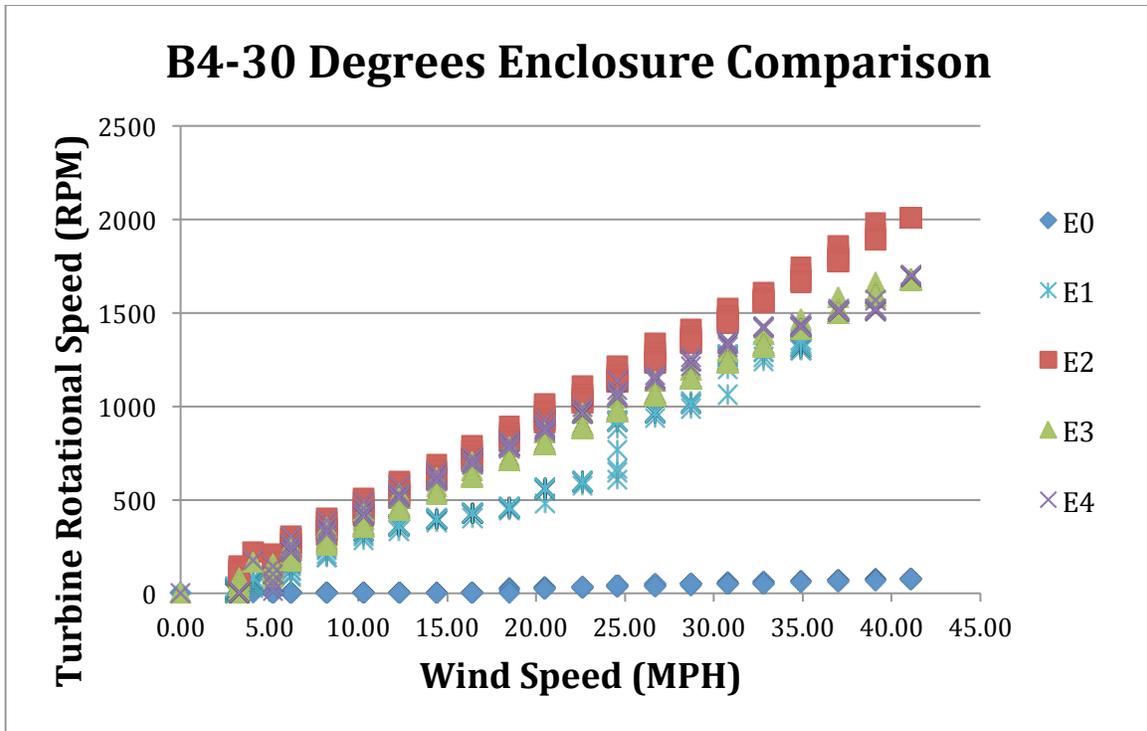

Figure 27. *The turbine with four blades at 30° (B4-30) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*
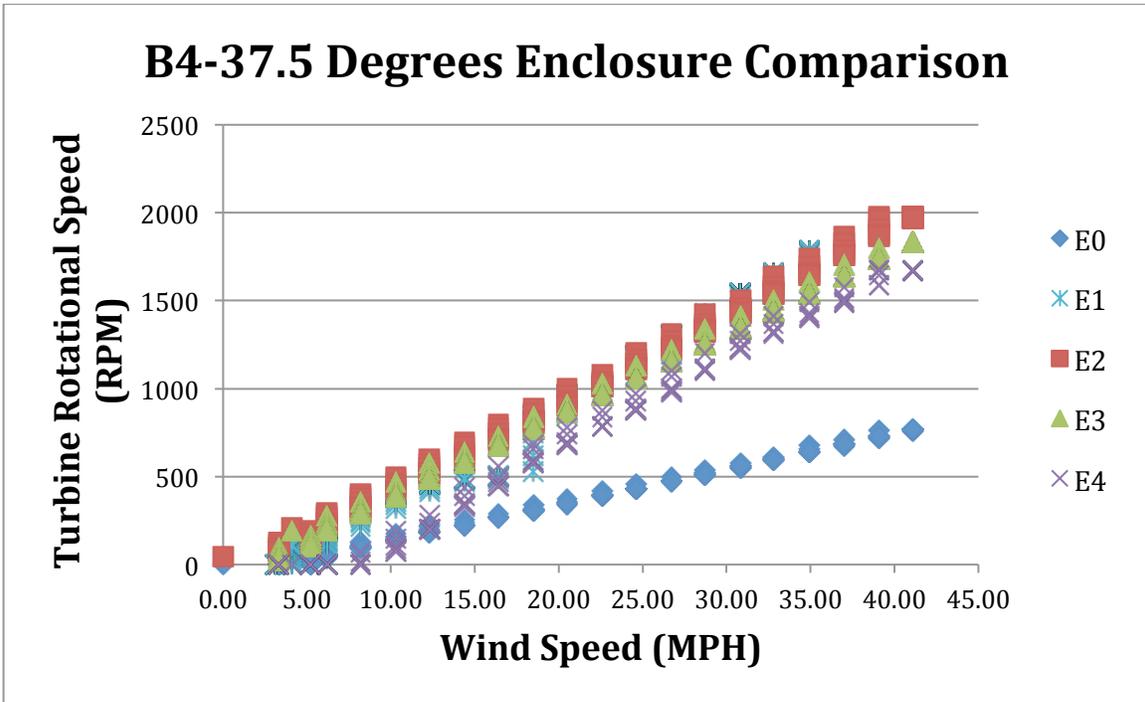
Figure 28. *The turbine with four blades at 37.5° (B4-37.5) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*
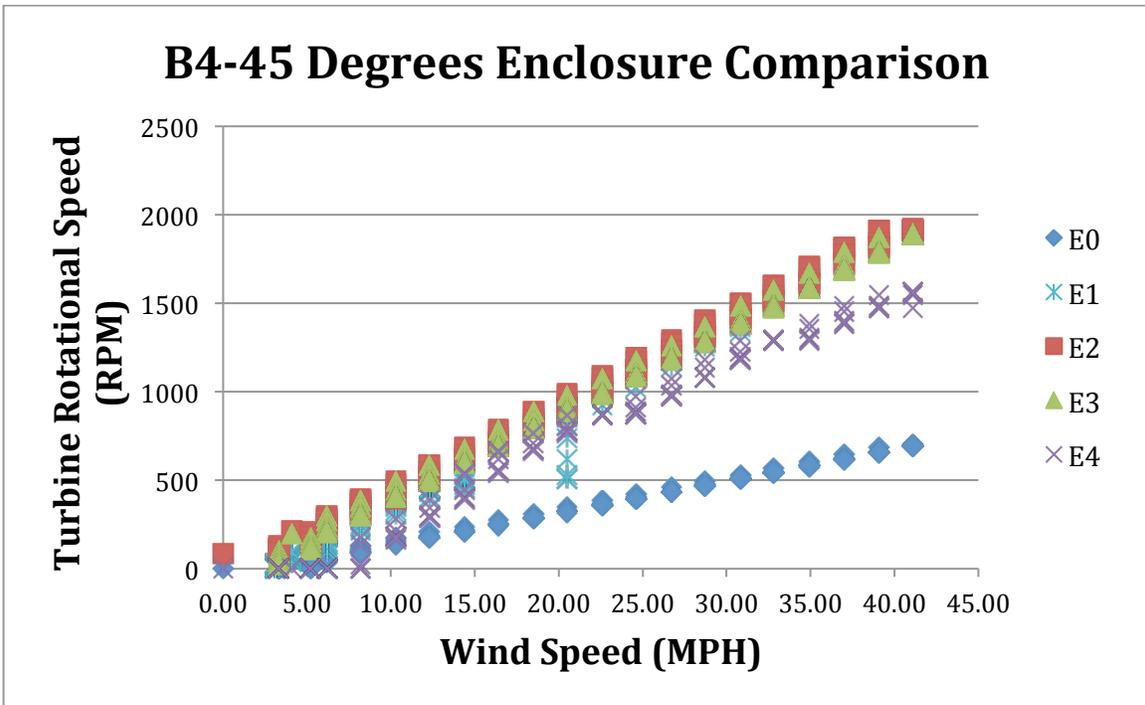

Figure 29. *The turbine with four blades at 45° (B4-45) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*
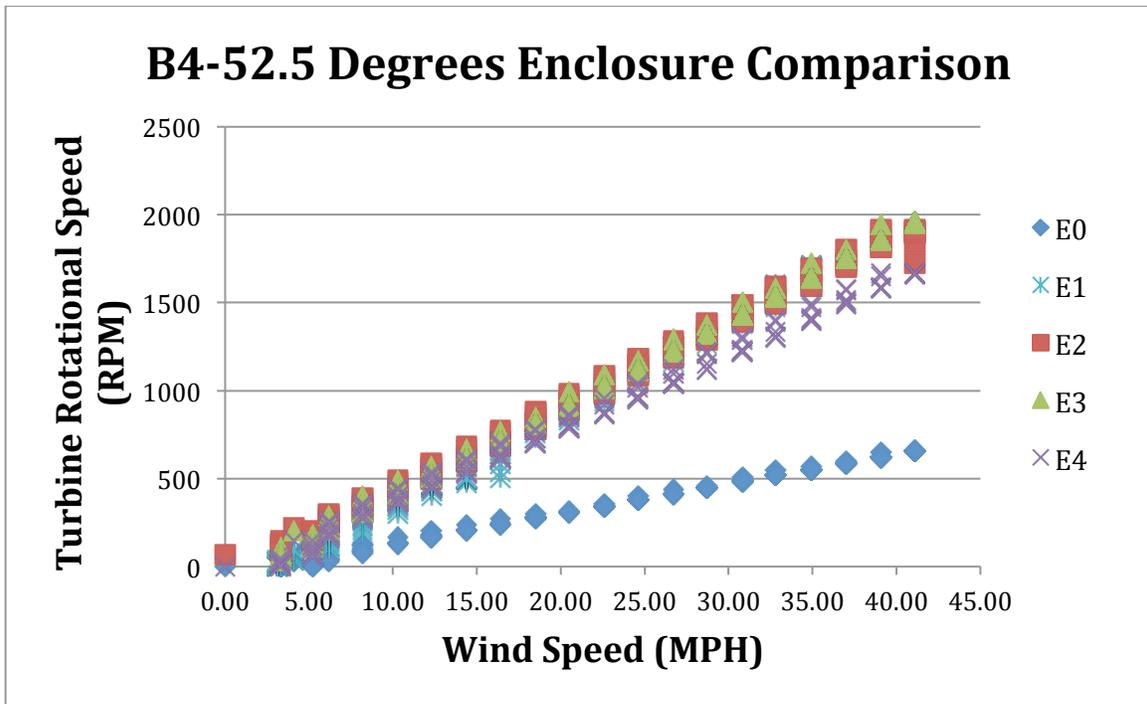
Figure 30. *The turbine with four blades at 52.5° (B4-52.5) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*
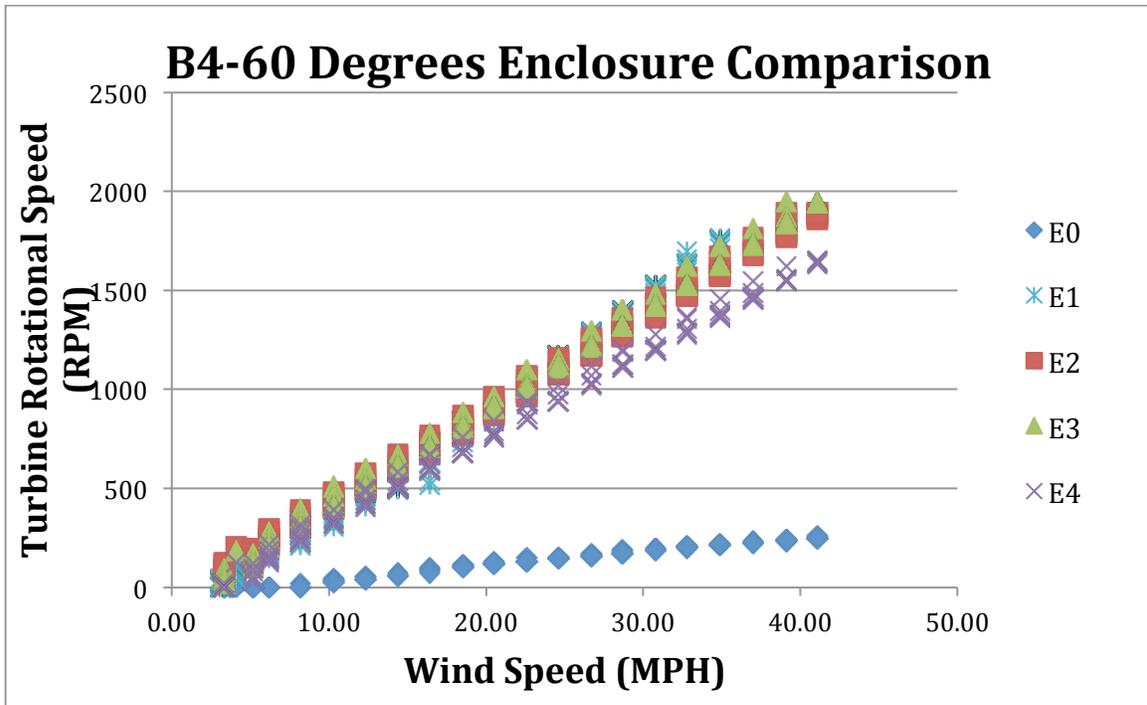

Figure 31. *The turbine with four blades at 60° (B4-60) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*
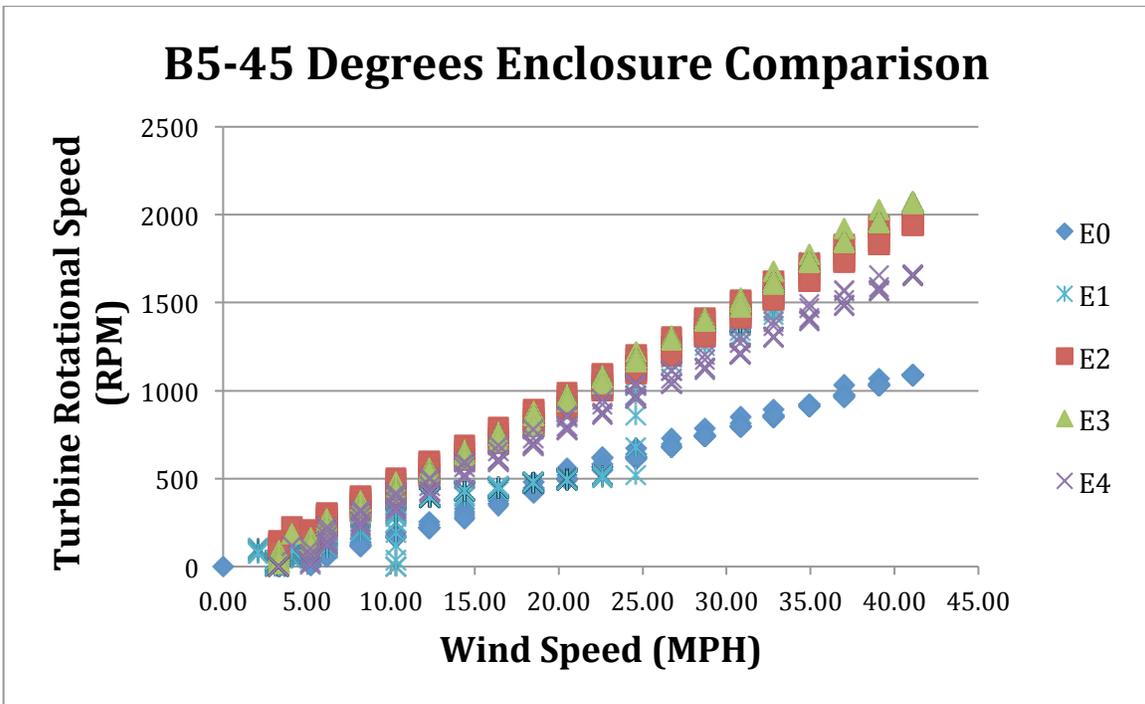
Figure 32. *The turbine with five blades at 45° (B5-45) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*

Figure 33. *The turbine with six blades at 45° (B6-45) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*
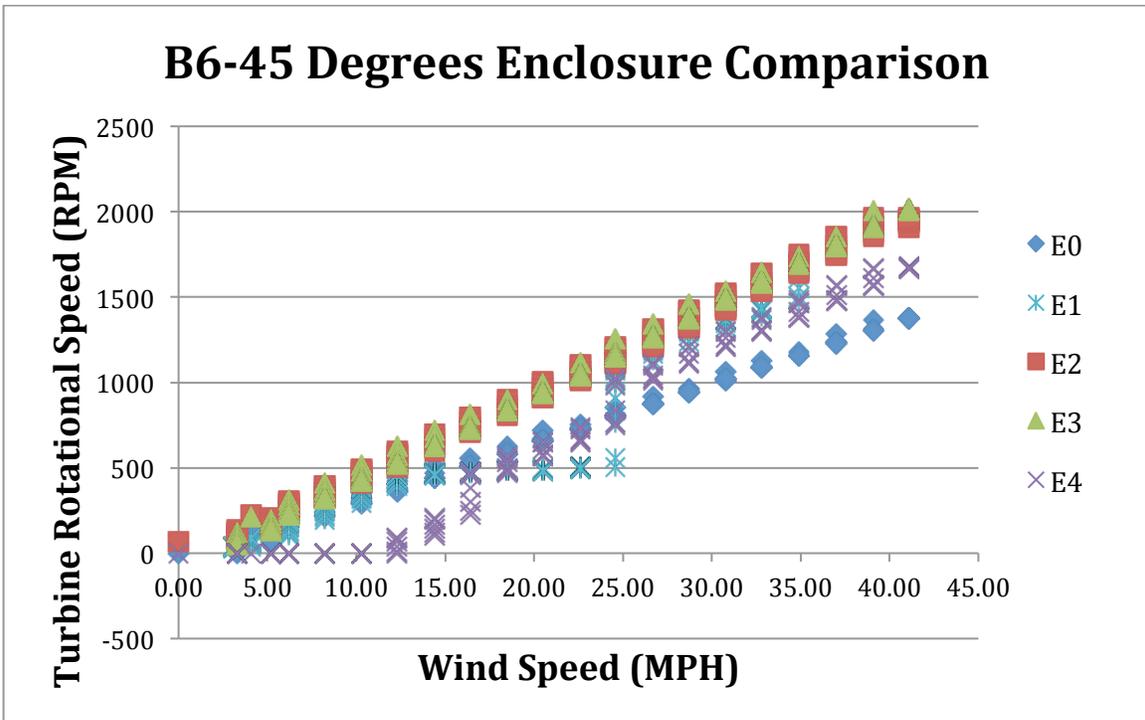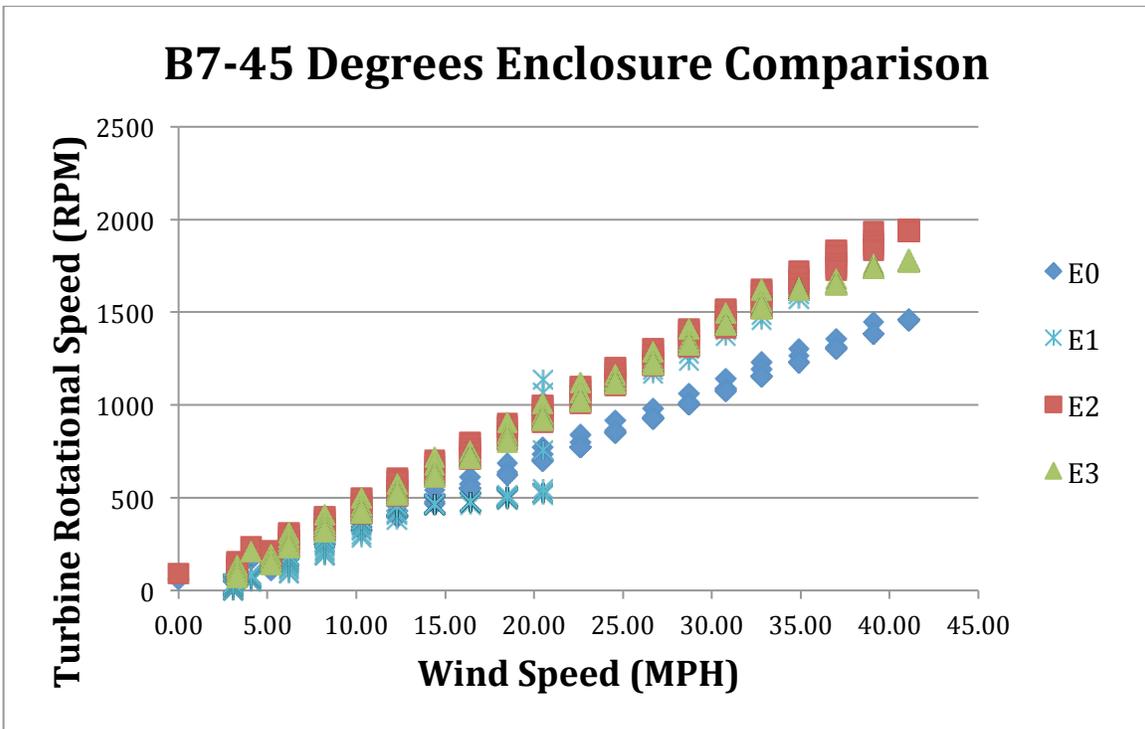
Figure 34. *The turbine with 7 blades at 45° (B7-45) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*
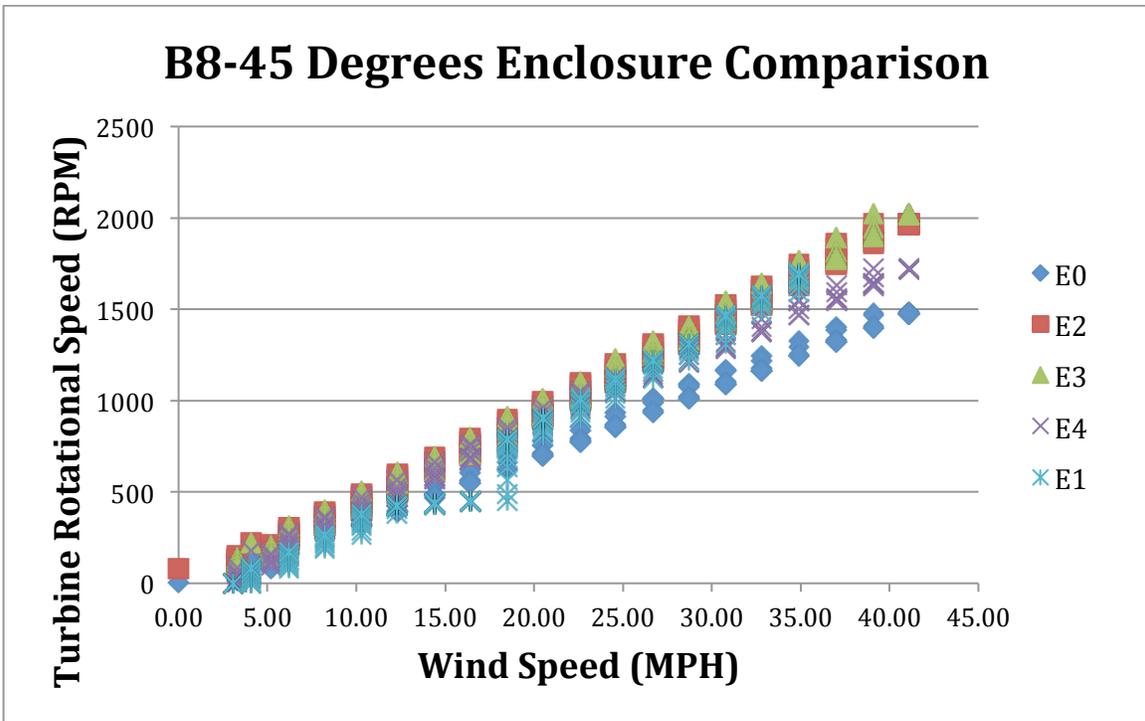

Figure 35. *The turbine with eight blades at 45° (B8-45) was tested without an enclosure (E0) and with four enclosures (E1, E2, E3, and E4) at wind speeds from 0 to 40 mph.*

The results of almost all of the turbines indicated that all four of the enclosures greatly improved the performance of the turbines. The slope information for the turbines is summarized in Figure 36. The concentration of blue in the left E0 column shows that the tests run without an enclosure most often resulted in lower slopes than with any of the four enclosures. The only exception was with the turbine with 2 blades, which had a low slope without an enclosure, but an even lower slope with Enclosure 3.

Enclosure 1 caused seven of the eleven enclosures to have the greatest increase in rotational speed, ω, of the tested conditions. Two turbines performed best with Enclosure 2 and two turbines performed best with Enclosure 3. Five of the eleven turbines had the lowest slope of the tests with enclosures in Enclosure 4 and none had the best performance in Enclosure 4.

Slope Comparison by Enclosure

	E0 Slope	E1 Slope	E2 Slope	E3 Slope	E4 Slope	
B2	3.138	23.78	46.88	2.566	38.59	Least Slope
B3	2.404	53.98	48.40	44.92	47.17	
B4-30	2.299	39.74	50.15	42.62	42.79	
B4-37.5	22.21	54.90	49.79	46.63	49.45	
B4-45	17.69	51.37	48.40	48.01	44.23	
B4-52.5	19.66	53.30	47.74	49.79	42.77	
B4-60	7.980	53.40	47.48	49.68	42.88	Greatest Slope
B5	34.29	51.30	48.33	52.72	43.99	
B6	35.31	47.29	49.40	51.07	50.65	
B7	38.83	51.45	48.62	46.27		
B8	39.00	52.40	49.33	50.35	44.04	

Figure 36. *The enclosure comparison table compares the slopes of a linear fit line for data of each turbine with each enclosure. The slopes relate ω/V_∞, or the ratio of turbine rpm to wind speed.*

d. Airfoils

Two turbines were created with airfoils. Both used the S1223 airfoil shape and the same angle, but one turbine had three airfoils while the other had five. The three-airfoil turbine was compared to the three-bladed flat-plate turbine, while the five-airfoil turbine was compared to the five-bladed flat-plate turbine. The performance of the turbine with airfoils, relative to the turbine with flat-plate blades can be seen in Figures 37-43.
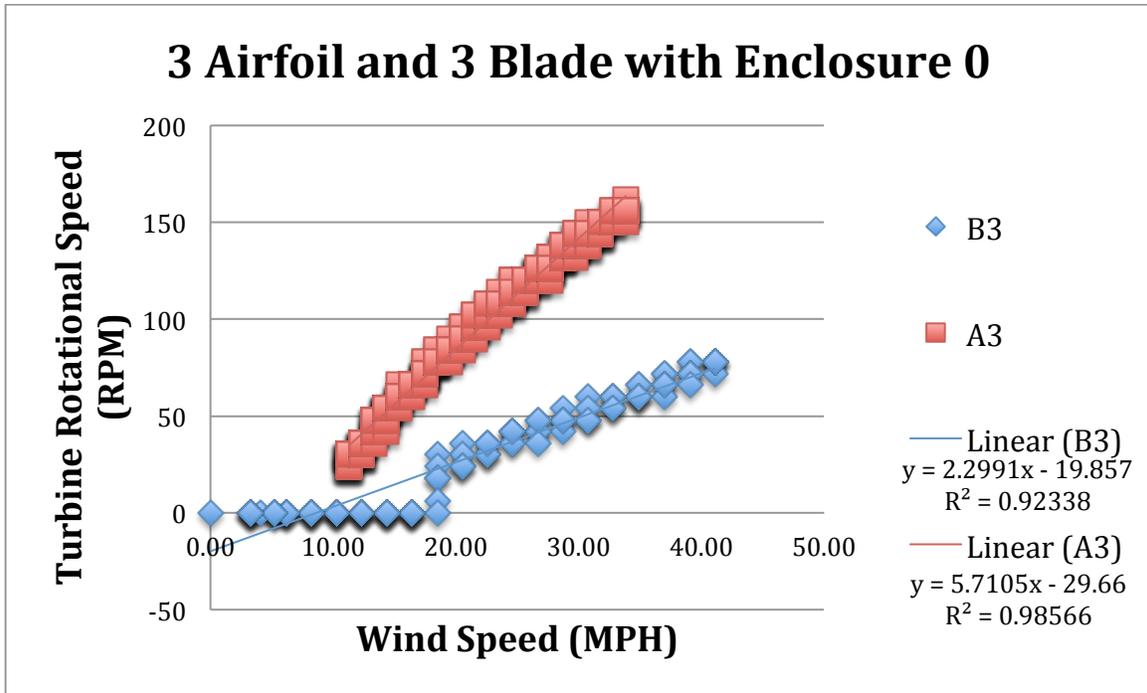
3 Airfoil and 3 Blade with Enclosure 0

Figure 37. *A vertical axis wind turbine with 3 airfoils and a vertical axis wind turbine of the same dimensions with 3 thin, flat-plate blades were tested with no enclosure in a wind tunnel with wind speeds up to 40 miles per hour. The rotational speed was measured in rpm and plotted against wind speed.*
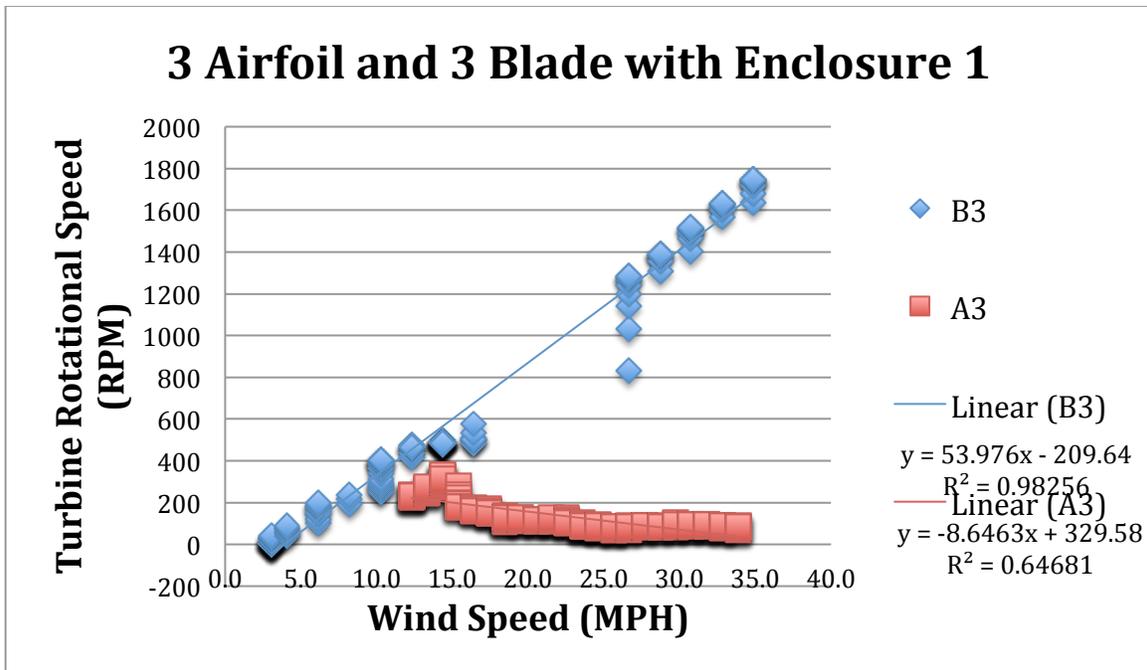

3 Airfoil and 3 Blade with Enclosure 1

Figure 38. *A vertical axis wind turbine with 3 airfoils and a vertical axis wind turbine of the same dimensions with 3 thin, flat-plate blades were tested with Enclosure 1 in a wind tunnel with wind speeds up to 40 miles per hour. The rotational speed was measured in rpm and plotted against wind speed.*

3 Airfoil and 3 Blade with Enclosure 3

B3
A3
Linear (B3)
y = 44.923x - 46.722
R² = 0.99433
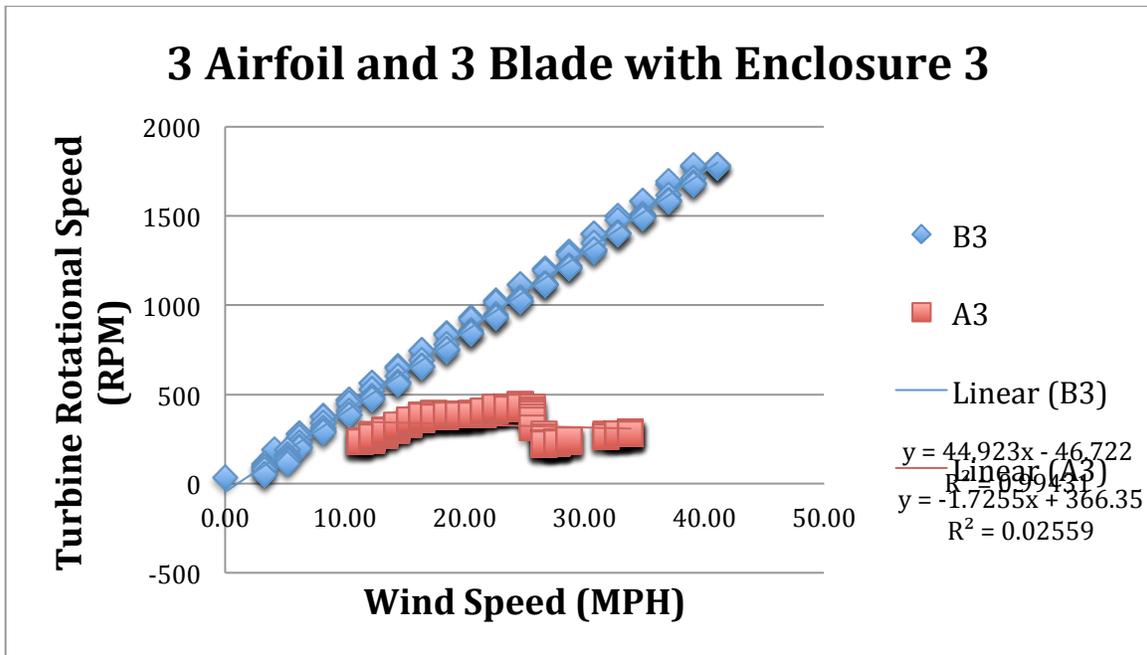Linear (A3)
y = -1.7255x + 366.35
R² = 0.02559

Figure 39. A vertical axis wind turbine with 3 airfoils and a vertical axis wind turbine of the same dimensions with 3 thin, flat-plate blades were tested with Enclosure 3 in a wind tunnel with wind speeds up to 40 miles per hour. The rotational speed was measured in rpm and plotted against wind speed.
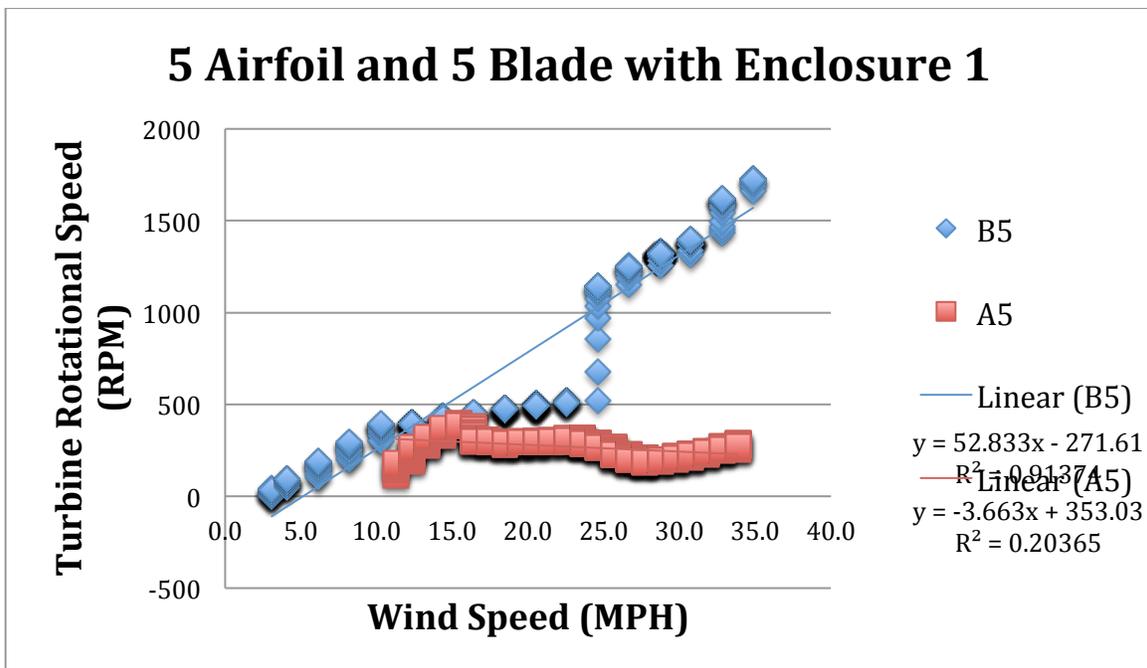

5 Airfoil and 5 Blade with Enclosure 1

B5
A5
Linear (B5)
y = 52.833x - 271.61
R² = 0.91374
Linear (A5)
y = -3.663x + 353.03
R² = 0.20365

Figure 40. A vertical axis wind turbine with 5 airfoils and a vertical axis wind turbine of the same dimensions with 5 thin, flat-plate blades were tested with Enclosure 1 in a wind tunnel with wind speeds up to 40 miles per hour. The rotational speed was measured in rpm and plotted against wind speed.
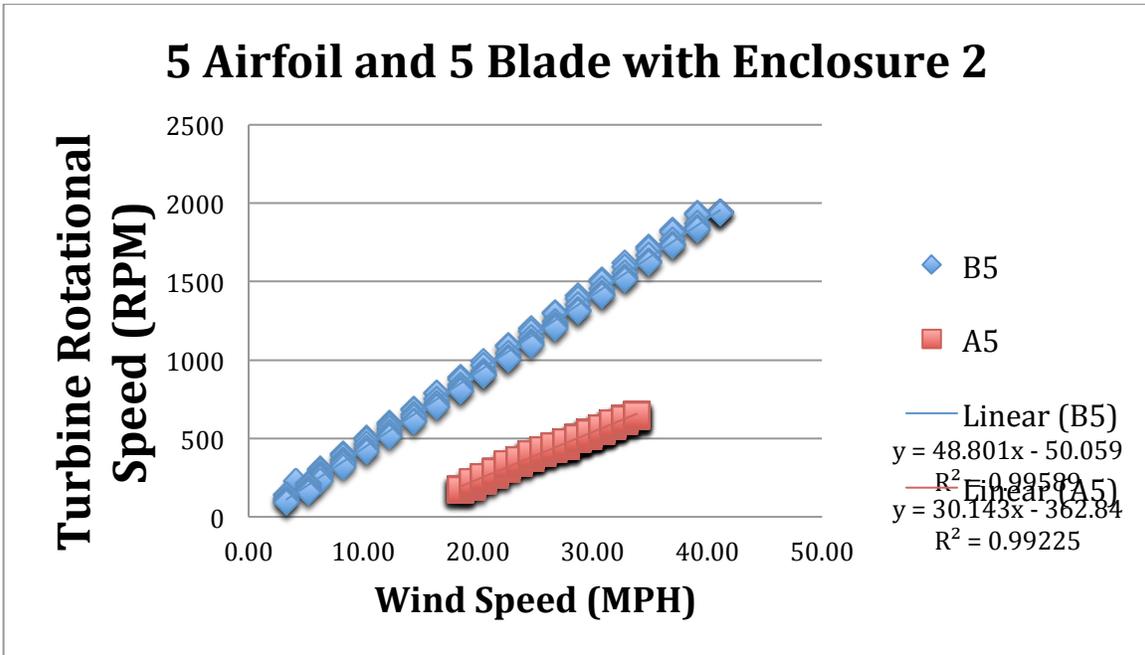
5 Airfoil and 5 Blade with Enclosure 2

Turbine Rotational Speed (RPM) vs Wind Speed (MPH)

Legend:
- B5
- A5
- Linear (B5)
  y = 48.801x - 50.059
  R² = 0.99589
- Linear (A5)
  y = 30.143x - 362.84
  R² = 0.99225

Figure 41. *A vertical axis wind turbine with 5 airfoils and a vertical axis wind turbine of the same dimensions with 5 thin, flat-plate blades were tested with Enclosure 2 in a wind tunnel with wind speeds up to 40 miles per hour. The rotational speed was measured in rpm and plotted against wind speed.*
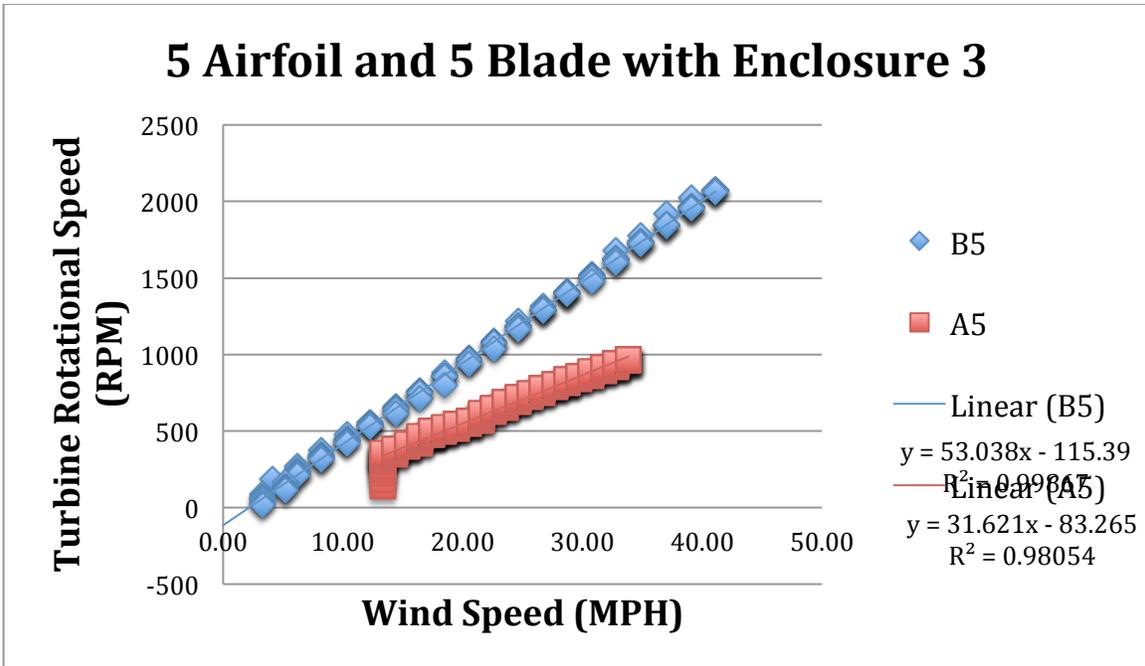
5 Airfoil and 5 Blade with Enclosure 3

Turbine Rotational Speed (RPM) vs Wind Speed (MPH)

Legend:
- B5
- A5
- Linear (B5)
  y = 53.038x - 115.39
  R² = 0.99867
- Linear (A5)
  y = 31.621x - 83.265
  R² = 0.98054

Figure 42. *A vertical axis wind turbine with 5 airfoils and a vertical axis wind turbine of the same dimensions with 5 thin, flat-plate blades were tested with Enclosure 3 in a wind tunnel with wind speeds up to 40 miles per hour. The rotational speed was measured in rpm and plotted against wind speed.*
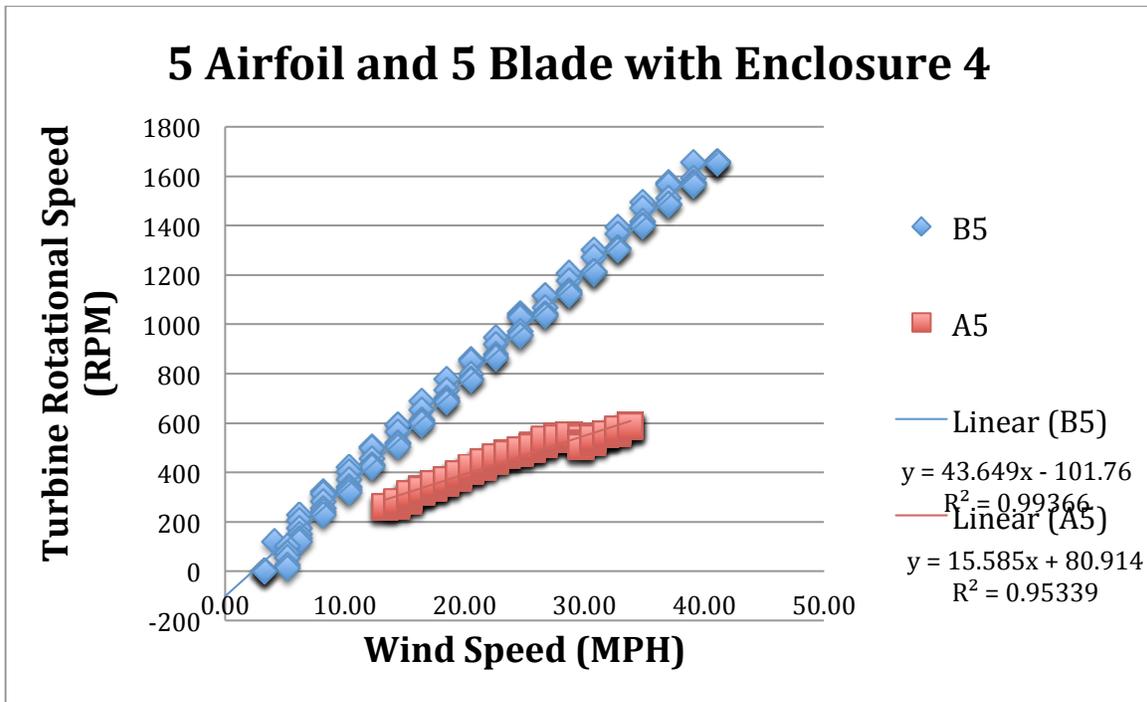
5 Airfoil and 5 Blade with Enclosure 4

Legend:
- B5
- A5
- Linear (B5)
  - $y = 43.649x - 101.76$
  - $R^2 = 0.99366$
- Linear (A5)
  - $y = 15.585x + 80.914$
  - $R^2 = 0.95339$

Axis labels: Turbine Rotational Speed (RPM) vs. Wind Speed (MPH)

Figure 43. *A vertical axis wind turbine with 5 airfoils and a vertical axis wind turbine of the same dimensions with 5 thin, flat-plate blades were tested with Enclosure 4 in a wind tunnel with wind speeds up to 40 miles per hour. The rotational speed was measured in rpm and plotted against wind speed.*

Figures 37-43 relate the curves of the three and five airfoil turbines to the three and five blade flat-plate turbines. Of seven tests that achieved results, the only airfoil turbine that performed better than its flat-plate counterpart was the three-airfoil turbine without a enclosure. In that case, the turbine with airfoils increase rotational speed at 2.3 times the rate that the flat plate turbine increased rotational speed. All of the other tests had the drag-type, flat-plate turbines with a higher slope than the lift-type airfoil turbines.

Three tests of turbines with airfoils resulted in the turbines having negative slopes. These tests, as shown in Figure 44 were the three-airfoil turbine in Enclosure 1 and Enclosure 3 and the five-airfoil turbine in Enclosure 1. Figure 44 shows the overall downward slope of the performance trend by giving a downward slope. Figures 38-40 show the data points for the specific tests and it can been seen that the data point are not consistently decreasing despite the overall slope. The rotational speed is increasing at low wind speeds and then the slope fluctuates between positive and negative and high and low.

In three instances, the airfoil-type turbines were incapable of operating in any wind, despite attempts to manually start their rotation. These three tests were the three-airfoil turbine with Enclosure 2 and Enclosure 4 and the 5-airfoil turbine without an enclosure. The failure to perform by these turbines is indicated by the grey boxes in Figure 44 and the absence of graphs for the three-bladed comparison

in Enclosure 2 and Enclosure 4 and for the five-blade comparison without an enclosure.

Airfoil Slope Comparison

	E0 Slope	E1 Slope	E2 Slope	E3 Slope	E4 Slope
A3	5.608	-8.047		-8.047	
B3	2.404	53.98	48.40	44.92	47.17
A5		-3.770	30.139	30.33	15.62
B5	34.29	51.30	48.33	52.72	43.99

Figure 44. *The airfoil slope comparison table compares the slopes of a linear fit line for data of turbines with airfoils to similar turbines with thin, flat-plate blades for each enclosure. The slopes relate ω/V_∞, or the ratio of turbine rpm to wind speed.*

7. Conclusions

a. Blade Number

The blade number tests indicated that all of the turbines performed similarly with all of the enclosures but dissimilarly without any enclosure, shown in Figure 12. This suggests that the turbines that performed relatively worse than the others without an enclosure are more susceptible to disruption by a countering wind, such as the wind that was blocked by the enclosures. Though torque has not yet been tested, physics would indicate that a turbine with more weight around the outer edges of the radius would have more momentum than a turbine with less weight when both turbines have equal rotational speed. Testing without an enclosure allows the oncoming wind to contact the blades that are on the upstream half of rotation and counteract, to some degree, the effect of the wind on the downstream half. In testing, the turbines with more blades, resulting in a higher weight, were the turbines that were affected the least by the counter wind, as shown in Figure 17.

Turbines with all blade numbers captured a comparable portion of the wind energy, but the turbines with fewer blades were more susceptible to resisting winds.

b. Blade Angle

The blade angle tests also indicate similar performance when enclosures are used and a clear variation when no enclosures are used, shown in Figure 19. As with the blade number tests, this indicated that some turbines are more susceptible to resisting winds than others. The turbines which were affected the most by wind on the upstream half of rotation were those with blade angles at the extremes of 30° and 60°. Turbines with thin, flat-plate blades at angles of 37.5°, 45°, and 52.5° had similar performance without an enclosure. The turbine with blade angles of 37.5° did the best by a marginal amount, followed by the turbines with blade angles of 52.5° and 45°, respectively.

c. Enclosures

Tests were conducted without any enclosure (E0) and with four different enclosures, Enclosure 1 (E1), Enclosure 2 (E2), Enclosure 3 (E3), and Enclosure 4 (E4). Eleven VAWT with thin, flat-plate blades were tested in each of the enclosures and their relative performance in each enclosure was compared using the slopes of a linear fit line of the data points produced. All of the turbines had their worst performance when tested without any enclosure, with the singular exception of the two-bladed turbine, the performance of which constituted its designation as a statistical outlier for data collected in Enclosure 3. It can be concluded that an enclosure does increase the performance of a VAWT.

The majority of the turbines, 7 of the 11, performed best in Enclosure 1 and 5 of the 10 VAWT performed worst (of the cases using enclosures) in Enclosure 4. All enclosures blocked the 90°, of the 180° facing the oncoming wind, that resisted the rotational direction. Enclosure 1, which gave the most favorable results, redirected

the airflow 45° by locating the exit 45° past the point in the enclosure which was directly opposite the inlet. Enclosure 4, which performed the least favorably, blocked the exit of the air over the 90° section that was opposite the 90° inlet section. It can be concluded that any enclosure that blocks the 90° section resisting the direction of rotation will improve the performance of the VAWT, and that the turbine performance is further improved when the airflow is redirected to remain within the enclosure past the point directly opposite the inlet.

d. Airfoils

The airfoils used in the VAWT with three and five airfoil-shaped blades were of the S1223 shape. With the exception of the three-airfoil turbine without an enclosure, every test indicated that the drag-type, flat-plate turbines performed better than the turbine with the same number of airfoils in the same enclosures.

Over some ranges of wind speeds, the rotational speed of the airfoil-type turbines would have a positive relationship with the wind speed, and over the other ranges of wind speeds, the rotational speed of the airfoil-type turbines would have an inverse (or negative) relationship with the wind speed. The slope values in Figure 44 are accurate representations of the drag-type turbines, the rotational speed of which increase linearly with a linear increase in wind speed. The slope values fail to address the curvilinear wind speed dependent relationship between the rotational speed of the airfoil-type turbines and the linear change in wind speed.

It can be concluded that thin, flat-plate turbines of the drag-type perform better than the S1223-shape airfoil turbines of the same blade number.

8. Future Work

a. Airfoil Blade Shape

Given the results of testing done on the turbines with flat blades and the single test done with airfoil blades, research could be done on an optimal design for airfoils that would serve as more efficient blades. Research would need to be graphically compared to existing flat plate and airfoil data and evaluated to determine which elements of the blade shape increase efficiency and what stress that places on the mechanical components. Airfoil traits that could be tested include shape, camber, pitch, and twist. Additional research should be conducted with regard to the possibility of mechanically manipulating the angle of the airfoil to change at particular azimuth angles to decrease the airfoil's wind resistance during the negative half of rotation.

b. Enclosure Design

Additional enclosures should be explored with the intent to find what angle of enclosure is the most effective in blocking wind from the negative portion of rotation and how far that enclosure should extend. Enclosures that block a portion of the wind, as opposed to enclosing the entire turbine could be flat or curved to fit the line of the turbine and it is yet untested which design is more efficient and which is more practical for mounting. In both flat and curved enclosures, it has not been tested whether the enclosure is more effective if it passes the midline that is parallel to the free stream flow or if the enclosure would be more effective ending prior to that midline. In the same line of thought, it is untested whether or not it is efficient for a flat enclosure to extend beyond the furthest point of the turbine. In a curved enclosure, it should be tested whether or not efficiency is increased by the enclosure continuing beyond the midline intersecting the axis and perpendicular to the direction of the free stream.

c. Power Output

Torque measurements are required to determine the actual power output from the VAWT at particular wind speeds. The rotational speeds presented were collected without any resisting torque applied to the shaft; therefore, the turbines tested did no work. In the expected operational environment, the wind turbine will run a generator. The size of the generator that can be run and the power output are dependent on the torque that is applied to the shaft by the turbine and need to be calculated to determine the feasibility of an enclosed VAWT design.

d. Mounting Structures

These enclosed vertical axis turbine are designed for the purpose of generating power on a household scale. They are likely to be installed by users who are unfamiliar with engineering fundamentals. It is well published that wind turbines are subject to higher wind speeds when they are mounted at higher altitudes relative to the terrain. The lack of user experience combined with need to

mount turbines as high as reasonably possible leads many users to mount turbines on their roofs. Turbines are subject to a lot of force from the wind, and enclosures increase the area impacted by the wind. The force of the wind resisted by the turbine translates to both a bending moment in the shaft of the mounting and a significant moment force at the point where the turbine is mounted to a structure.

e. Computational Fluid Dynamics Modeling

In parallel to this study of enclosed vertical axis wind turbines, the turbines should be modeled using computational fluid dynamics (hereafter referred to as CFD) software. The turbines that should be modeled are rotating about an axis and will both resist the force of the free stream flow and will be moved by the free stream. The airfoils will constantly change pitch relative to the free stream as the azimuth angle changes, which is a further complication in creating the CFD model. The models required to mimic this empirical study would be fairly complex and, as such, have not been adequately prepared to complement this study. Due to the variability of the wind and the potential for gusting and changes in wind speed, a CFD model alone cannot substitute for testing, but it can provide direction for further studies by highlighting areas of high stress in the blades and mounting and can provide insight into the path of the wind as it is redirected by contact with the turbine and enclosure.

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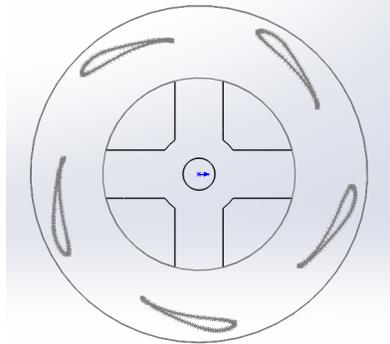
Appendix

Naming Conventions

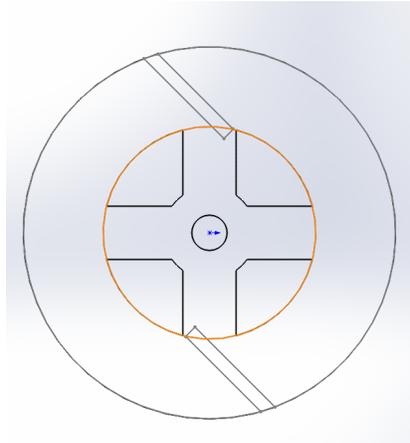**A3**   The vertical axis turbine with three S1223 airfoil blades.

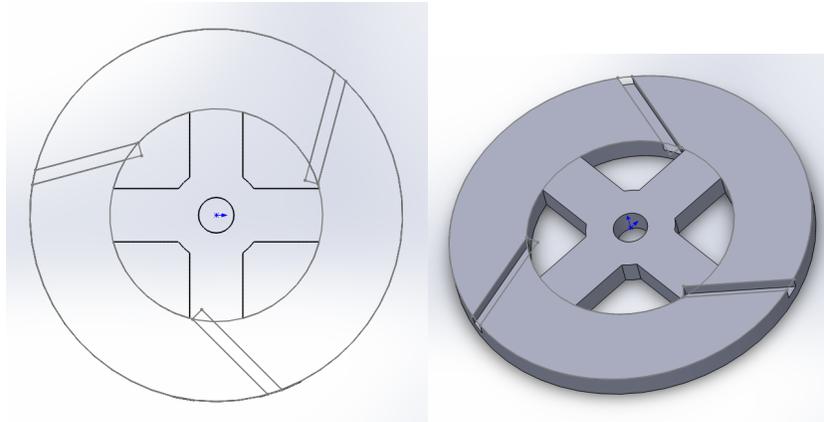**A5**   The vertical axis turbine with five S1223 airfoil blades.

B2   The vertical axis turbine with 2 thin, flat-plate blades at a 45° angle. The only turbine with two blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.
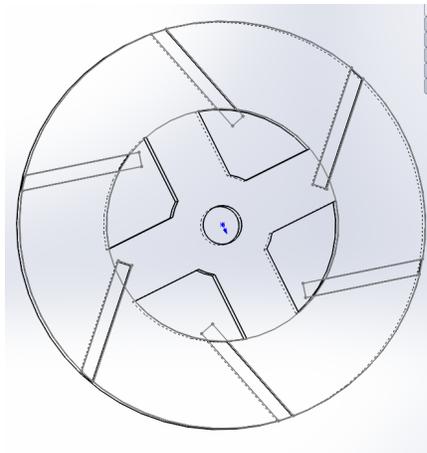

B3   The vertical axis turbine with 3 thin, flat-plate blades at a 45° angle. The only turbine with three thin, flat-plate blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.

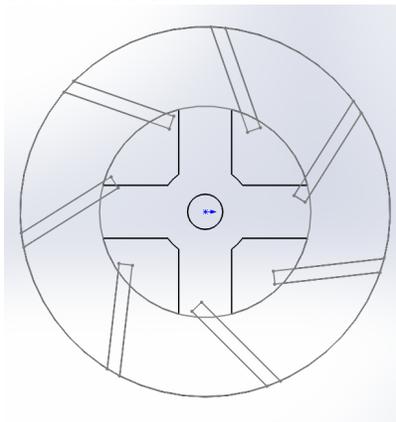**B4**   The vertical axis turbine with 4 thin, flat-plate blades at a 45° angle. When only the blade number is specified, the turbine with blades at a 45° angle is indicated.

B4-30°   The vertical axis turbine with 4 thin, flat-plate blades at a 30° angle.

B4-37.5°   The vertical axis turbine with 4 thin, flat-plate blades at a 37.5° angle.

B4-52.5°   The vertical axis turbine with 4 thin, flat-plate blades at a 52.5° angle.

B4-60°   The vertical axis turbine with 4 thin, flat-plate blades at a 60° angle.

B5   The vertical axis turbine with 5 thin, flat-plate blades at a 45° angle. The only turbine with five thin, flat-plate blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.

B6   The vertical axis turbine with 6 thin, flat-plate blades at a 45° angle. The only turbine with six blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.
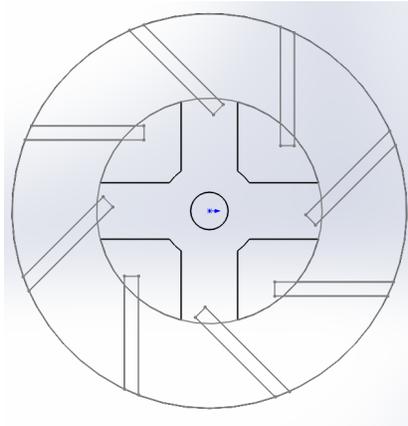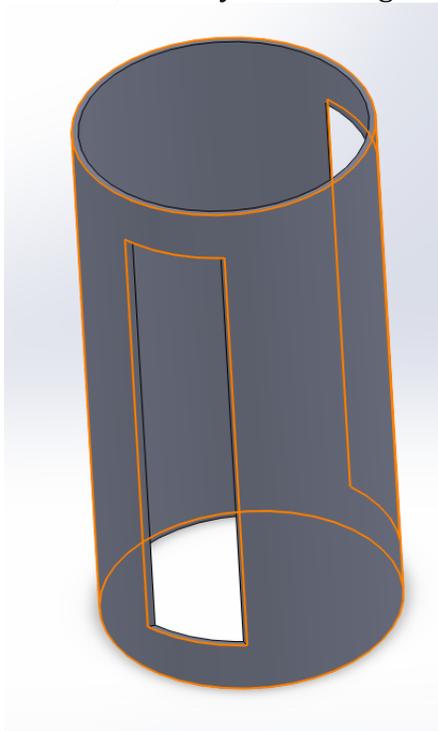

B7   The vertical axis turbine with 7 thin, flat-plate blades at a 45° angle. The only turbine with seven blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.

B8	The vertical axis turbine with 8 thin, flat-plate blades at a 45° angle. The only turbine with two blades has a blade angle of 45°, so the angle is assumed unless otherwise stated.

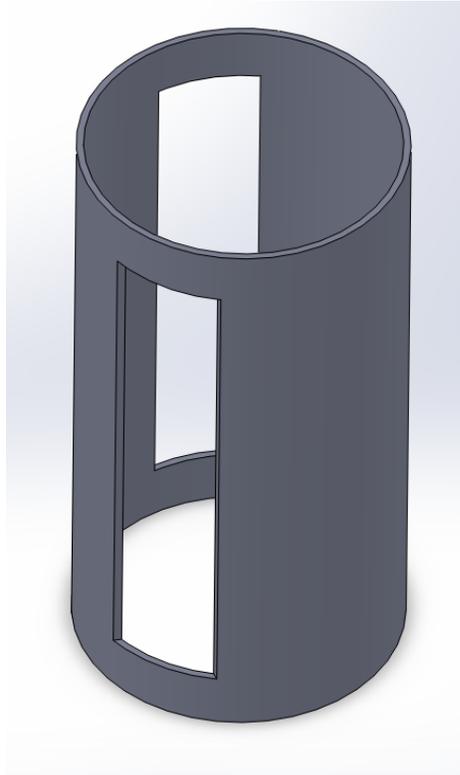|	
E0	E0 or Enclosure 0 refers to the testing condition when no enclosure is being used.

E1	E1 or Enclosure 1 refers to the enclosure with an outlet approximately 210° after the inlet, thereby redirecting the wind vector within the enclosure.

E2	E2 or Enclosure 2 had the outlet directly across from the inlet.

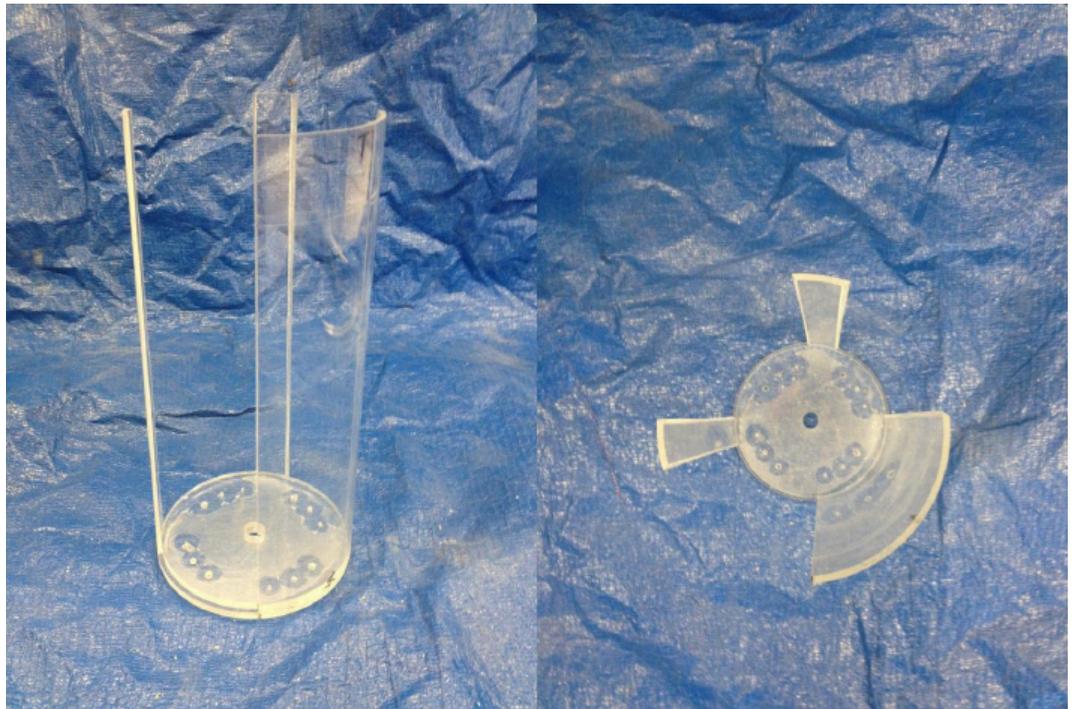|	
E3	E3 or Enclosure 3 was a simple 90° arc blocking wind on the half of rotation that resists the wind.

Image: Enclosed Vertical Axis Wind Turbines, Richard Holak and Michael Mourkas[13]

E4   E4 or Enclosure 4 consisted of two identical 90° arcs, one on the upstream half blocking the side where the wind resists the rotational speed and one blocking air from exiting directly opposite the inlet and forcing the wind to change direction within the enclosure.
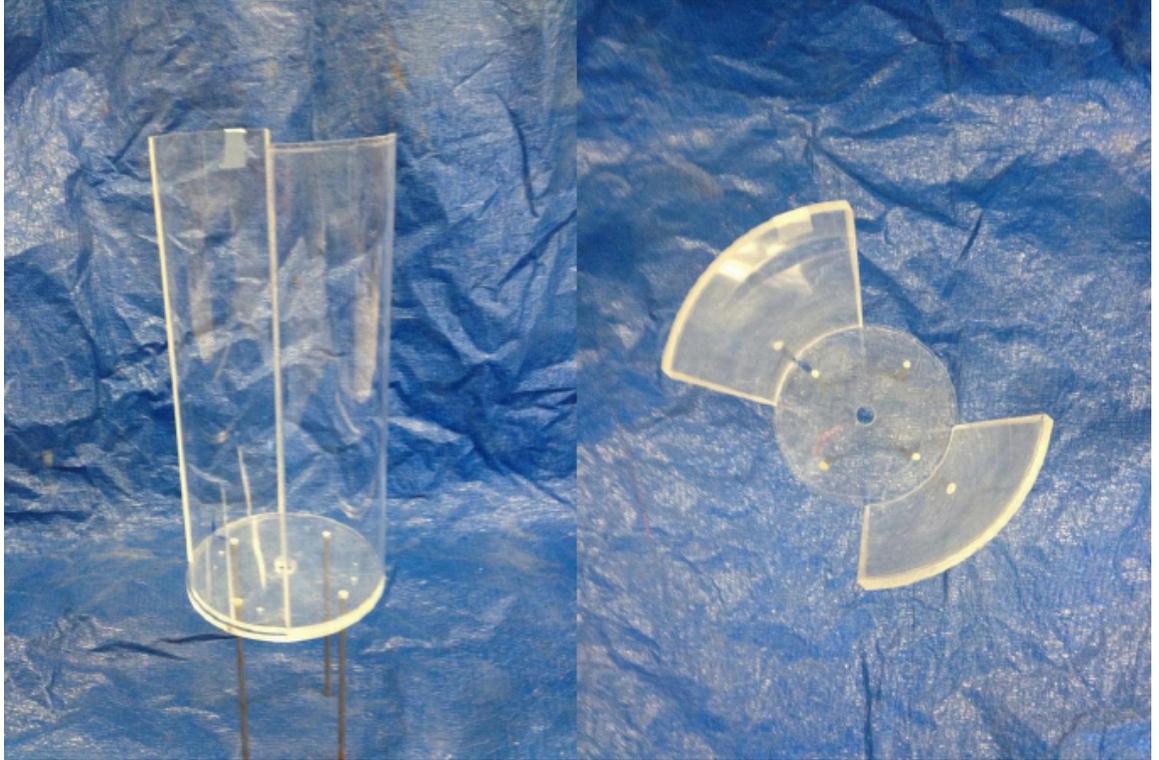

Image: Enclosed Vertical Axis Wind Turbines, Richard Holak and Michael Mourkas[13]