

Vertical Axis Wind Turbine
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1. Introduction

1.1 Background

Wind power systems have been recognized as one of the major, effective renewable systems capable of converting massive fluid flow into usable and maintainable power source. Wind generated power turbines have been around for centuries and is regarded as one of the first structures to take energy from nature and transform it into a form of power/electricity. Over the course of history, the design of the wind turbine has been refined through the evolving demands and needs of the people. From the original concept, two branches were developed: Vertical and Horizontal Axis Wind Turbines.

Horizontal axis wind turbines (HAWT) are most commonly used in large-scale communities to generate enormous quantities of power due to its capability to produce more electricity from a given amount of wind. Because of its sheer size and design, as the wind flows through the face of its blades, the amount of surface area it covers is significant allowing a larger wind/power output to be generated. Because of its power output, the HAWT can power large communities. They are, however, difficult to maintain because their motors are generally part of the turbines themselves, and are located high above ground, making it arduous to access for repairs. HAWT also have to be positioned to face where the wind is blowing to achieve the blade's maximum performance. This means constantly repositioning the turbines whenever the wind changes directions.

Vertical axis wind turbines (VAWT), on the other hand, are smaller but can fulfill power generation methods that the HAWT cannot achieve. Unlike HAWT, which has to be positioned high enough for wind to reach its blades, the VAWT can be built from the ground and require less repositioning for it to start. A main advantage the VAWT has over HAWT is that the vertical blades are designed to capture wind flow at any angles. This will provide fewer problems with regards to positioning the turbine relative to the wind flow. VAWT are also smaller in size making it the ideal type of power generator to be implemented in a small Alaskan village.

Although more economically friendly than its counterpart, HAWT is not suitable for a small rural Alaskan setting in terms of production and maintenance costs. VAWT is smaller and therefore easier to maintain compared to HAWT. Vertical Wind Turbines also have different types that differ in performance and design.

1.2 Darrieus and Savonius Wind Turbines

The vertical wind turbines come in two distinct types: the Darrieus and Savonius. George Darrieus' original design in 1927 consisted of two straight airfoils connecting the top and the bottom of the rotating shaft. This resulted in an oval shape between the blades with the vertical shaft in the center. Darrieus' design operates by having the blade speed to be multiple of the wind speed. A Darrieus turbine isn't self-starting, so it requires an external device to rotate the blade into sufficiently high speed. The mechanical features of Darrieus' turbines, such as powertrain, generator, and controls, are located at the bottom, which makes it easier to maintain. The negative effects from the original Darrieus turbine were violent vibrations, which caused the blades to fail, high noise level and low efficiency; however, VAWT causes less electromagnetic interferences than HAWT.

Airflow creates two types of aerodynamics forces: drag forces, which are in the direction of the airflow and lift forces, which are perpendicular to the airflow. These forces are used to generate the forces needed to rotate the blade on a wind turbine. The lift based turbine blades are basically an airfoil or a wing. The wind speed and the pressure difference is created between the upper and the lower surfaces as the air flows which causes the pressure at the lower surface to be greater creating a lift on the blade. Lift based turbines have a higher rotational speed than the drag based turbines therefore creating more energy from the wind.

The Savonius turbine, introduced by S. J. Savonius in 1922, consist of two cups or half drums fixed to the central shaft in opposite locations. The cup or the drum will catch the wind causing the shaft to rotate while bringing the other cup or drum into the flow of the wind. Then the other cup or drum will catch the wind causing the shaft to perform a full rotation. Savonius turbine has evolved from cups and drums into a fluted bladed device, which generates higher efficiency and less vibration. Since Savonius turbines are resistant to turbulence, it can be mounted near the ground. Unlike Darrieus, the Savonius turbine doesn't require an external motor to rotate the blade to receive the full potential of the wind because this turbine is based on drag forces. The drag based wind turbine requires the airflow force against the surface to rotate the blades. The drag increases as the area of the surface facing the wind increase. The drag based wind turbines have slow rotational speed and high torque capability. Savonius turbines are designed based on the drag force while the Darrieus turbines are designed based on the lift force to pull the blades along for rotation.



Figure 1. Hybrid Helical Design

1.3 Lift Designs: Helical vs. Straight Blades

Since the blade types vary in different vertical axis wind turbines, this project focused on straight blades and helical blades. Straight blades could be designed in many ways for example; Darrieus' first design with the blades connecting the top and bottom of the rotating shaft, or P.J Musgrove's "H-blade" design which straightened out Darrieus' blades and installed frames to extend the blades further from the rotating shaft causing it to resemble the letter "H". Although the straight blade design is efficient, its inability to self-start was too much of a problem for this project. From the straight blade design of Darrieus and Musgrove came a hybrid helical design that helps the blades see the same wind speed at the same angle of attack resulting in a much smoother spin with less vibration and higher efficiency.

This hybrid helical design, like the one shown in Figure 1, was chosen for this project because it is a mix of the two fundamental vertical axis wind turbine types. As mentioned above, the Darrieus wind turbine is not self-starting. Therefore, in order to compensate for this problem, Savonius' concept of curves was implemented into this design. The hybrid helical design incorporates the strengths of the two vertical axis wind turbine types and combined them to make one design that can be efficient and powerful at the same time.

Laminar and turbulent flow conditions are essential in determining the wind turbine's final design. Depending on the condition of the flow, the blades might or might not start. The angle of attack for the wind is taken into consideration for the blades' functionality as well. In order to maintain a laminar flow, which is the flow required for the generation of a lift force [1], the angle of attack should not exceed 20 degrees. An angle greater than 20 degrees will cause the flow along the blade to become turbulent, thus causing it to stall. This will also cause additional problems for the system including vibrational and efficiency complications.

1.3 Theoretical Equations

The equations and calculations needed for this project are related to the wind power, Tip-Speed Ratio (TSR), power of the blade, and maximum rotor efficiency.

$$P = \frac{1}{2} * \rho * A * v^3 \quad [1]$$

where: P = power in the wind (W)

ρ = density of air (1.225 kg/m³ @ 15C & 1 atm)

A = cross-sectional area wind passes through

v = wind speed normal to area (m/s)

$$TSR = \frac{\text{rotor tip speed}}{\text{wind speed}} = \frac{\omega * R}{v} \quad [2]$$

where: TSR = Tip-Speed Ratio

ω = rotational speed (rad/s)

R = rotor radius (m)

v = wind velocity "free stream" (m/s)

$$P_{\text{shaft}} = T * \omega \quad [3]$$

where: P_{shaft} = power created on the shaft (W)

T = torque on the shaft from airfoil (W)

ω = rotational speed (rad/s)

Equation 1 was used to get the theoretical power of the wind. This is how much power the wind can generate and therefore is the maximum amount of power the wind turbine can produce (if it was 100% efficient). This 100% efficiency is not the case though, because Betz's law shows us this, a wind turbine can only capture 59.3% of the kinetic energy in the wind. Therefore the most power the turbine can produce is 59.3% of the power calculated in equation one.

Equation 2 was used to acquire the rotational speed of airfoil while spinning around the shaft. With a set Tip Speed Ratio and a known wind velocity, the rotational speed of the airfoil can be attained mathematically.

Equation 3 was used to get the power created by the airfoil, and therefore the power extracted by the wind turbine. This is the power that has the ability to be changed to electricity. The ANSYS software was used to get the force created by the airfoil that was tangential to the shaft. This tangential force was used to acquire the torque created on the shaft by the airfoil, and sequentially used in equation three.

2. Project Statement

1. Design and construct a vertical axis wind turbine prototype that can be implemented into an Alaskan village.
2. Our deliverables include the following:
 - a.) An original vertical blade design
 - b.) Prototype of the blade's cross section.
 - c.) Data from Computational Fluid Dynamics (CFD) simulation.
 - d.) Report

3. Scope of Project

1. A self-starting vertical axis wind turbine that can generate power to supply a small Alaskan village.
2. Project Limitations: Testing facility and time.

4. Methods

The vertical axis wind turbine blade was designed using computer-based programs that will aid with modeling and fluid flow simulation. The primary program that was used for the design phase of this project was ANSYS. Primary use of this software was utilized to provide Computational Fluid Dynamics (CFD) simulation for a proposed airfoil design. This simulation provided essential numerical data that will determine whether the vertical blade design meets the requirements and qualifications specified in the deliverables for the blade to perform optimally. A secondary program, Solidworks, was utilized to create a 3D model and renderings of the blade design that will be used to create a prototype. The geometry of the blade, the numerical data from the CFD simulation, and the lift and drag force coefficients will be determined using the aforementioned programs for this project.

4.1 Geometry

The geometry of the vertical axis wind turbine blade was an essential aspect of the performance of the design. Deciding on a specific geometry of the blade depended on the data acquired during the ANSYS CFD simulation. There were different parts of airfoil geometry that were taken into account in selecting an airfoil shape, as seen in Figure 1. The coordinates of the upper and lower surface can characterize airfoil geometry. It is often summarized by a few parameters such as: maximum thickness, maximum camber, position of max thickness, position of max camber, and leading edge radius. A reasonable airfoil section can be generated given these parameters.

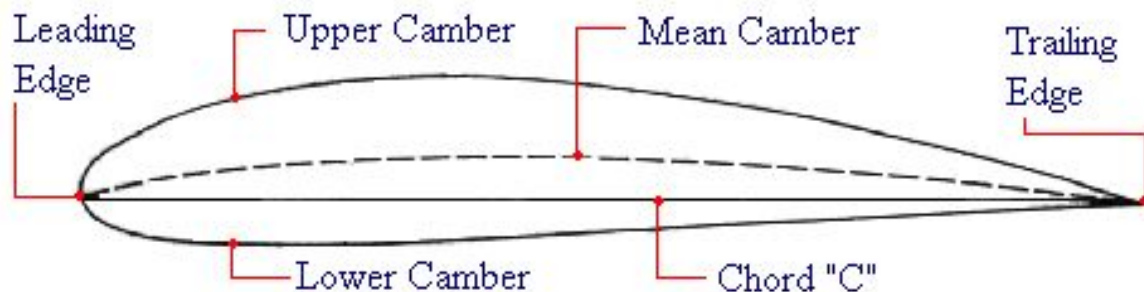


Figure 1. Different parts of an airfoil. [1]

Depending on the shape of the airflow and how many digits it has in its camber line, an airfoil can be categorized by a NACA number. For example, the camber line of 4-digit sections was defined as a parabola from the leading edge to the position of maximum camber, then another parabola back to the trailing edge. NACA 5 has the same thickness but uses a camber line that has more curvature towards the nose. NACA 6, on the other hand, has sections that were generated from a more or less prescribed pressure distribution and were meant to achieve some laminar flow [2]. These aspects were focused on when simulating using ANSYS's CFD simulation.

4.2 ANSYS Computational Fluid Dynamics

ANSYS's computational fluid dynamics simulation program was utilized to create a fluid based simulation that helped in choosing the blade design based on the numerical data that ANSYS provided. Airfoil profile data was required for the simulation. In order to utilize this function, NACA airfoil geometry profile data was extracted from an online source. The shape was examined in terms of pressure loads, velocity, and its drag and lift properties. As shown in Figure 2, the shape was examined to determine the where the pressure loads are located.

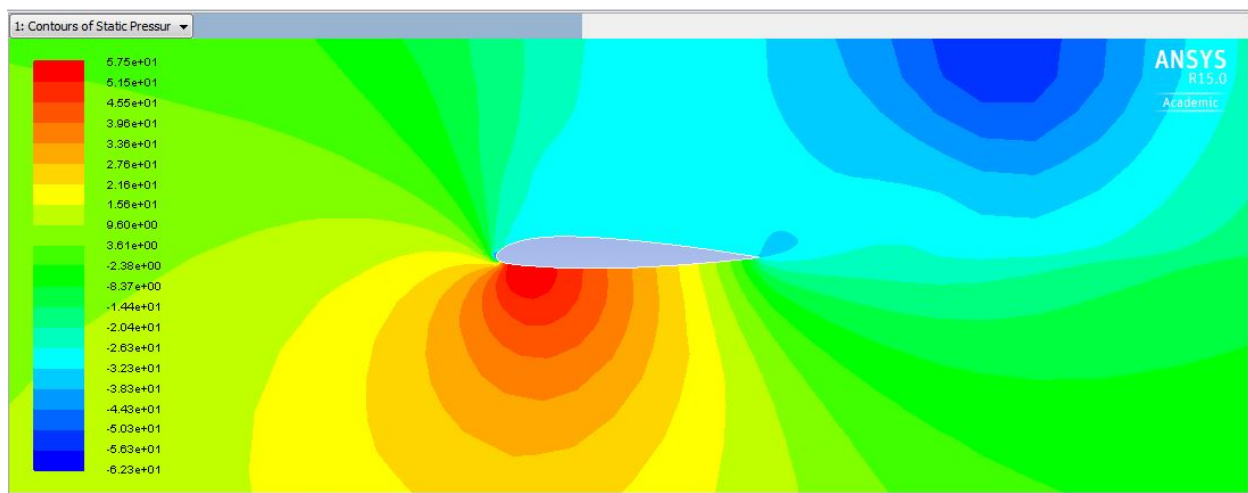


Figure 2. Pressure loads on a NACA 5 airfoil using ANSYS CFD simulation

Along with pressure load analysis, velocity vectors, as seen in Figure 3, was also examined using ANSYS. This is a helpful tool for determining the magnitude and the direction of fluid flow in relation to the airfoil shape.

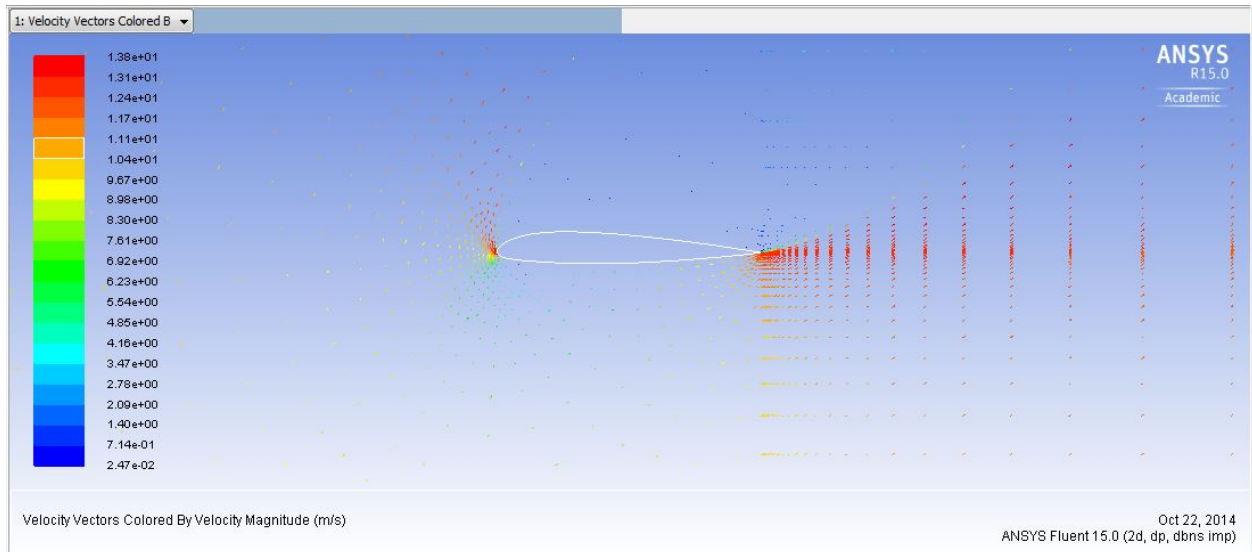


Figure 3. Velocity vectors provide an analysis of the magnitude and direction of flow. Aside from pressure and velocity analysis, the primary function of ANSYS CFD simulation is to determine the coefficients of drag and lift, as shown in Figure 4.

| | | | | | | | | | | | | |
|---------------------------|---------------------------|---------|-----------|-------------------------|---------|------------|---------------------------|--|--|--------------------|--|--|
| Net | (-0.09766157 58.968985 0) | | | (0 0 0) | | | (-0.09766157 58.968985 0) | | | (-0.0019532314 1.1 | | |
| Forces - Direction Vector | (7.071 7.071 0) | | | | | | | | | | | |
| Zone | Forces (n) | | | Coefficients | | | | | | | | |
| airfoil | Pressure | Viscous | Total | Pressure | Viscous | Total | | | | | | |
| | 41.628312 | 0 | 41.628312 | 0.83256625 | 0 | 0.83256625 | | | | | | |
| Net | 41.628312 0 41.628312 | | | 0.83256625 0 0.83256625 | | | | | | | | |
| Forces | Forces (n) | | | Coefficients | | | | | | | | |
| Zone | Pressure | | | Viscous | | | Total | | | Coefficients | | |
| airfoil | (-0.09766157 58.968985 0) | | | (0 0 0) | | | (-0.09766157 58.968985 0) | | | (-0.0019532314 1.1 | | |
| Net | (-0.09766157 58.968985 0) | | | (0 0 0) | | | (-0.09766157 58.968985 0) | | | (-0.0019532314 1.1 | | |
| Forces - Direction Vector | (-7.071 7.071 0) | | | | | | | | | | | |
| Zone | Forces (n) | | | Coefficients | | | | | | | | |
| airfoil | Pressure | Viscous | Total | Pressure | Viscous | Total | | | | | | |
| | 41.766427 | 0 | 41.766427 | 0.83532853 | 0 | 0.83532853 | | | | | | |
| Net | 41.766427 0 41.766427 | | | 0.83532853 0 0.83532853 | | | | | | | | |

Figure 4. A table showing the calculated coefficients of drag and lift using ANSYS CFD simulation.

The airfoils were analyzed around an XY coordinate system to determine the lift & drag coefficients, as well as the pressures and velocity profile at different angles. The given parameters that were used to input data into the simulation are as follows:

- 10 MPH wind velocity
- Tip Speed of 6

From these given parameters and using the ANSYS CFD Simulation, the tangential force required to create the lift, the torque, and the produced power were calculated and recorded.

4.3 Solidworks Modeling

Solidworks was used in conjunction with ANSYS to simulate and design the vertical blades. This program was the primary tool to create 3D models of the design. The 3D drawings done with this program were imported into ANSYS to be further examined using the CFD simulation. After choosing a geometry based on the lift and drag coefficients and how well the blade design performs in a specified fluid flow simulation, 3D models were generated to create renderings for prototype printing. A 3D model of an airfoil sheet shape is shown in Figure 5, along with a picture of the solid shape airfoil design in Figure 6.

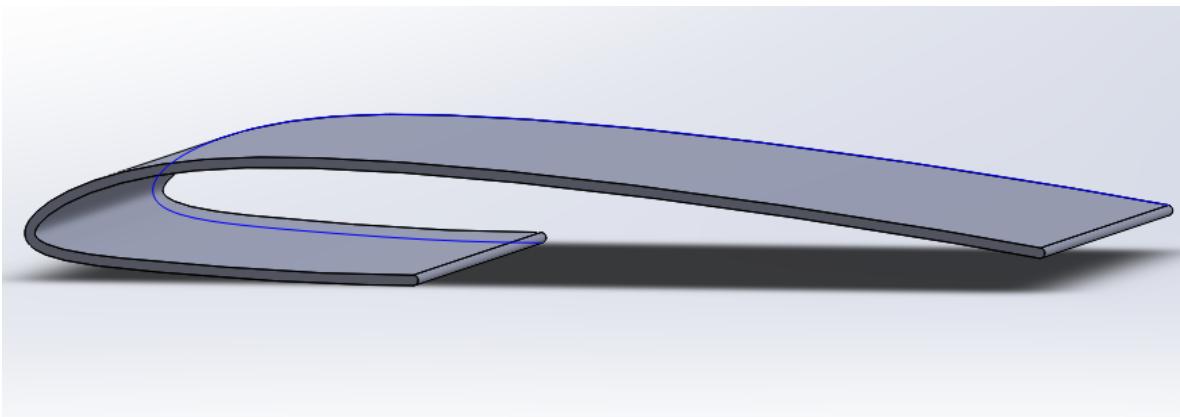


Figure 5. Airfoil sheet design using Solidworks 3D modeling

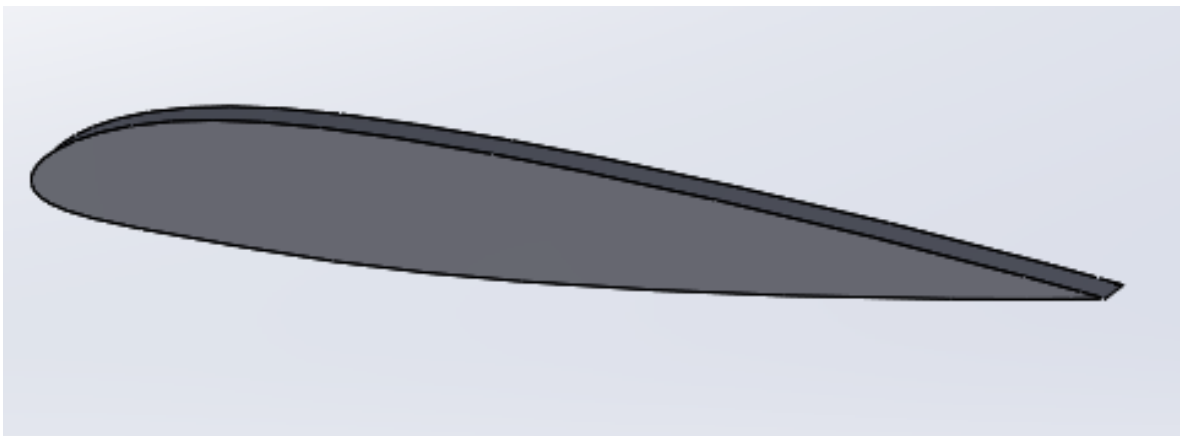


Figure 6. Solid Airfoil design using Solidworks 3D modeling

4.4 Prototype Designs

Two airfoil designs were considered for this project: A solid airfoil shape and an airfoil sheet. Different models were analyzed in order to determine which design would offer more power while keeping it at minimal construction costs.



Figure 7. Solid airfoil design (left), Airfoil sheet design (middle), Base (right)

The vertical axis wind turbine blade was printed to create a prototype. The models were printed out at the Engineering lab design building. The blades were printed with an attached shaft that will be able to assemble with a base. The base, as shown in figure 6, was designed using Solidworks. Along with these, a tapered roller bearing was also assembled with the parts, in order to have a functioning working prototype model.

5. Results

Table 1. Results from solid airfoil shape with a 20% camber using ANSYS CFD Simulation.

| Airfoil 20% Camber | | | |
|---------------------------|----------------------------|--------------------|-----------------|
| Quadrant, Angle | Tangential Force, N | Torque, N*m | Power, W |
| QI, 45 deg | -0.098 | -0.049 | 5.860 |
| Positive 90 deg | 0.225 | 0.112 | 13.487 |
| QII, 45 deg | -0.931 | -0.466 | 55.864 |
| Neg 0 deg | --- | --- | --- |
| QIII, 45 deg | -12.825 | -6.412 | 769.470 |

| | | | |
|----------------|--------|--------|----------|
| Neg 90 deg | -0.259 | -0.129 | 15.519 |
| QIV, 45 deg | -5.469 | -2.734 | 328.120 |
| Positive 0 deg | --- | --- | --- |
| Average | 19.356 | 9.678 | 1161.345 |

Table 2. Results from airfoil sheet shape with a 20% camber using ANSYS CFD Simulation

| Airfoil Sheet 20% Camber | | | |
|---------------------------------|----------------------------|--------------------|-----------------|
| Quadrant, Angle | Tangential Force, N | Torque, N*m | Power, W |
| QI, 45 deg | -1.5215684 | -0.761 | 91.294 |
| Positive 90 deg | 1.3243109 | 0.662 | 79.459 |
| QII, 45 deg | -0.56476753 | -0.282 | 33.886 |
| Neg 0 deg | --- | --- | --- |
| QIII, 45 deg | -13.027246 | -6.514 | 781.635 |
| Neg 90 deg | -4.3652372 | -2.183 | 261.914 |
| QIV, 45 deg | -3.6683675 | -1.834 | 220.102 |
| Positive 0 deg | --- | --- | --- |
| Average | 21.823 | 10.911 | 1309.373 |

6. Discussion

From the calculations and the simulations done for the two models, it was determined that the airfoil sheet has higher power generated than the solid airfoil model. This difference is slightly significant between the two with a 148.0-Watt difference. This is crucial to selecting which model is more suitable for an Alaskan village in terms of construction costs, efficiency, and the power produced of the wind turbine.

7. Conclusion

For the purpose of this project, two different airfoil shapes were analyzed to determine which of the two are better contenders to being implemented into an Alaskan village. Selecting an airfoil shape that will be designed into a vertical axis wind turbine blade depended on factors that will benefit the village in terms of construction costs, efficiency, and the power produced by the wind turbine. From the simulation data collected, it was determined that an airfoil sheet shape is a better choice for the wind turbine blade design because of its higher produced power generated and its cost friendly construction materials compared to the solid airfoil shape.

References

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Wind tunnel and numerical study of a small vertical axis wind turbine:

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Horizontal vs Vertical:

http://apps.webofknowledge.com/full_record.do?product=UA&search_mode=Refine&qid=2&SID=3AYBZ8jMul4vEEP3Co4&page=2&doc=18