

Design of an Alternative Hybrid Vertical Axis Wind Turbine

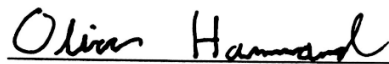
A Major Qualifying Report Submitted to the Faculty of the

WORCESTER POLYTECHNIC INSTITUTE

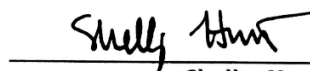
In partial fulfillment of the requirements for the

Degree of Bachelor of Science

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Abstract

The goal of this project was to design a vertical axis wind turbine for urban use. Throughout this project, wind velocities were monitored using anemometers located on buildings at Worcester Polytechnic Institute. Using the analyses of wind velocities in this urban location and evaluations of different turbine types with respect to these wind characteristics, it was determined that a new type of turbine should be created. It was determined that a turbine that incorporated both lift and drag would be beneficial. The design of this turbine included airfoils along with a shroud for protection and increased wind velocities. The overall design was created, manufactured, and tested.

Capstone Design Experience ABET Requirement

To fulfill the requirements for a Major Qualifying Project (MQP), this project must meet the requirements for a capstone design experience. The Accreditation Board for Engineering and Technology (ABET) defines this as an “experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political”¹. For this project, a vertical axis wind turbine was designed, which included airfoils, a shroud, a cam track, and a mounting system. The following considerations were included in the design.

Economic

This project was completed with several economic considerations in mind. The turbine was made out of inexpensive materials, most of which can be purchased locally. Since small turbines do not create a large amount of electricity, this turbine must be inexpensive in order for its electricity generation to offset the purchase cost over time. This fact heavily influenced design and materials decisions.

Environmental/Sustainability

The burning of fossil fuels is not a sustainable way to generate energy, and it has been causing great harm to the environment. Any contribution to the field of green energy, such as wind turbines, can help to shift energy production away from fossil fuels and toward renewable resources. This turbine is designed for small scale, urban applications,

¹ (Worcester Polytechnic Institute n.d.)

which is not a place where they are currently utilized to any significant degree. Expanding this market would decrease cities' reliance on traditional energy sources, creating a more sustainable and environmentally friendly energy environment there.

Manufacturability

Manufacturability was taken into consideration for every aspect of the design. The ease and cost of manufacturing, as well as the availability and cost of materials, all influenced design decisions. The turbine has potential to be created by any person with some degree of mechanical aptitude because of its simplistic design.

Health and Safety

Health and safety were also considered in the design. One reason for the addition of the shroud was to improve the safety of the turbine by enclosing all of the moving parts. Decisions on materials included thought of their safety and toxicity, and the less harmful options were chosen. Also, an airfoil was chosen which would not increase its speed greatly in high winds, thereby lowering the risk of the turbine breaking during storms.

Fulfillment of Majors

This report represents the work of three WPI undergraduate students submitted to the faculty as evidence of completion of a degree requirement. The members of this project consisted of an Environmental Engineer, a Physics/Civil Engineer, and a Mechanical Engineer. Below is the breakdown of how it satisfied each of the majors.

Civil and Environmental Engineering

The major aspects of this project that related to Civil and Environmental Engineering included wind analysis and turbine design. The wind analysis consisted of data

collection from the anemometers and data analysis with Microsoft Excel and WASP. Wind patterns were discerned for this urban environment, and were taken into consideration in the turbine design. In addition, the positive environmental impact of using turbines instead of fossil fuels goes along with the civil and environmental engineering major. Turbines like the one designed in this project would help expand the market for renewable wind energy and help to decrease the need for fossil fuels.

Engineering Physics

Almost all aspects of this project related to Engineering Physics, including the wind analysis and the examination of turbine, airfoil and shroud designs. The movement of air in the atmosphere (wind), as well as around objects like airfoils and shrouds, are all complex events described by physics. These concepts were combined with engineering tasks such as shroud design and CFD analysis, airfoil evaluation, and design of the cam track.

Mechanical Engineering

The aspects of this project that related to Mechanical Engineering include the overall design and construction of the turbine, shroud, and airfoils. The design of the airfoils was done using fluid mechanics, and the manufacturability of the airfoils was done using engineering mechanics. The design of the turbine required analyses involving engineering mechanics, and the design of the shroud required analyses involving fluid mechanics. Major engineering components included airfoil evaluation and overall manufacturing of the turbine, along with with the modeling of the turbine and mounting system for manufacturing purposes.

Acknowledgements

We would like to thank:

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For his guidance with equipment, data collection, and expertise in the wind lab and how it works.

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For inspiring this project and allowing for us to see his creations.

Table of Contents

1.	Introduction	1
1.1	Problem.....	2
1.2	Goal, Objectives, and Approach.....	3
2.	Background	5
2.1	Types of Renewable Energy	5
2.2	Wind Farming.....	6
2.3	Wind Power Availability.....	6
2.4	Current Use of Wind Power	9
2.5	WAsP.....	10
2.6	ArcGIS.....	10
2.7	How Power is Generated	11
2.8	Power Estimation	11
2.9	Type of Turbines	14
2.9.1	Horizontal Axis Wind Turbines.....	14
2.9.2	Vertical Axis Wind Turbines	15
2.10	Turbine Designs.....	15
2.10.1	Savonius Turbine Type	15
2.10.2	Darrieus Turbine Type.....	16
2.10.3	Gorlov Helical Turbine Type	18
2.11	Turbine Enclosures and Shrouds.....	19
3.	Methodology.....	23
3.1	Analyzing Wind Patterns.....	23
3.2	Comparing Turbine Types	24
3.2.1	Manufacturing the Turbine.....	24
3.3	Analyzing Blades	25
3.3.1	Airfoil Stall	26
3.3.2	Manufacturing the Blades.....	28
3.4	Design of the Shroud.....	28
3.4.1	Manufacturing the Shroud.....	29
3.5	Testing the Chosen Turbine	29
4.	Results.....	30

4.1	Wind Analysis Results	30
4.2	Turbine and Shroud Development.....	42
4.2.1	Turbine Design	42
4.2.2	Airfoil Design	52
4.2.3	Shroud Design	54
4.2.4	Final Assembly.....	59
4.2.5	Manufacturing.....	64
4.3	Testing Results	66
5.	Conclusions and Recommendations	68
6.	Bibliography	70
7.	Appendix	72
7.1	Additional Figures from Shroud Analysis	72
7.2	Photos of the Turbine	78

Table of Figures

Figure 1: United States Annual Average Wind Speed (30 Meters).....	7
Figure 2: Annual Average Wind Speed (80 Meters).....	8
Figure 3: Massachusetts Wind Power (50 meters).....	9
Figure 4: Approximate Tip Speed Ratio vs. Power Coefficient for different blade types	14
Figure 5: How a Savonius rotor works	16
Figure 6: Workings of a lift-type VAWT	17
Figure 7: CAD model of a Gorlov Helical Blade VAWT	19
Figure 8: Airflow in and out of a shrouded wind turbine (figure created by MQP group)	20
Figure 9: Enclosure setup used by Holak and Mourkas	21
Figure 10: Sample results from Holak and Mourkas: Six-blade turbine with four different enclosures	22
Figure 11: Airfoil design stall.....	27
Figure 12: Wind Potential surrounding WPI, scale 1:15,000m	31
Figure 13: Locations of WPI buildings with anemometers	32
Figure 14: Campus Center Wind Speed Data.....	33
Figure 15: East Hall Data from 2011-2013 over varying months.....	34
Figure 16: Wind Rose of Green Roof Data from September to October 2013	35
Figure 17: Wind rose for 210°	36
Figure 18: Daniels Hall Wind Speed Data.....	37
Figure 19: Daniels Hall Wind Speed Histogram	38
Figure 20: Campus Center Wind Speed Histogram.....	38
Figure 21: Daniels Hall Reynolds Number Histogram	41
Figure 22: Campus Center Reynolds Number Histogram	41
Figure 23: East Hall Reynolds Number Histogram	42
Figure 24: Hybrid VAWT.....	44
Figure 25: Model of the mixed design without airfoils.....	46
Figure 26: Spring loaded cam concept.....	48
Figure 27: Blade with cam follower	48
Figure 28: Lift Path	50
Figure 29: Drag Path.....	50
Figure 30: Full Path	51
Figure 31: Graph of the angle of attack of the blade through one rotation.....	52
Figure 32: Modified OAF095 airfoil used	54
Figure 33: Preliminary Shroud Design.....	55
Figure 34: Funneled Shroud Design	56
Figure 35: Drawing of the final shroud design.....	57
Figure 36: CFD results for the final shroud design (shroud #26)	58
Figure 37: Complete turbine model.....	59
Figure 38: Exploded view of the mounting system.....	60
Figure 39: Exploded view of the components for blade rotation.....	61
Figure 40: Drawing of parts relating to blade rotation	62

Figure 41: Profile view of the turbine showing height	63
Figure 42: Plan view of the turbine with dimensions	63
Figure 43: Shroud #10 Fluent Analysis.....	72
Figure 44: Shroud #11 Fluent Analysis.....	73
Figure 45: Shroud #12 Fluent Analysis.....	73
Figure 46: Shroud #17 Fluent Analysis.....	74
Figure 47: Shroud #22 Fluent Analysis.....	74
Figure 48: Shroud #23 Fluent Analysis.....	75
Figure 49: Shroud #25 Fluent Analysis.....	75
Figure 50: Shroud #27 Fluent Analysis.....	76
Figure 51: Shroud #28 Fluent Analysis.....	76
Figure 52: Shroud #30 Fluent Analysis.....	77

1. Introduction

Traditional energy sources, such as non-renewable coal and oil, are burned to produce energy. This process creates a negative impact on the environment, primarily through the release of greenhouse gases and, to a smaller extent, toxic gases. These gases can affect the climate and the air quality of the Earth. Because these fossil fuels are being depleted, the principal investigators are exploring the use of green energy as an alternative to non-renewable energy resources.

Green energy or Eco energy are terms used to describe energy produced or generated by natural, renewable resources that cause minimal negative impacts to the environment. Wind, solar, geothermal, hydro, and bio energy are all considered green. Green energy involves generating power from natural phenomena like wind, sunlight, tides, plants and geothermal heat generated deep within the earth. For example, wind power can be harnessed by allowing the wind to rotate turbines, and converting the rotational energy to electricity. Large turbines can be connected to a system where power is collected, stored and distributed, in some cases powering entire communities. Sustainable alternatives and green energy resources account for almost 16 percent of global energy consumption today and are growing steadily².

Clean energy resources use the Earth's natural energy flows, which cause minimum negative environmental impact. Developing green energy mainly aims at generating power while creating minimal waste and pollution. The globally changing economic and environmental conditions have forced some nations and organizations to rearrange their

² (Green Energy From Natural and Renewable Resources 2013)

strategies, moving slowly away from the conventional burning of fossil fuels and working towards a lower carbon existence. The primary goal of developing and promoting alternative, renewable sources of energy is to reduce energy costs and greenhouse gas emissions³.

1.1 Problem

While progress has been made to advance the technology required to create an efficient large-scale wind turbine, such turbines cannot be used in all locations due to space and financial limitations. In these areas, more affordable turbines, sized to power individual homes, are necessary. Urban areas are excellent examples of space-limited regions; here space is limited to the extent that a turbine must be mounted on roofs of buildings. Such turbines are currently on the commercial market, however, they generally are expensive and do not create sufficient power to offset the cost of such a device over its lifetime. A rooftop turbine designed for an urban environment that is more efficient and less costly to manufacture would be an excellent energy production option for consumers. There is a need for such a turbine to be developed to allow residents in urban areas a better renewable energy option.

Previous MQPs have investigated the practicality of shrouded Vertical Axis Wind Turbines and VAWTs for urban use in general. One past MQP, *Vertical Axis Wind Turbine Evaluation and Design* by Deisadze, et al. (2013), focused on the effect of a shroud on the power output of simple Savonius and Darrieus turbine blades. The project also investigated vibrations in the turbine and how those would be transmitted to a roof. In another past MQP, *Enclosed Wind Turbines* by Brandmaier, et al. (2013), different shroud

³ (Green Energy From Natural and Renewable Resources 2013)

designs were compared on a turbine with flat blades. Neither of these MQPs investigated blade design and both chose basic blades for testing^{4,5}. Since the type, size, and particular design of turbine blades has a large effect on the efficiency of a turbine, it is an area that should receive further consideration⁶.

1.2 Goal, Objectives, and Approach

The goal of this project is to design and develop a vertical axis wind turbine (VAWT) for urban residential use. The VAWT will be designed to operate in conditions with wind patterns found in urban settings and will be sufficiently mechanically efficient to be a viable option for consumers. While optimizing the VAWT for urban settings, special attention will be paid to the type and design of the blades, since that is the most variable component of the system. In order to accomplish this goal, the following objectives will be addressed:

1. Analyze wind patterns and characteristics in an urban environment.
2. Evaluate various turbine blade designs to predict which would be best for urban households based largely on efficiency but also on the following factors:
vibrations, noise, esthetics, reliability, manufacturability and cost to build.
3. Determine the efficiency of the best blade design(s) by manufacturing them, creating an experimental setup, and performing testing.

The background research on wind power availability, wind turbines, and wind turbine blade design. The past MQPs were helpful in this regard, as they provided information on wind patterns, along with general equations that will be used during the initial investigation of blade types.

⁴ (Brandmaier, et al. 2013)

⁵ (Deisadze, et al. 2013)

⁶ (Ragheb and Ragheb, Wind Turbines Theory - The Betz Equation and Optimal Rotor Tip Speed Ratio 2011)

The collection and analysis of data from wind anemometers around the WPI campus helped in characterizing wind patterns and determining which turbine types were worth investigating. Since the design did not have to include a shroud, there was a wide range of possibilities for blade types. Each was evaluated, taking not only efficiency into account but also vibrations, noise, manufacturability, esthetics, reliability, and other factors. Then, using this information, the best turbine was chosen and specific blade types were evaluated for use in that turbine. Finally, the best complete turbine design was chosen, prototyped, and tested in an outdoor environment to accurately evaluate its efficiency. The wind analysis, design conclusions, and testing results can be found in Section 4.

2. Background

The United States currently relies heavily on coal, oil, and natural gas for energy. Fossil fuels are non-renewable and are becoming too expensive and environmentally damaging to retrieve. There are a variety of alternative energy resources which are renewable, such as wind and solar energy. These other resources are constantly replenished and will never run out. Wind is a clean source of renewable energy that produces no air or water pollution. This energy is needed to provide an alternative power source for everyday life. Since the only major cost involved in producing energy from wind is the initial construction and installation of the turbine, wind energy has the potential to lower energy costs while it provides a more sustainable means of producing energy⁷.

2.1 Types of Renewable Energy

There are five main types of renewable energy: solar, geothermal, biopower, hydro power, and wind⁸. These energy types will be the future to a cleaner more energy efficient world.

Wind power captures the wind in the atmosphere and converts it into mechanical energy then into electricity. There are three main types of wind power; utility-scale wind, distributed or small wind, and offshore wind. Utility-scale wind describes wind turbines larger than 100 kilowatts. The electricity from these turbines is delivered to a power grid and distributed to the user by electric utilities or power system operators. Distributed wind is wind which uses turbines of 100 kilowatts or smaller to directly power a home, farm or

⁷ (Wind 101: The Basics of Wind Energy 2013)

⁸ (Green Energy From Natural and Renewable Resources 2013)

small business for its primary use. Last, offshore wind is wind power that consists of wind turbines that are set up in bodies of water around that world⁹.

2.2 Wind Farming

A wind farm is a group of wind turbines located in the same area and that are used to produce energy. A large wind farm may consist of hundreds of individual wind turbines and may cover hundreds of square miles, but the land between the turbines may be used for agricultural or other purposes. Compared to the environmental impact of traditional energy sources, the impact of wind power is relatively minor. Wind power consumes no fuel and emits no air pollution. The energy needed to manufacture and transport the materials required to build a wind farm is equivalent to the energy produced by the farm after just a few months.

2.3 Wind Power Availability

New installations place the U.S. on a trajectory to generate 20 percent of the nation's electricity by 2030 solely from wind energy. Growth in 2008 put \$17 billion into the economy, positioning wind power as one of the leading sources of new power generation. Wind projects completed in 2008 also accounted for about 42 percent of the entire new power-producing capacity added in the U.S. during the year. Wind power in the U.S. provides enough electricity to power the equivalent of nearly 9 million homes, avoids the emissions of 57 million tons of carbon each year, and reducing expected carbon emissions from the electricity sector by 2.5 percent¹⁰.

⁹ (RenewableEnergyWorld.com 2013)

¹⁰ (Wind 101: The Basics of Wind Energy 2013)

Figure 1 shows the predicted average annual wind speeds at a 30 meter height. Areas with good exposure to prevailing winds and annual average wind speeds around 4 meters per second or greater at a 30 meter height are generally considered to have a suitable wind resource for small wind projects. Small wind turbines are typically installed between 15 and 40 meters high¹¹.

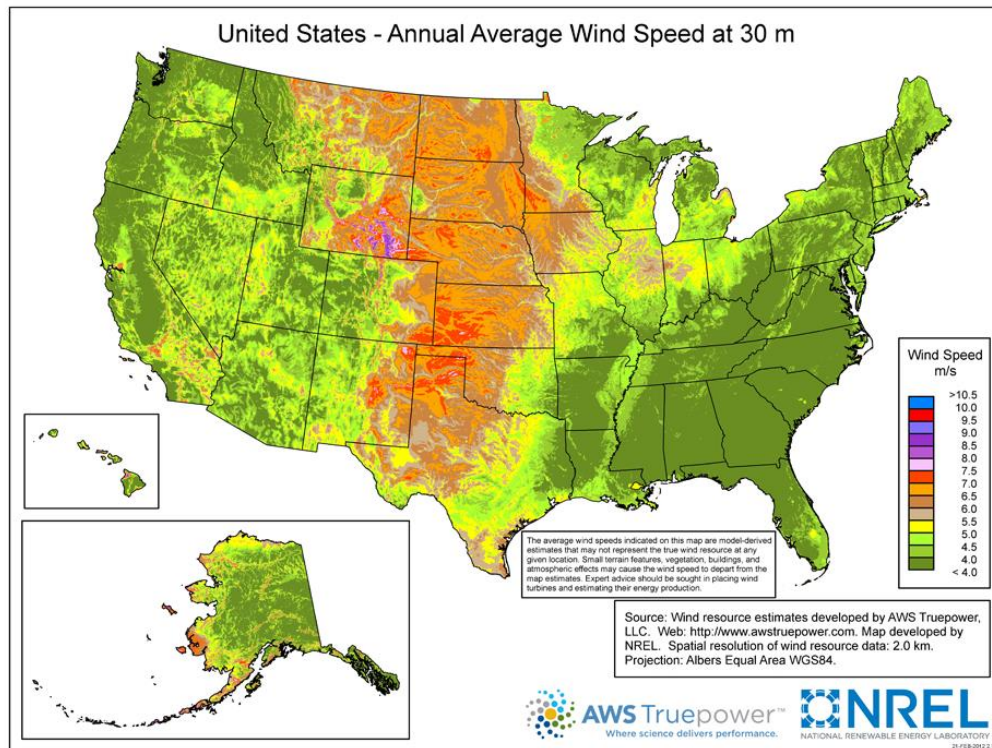


Figure 1: United States Annual Average Wind Speed (30 Meters)¹²

Figure 2 shows the predicted average annual wind speeds at a height of 80 meters. Areas with annual average wind speeds around 6.5 meters per second and greater at an 80 meter height are generally considered to have a wind resource suitable for wind

¹¹ (Stakeholder Engagement Outreach 2010)

¹² (Stakeholder Engagement Outreach 2010)

development. Utility-scale, land-based wind turbines are typically installed between 80 and 100 meters high¹³.

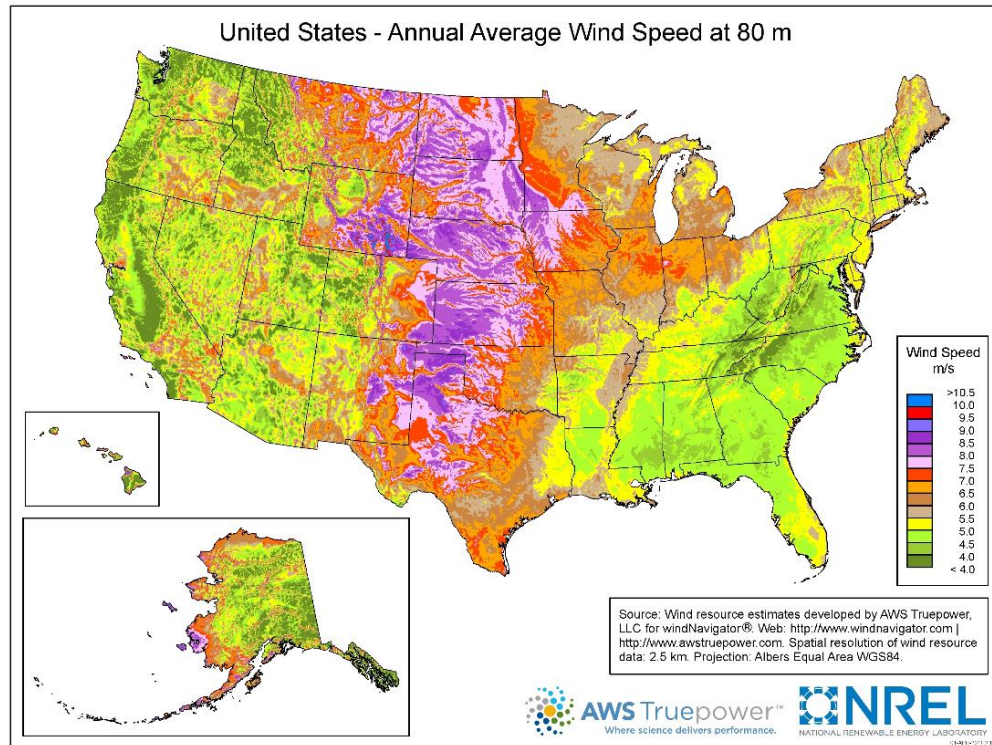


Figure 2: Annual Average Wind Speed (80 Meters)¹⁴

Figure 3 shows the available wind power in Massachusetts and the estimated density at 50 meters above ground. It also depicts the areas that could be used for community-scale wind development using wind turbines at 50 to 60 meter heights. These are generally along the coastline, with some isolated locations in mountainous sections of the state.

¹³ (Stakeholder Engagement Outreach 2010)

¹⁴ (Stakeholder Engagement Outreach 2010)

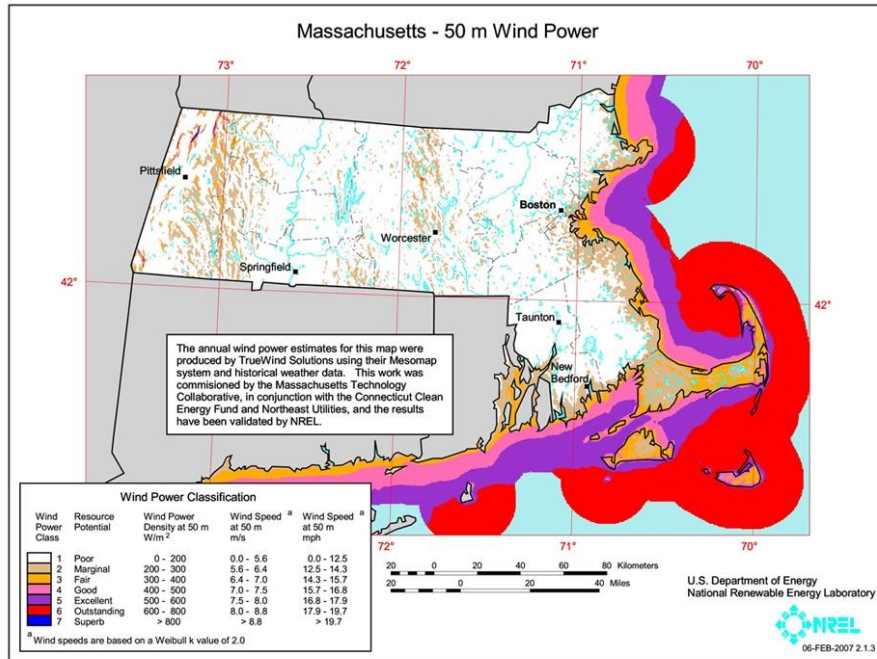


Figure 3: Massachusetts Wind Power (50 meters)¹⁵

2.4 Current Use of Wind Power

Small-scale wind turbines are a 156 million dollar industry with numbers growing by the year. The benefits of home wind systems are numerous and include: independence from the electric grid, fast payback periods, and demonstrating that 20 percent wind power (which is the government's stated goal for the country's energy mix for 2030) can be achieved by any individual in less than a year¹⁶.

Up above the rooftops wind flows are relatively unimpeded, but wind behaves very differently near built structures such as houses or other large buildings. This is because the turbines cause turbulence at roof level so living in or near a metropolitan area means that

¹⁵ (Stakeholder Engagement Outreach 2010)

¹⁶ (Trimble 2013)

installing a wind turbine is likely not an option¹⁷. Therefore, these rooftop turbines are currently more suited to rural areas where wind flow is open and unobstructed by surrounding buildings, sculptures, or trees.

2.5 WAsP

Wind Atlas Analysis and Application Program (WAsP) is a computer program that utilizes user inputted wind data to predict wind climates, map wind resources, and calculate power productions from wind turbines and wind farms. The program was developed by DTU Wind Energy in Denmark, and is now the worldwide industry standard software for wind resource assessment and siting of wind turbines. While it is usually used in rural areas, it does include complex terrain flow, roughness, and sheltering obstacles model which makes it adaptable for urban areas¹⁸.

2.6 ArcGIS

ArcGIS is a geographic information system (GIS) that integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information. GIS allows users to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. The data layers that were used in the creating of this map included various maps that had previously been uploaded to WPI's server. In order to estimate the greatest wind potential near WPI a map entitled "Wind Power Availability" was obtained from ArcGIS's online resources.

¹⁷ (Trimble 2013)

¹⁸ (WAsP - the Wind Atlas Analysis and Application Program 2013)

2.7 How Power is Generated

Wind turbines serve as a means to convert the kinetic energy of wind into power. This process begins when wind contacts the turbine blades and transfers some of its kinetic energy to them, forcing them to rotate. Since the blades are connected to the main shaft through the rotor, the shaft rotates as well, creating mechanical energy. The main shaft is usually connected to a gear box which rotates a parallel shaft at about 30 times the rate of the main shaft. At high enough wind speeds, this amplification creates sufficient rotational speeds for the generator to produce electricity. Most generators used in wind turbines are off-the-shelf and use electromagnetic induction to produce an electrical current¹⁹. These generators consist of an assembly of permanent magnets surrounding a coil of wire. The shaft connects to the magnet assembly, spinning it around the stationary coil of wire and creating a voltage in the wire. The voltage is what drives the electrical current out of the wire and into power lines to be distributed²⁰.

2.8 Power Estimation

The electrical current produced by a wind turbine is quantified in terms of power, usually in units of watts or kilowatts. Equations have been developed for the purpose of predicting the amount of power a wind turbine will generate. The influence of variables such as wind speed, turbine radius, and rotor rotational speed on the power output has been explored in past research and the resulting equations are presented below.

¹⁹ (How Wind Turbines Generate Electricity 2013)

²⁰ (Layton 2013)

Equation (1) provides a means for calculating the approximate amount of power produced by a turbine; where P = Power [W], ρ = Air density [kg/m^3], A = Swept area [m^2], V = Wind speed [m/s], and C_p = Power coefficient.

$$P \approx \frac{1}{2} * \rho * A * V^3 * C_p \quad (1)$$

Ideally, power scales linearly with the area swept out by the turbine blades, and cubically with the speed of the wind as it contacts the blades. However, these relationships have some variation depending on the design of each particular turbine²¹. The power coefficient at the end of the equation accounts for the efficiency of the turbine in converting the wind's kinetic energy into mechanical energy. The theoretical maximum power coefficient, or Betz limit, is 0.59. However, most wind turbines operate at a power coefficient of less than 0.45. Beyond that loss in efficiency, there are also small losses resulting from the gearbox, bearings, and generator²².

As shown in (2), the power can also be estimated using the estimated torque (τ , [$\text{N}\cdot\text{m}$]) and experimental data for the rotational speed of the rotor, ω , in rad/s ²³.

$$P = \tau * \omega \quad (2)$$

For turbines which use drag forces (not lift forces), (3) can be used to estimate the amount of torque in the system, where R is the radius of turbine in meters²⁴.

$$\tau = \frac{1}{2} * \rho * V^2 * A * R \quad (3)$$

²¹ (Brandmaier, et al. 2013)

²² (npower n.d.)

²³ (Brandmaier, et al. 2013)

²⁴ (Brandmaier, et al. 2013)

By combining (2) and (3), the power generated experimentally can be compared to the predicted power generation from (1). This would approximate whether or not the predicted power efficiency was met.

The tip speed ratio, λ , defines the relationship between blade tip speed and incident wind speed²⁵. The expression used to calculate it is shown in (4).

$$\lambda = \frac{\omega * R}{V} \quad (4)$$

Figure 4 shows the relationship between the tip speed ratio and the power coefficient for various blade types. For each type, there is a unique curve, and therefore a unique optimal tip speed ratio which corresponds to the maximum power coefficient that can be achieved. For example, a Savonius rotor will produce a maximum power coefficient of about 0.31 at a tip speed ratio of about 0.9. However, a Darrieus rotor produces a maximum power coefficient of around 0.35 at a much higher tip speed ratio of around 5.8. To be most efficient, a blade and rotor should be designed to perform near its optimal tip speed ratio at wind speeds it is likely to encounter²⁶.

²⁵ (Deisadze, et al. 2013)

²⁶ (Ragheb and Ragheb, Wind Turbines Theory - The Betz Equation and Optimal Rotor Tip Speed Ratio 2011)

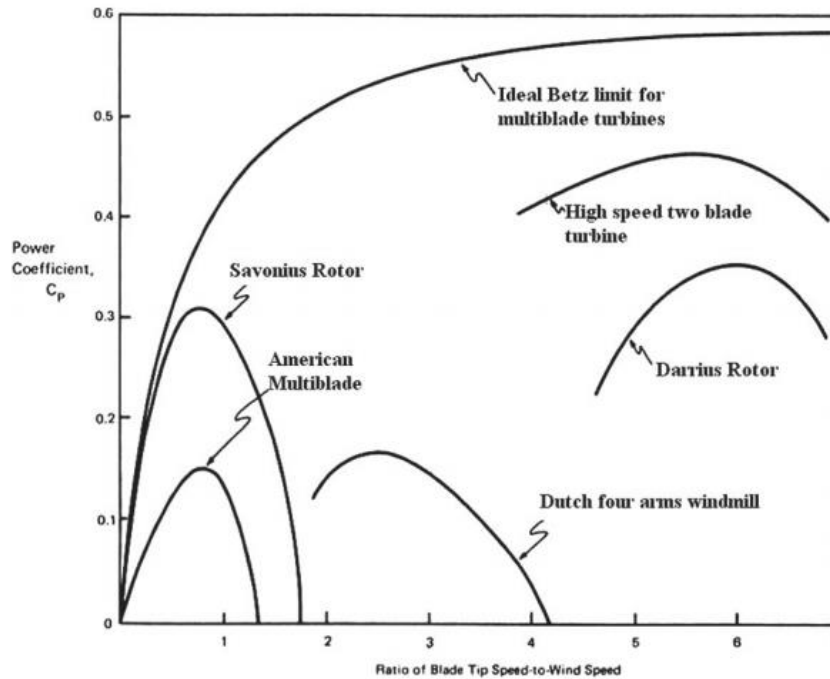


Figure 4: Approximate Tip Speed Ratio vs. Power Coefficient for different blade types

2.9 Type of Turbines

2.9.1 Horizontal Axis Wind Turbines

Turbines generally can be grouped into one of two categories: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). Horizontal axis wind turbines are what is commonly thought of when someone is talking about a wind turbine²⁷. The horizontal axis wind turbine can be visualized as a conventional box fan, a set of blades connected to a shaft that is parallel to the ground; however, the function of the turbine is the opposite of a box fan. It normally consists of two to three blades²⁸ connected to a shaft that is connected to a generator which will produce energy from the shaft work. There are two main types of HAWTs, ones that face into the wind and ones that face away from the

²⁷ (Eriksson, Bernhoff and Leijon 2006)

²⁸ (U.S. Department of Energy 2013)

wind²⁹. Turbines that face into the wind require a rudder or some other type of mechanism to be able to self-orientate to face the incoming wind. Those that face away from the wind do not need this rudder to self-orientate, however they suffer from a vibration due to the support tower blocking part of the wind flow.

2.9.2 Vertical Axis Wind Turbines

Vertical axis wind turbines operate on the same principle of converting rotational movement due to wind into shaft work, which is then converted into electricity through the use of a generator. VAWTs contain a shaft that is perpendicular to the ground (as opposed to the parallel shaft used by the HAWT). Unlike the HAWTs, the VAWTs can catch the wind regardless of the position that they are facing, which can lead to them being more versatile. Also, VAWTs are able to function in more irregular wind patterns than HAWTs are able to. There are two primary blade designs that are used for VAWTs that operate on different principles: the Savonius type and the Darrieus type.

2.10 Turbine Designs

2.10.1 Savonius Turbine Type

Savonius type blade design uses aerodynamic drag from wind to rotate the blades and produce power. Savonius type blades are rugged and simplistic. This can reduce costs since they are easier to manufacture, need less maintenance, and can last longer in harsher environments. However, they are roughly half as efficient as other lift type (such as the Darrieus) designs³⁰. An example of a Savonius blade type design is seen below in Figure

²⁹ (Ragheb, Wind Energy Converters Concepts 2013)

³⁰ (Halstead 2011)

5³¹. In a simple Savonius turbine, the blades would meet at the center axis, however, in this one, they are offset by a distance e in order to create more power.

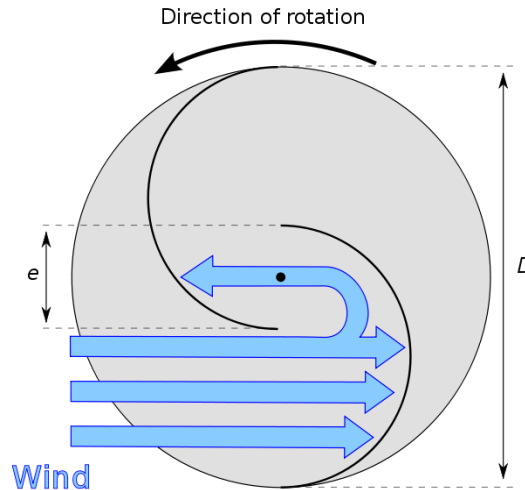


Figure 5: How a Savonius rotor works

2.10.2 Darrieus Turbine Type

Darrieus type blades use lift forces from wind to rotate the blades. The blades have an airfoil shape, and instead of being oriented horizontally as they would be on an airplane, they are oriented vertically. The air that travels along the outside of the curve (what would be the top of a wing) must travel at a greater speed than the air on the inside of the blade. This creates an area of lower pressure on the outside of the blade, and therefore a net force on the blade to the outside. By controlling the angle of the blade, this net force causes the blade to rotate.

There are many different variations of the traditional Darrieus type, also referred to as the “egg-beater” type; these variations include the Giromill (or the “H-Type” Darrieus), the Gorlov helical turbine, and the cycloturbine³². Due to the blade going into the wind as

³¹ (Ugo14 2008)

³² (Aggeliki 2011)

opposed to with the wind (as it does in the Savonius type blade), it can spin faster than the speed of the wind, which results in a higher efficiency. However, this higher efficiency comes with a great cost. The blade is harder to manufacture than a Savonius blade, increasing the cost of production. Also, normal Darrieus type VAWTs are not self-starting, and thus needs to have a motor or other solution to bring it up to a sufficient speed where it can start producing its own energy³³. A simple analysis of how a Giromill type Darrieus wind turbine works can be seen below in Figure 6³⁴.

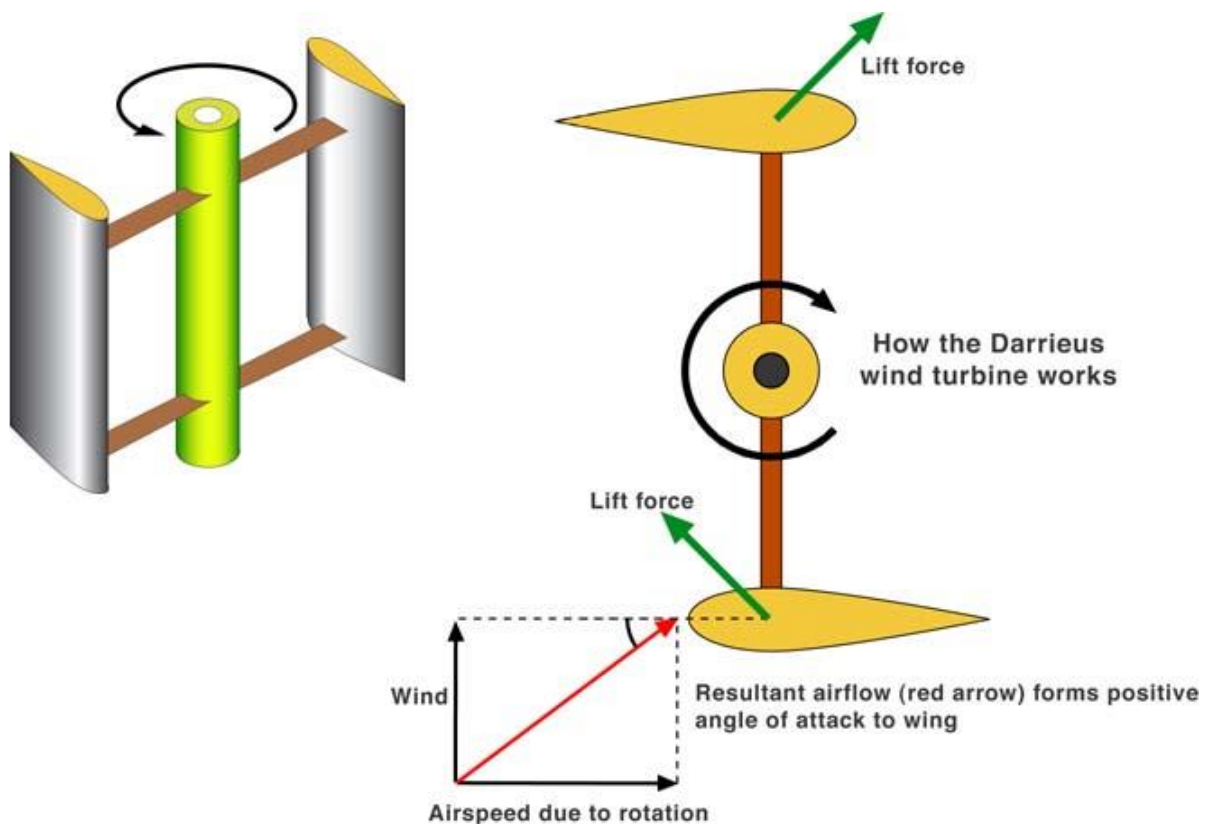


Figure 6: Workings of a lift-type VAWT³⁵

³³ (Ragheb, Vertical Axis Wind Turbines 2013)

³⁴ (GrahamUK 2005)

³⁵ (GrahamUK 2005)

2.10.3 Gorlov Helical Turbine Type

The Gorlov Helical blade type is a derivative of the Darrieus blade type, originally developed by its namesake Alexander M. Gorlov to be used in hydro-power applications. It attempts to solve the problems of vibration and noise in the original Darrieus design by having helical curved blades as opposed to straight blades. In the traditional Darrieus setup, as the blades rotate the angle of attack will change, resulting in areas throughout the rotation where the blade is in a stall. This causes vibration which will reduce the life of the turbine, along with causing noise which is especially unwanted in urban settings. The Gorlov blade type, on the other hand, is curved in a helical fashion, which means that throughout its rotational path, at least part of the blade will not be in a stall, which greatly reduces the vibration and the noise generated. A picture of a Gorlov helical blade type can be seen below in Figure 7.

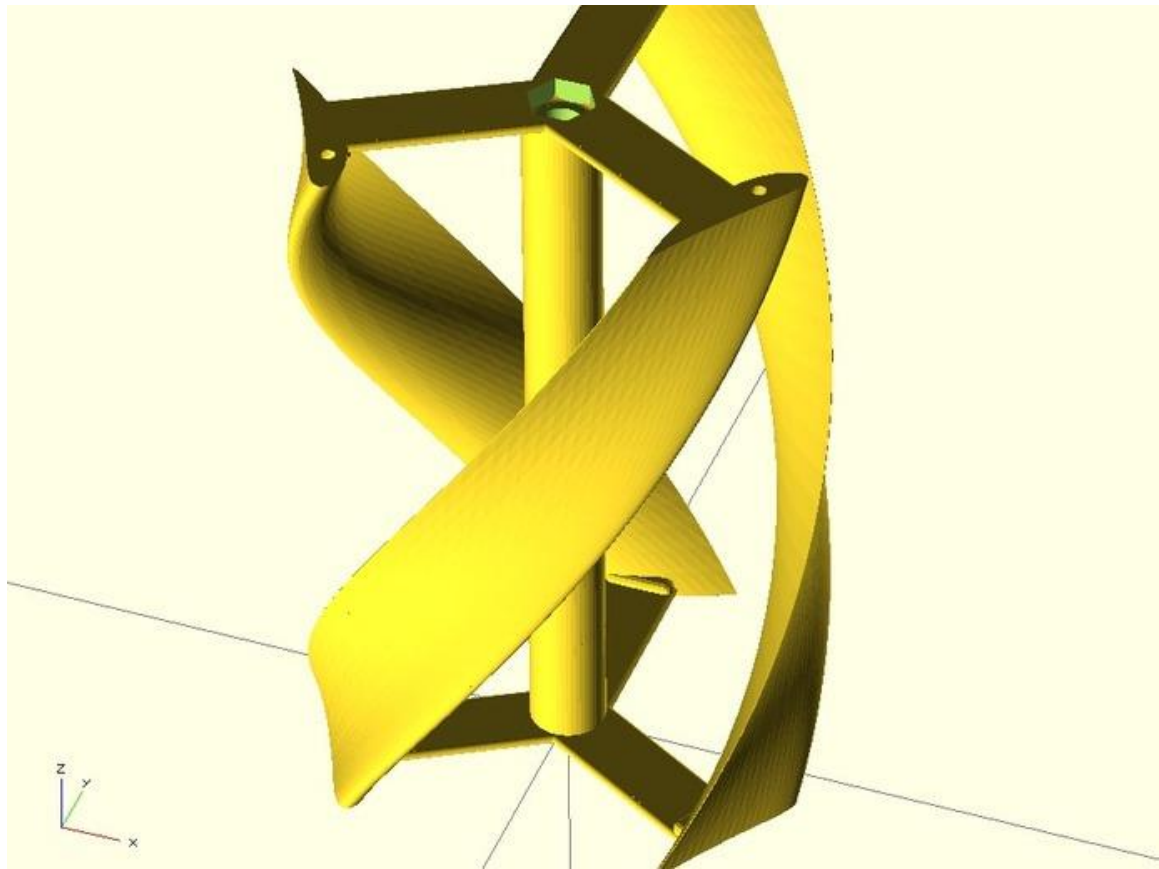


Figure 7: CAD model of a Gorlov Helical Blade VAWT³⁶

2.11 Turbine Enclosures and Shrouds

When designing turbines for maximum efficiency, the design of the blades is not the only aspect that needs to be considered. An enclosure around a VAWT can be designed in such a way that it creates a funnel effect, resulting in an increased airflow to the turbine, thus increasing the rotations per minute³⁷. This enclosure can also have the advantage of eliminating cross winds, and protecting the turbine from environmental hazards such as birds. A simple diagram of a shrouded wind turbine can be seen below in Figure 8.

³⁶ (qharley 2011)

³⁷ (Holak and Mourkas 2012)

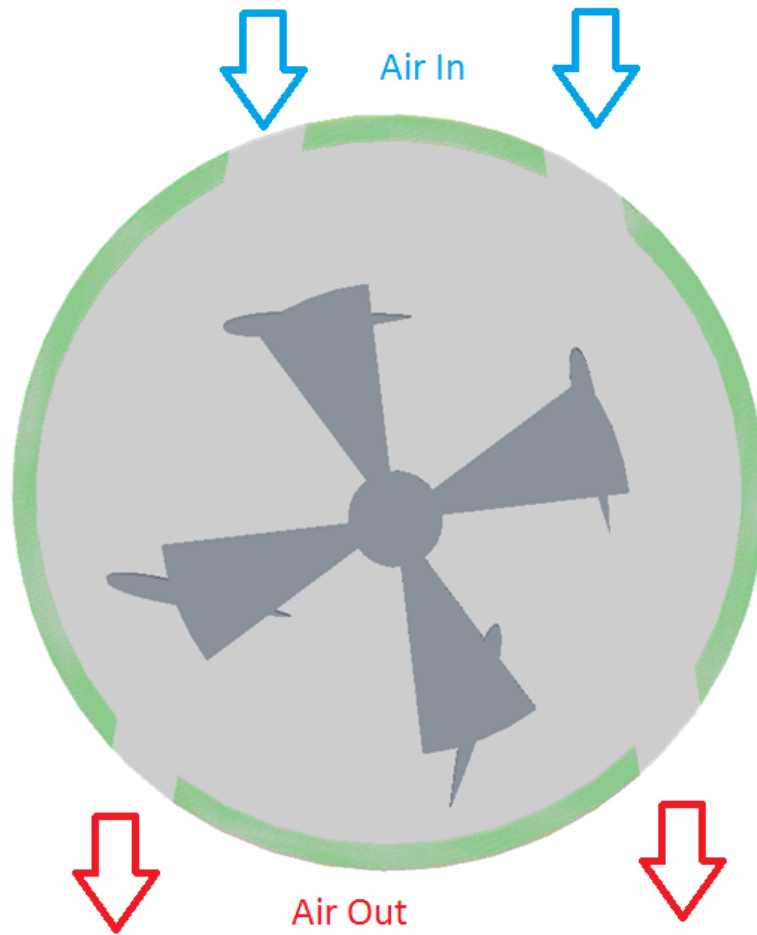


Figure 8: Airflow in and out of a shrouded wind turbine (figure created by MQP group)

Previous MQPs have investigated in length the effectiveness of a shroud on a Savonius drag type VAWT. The enclosure setup used by Holak and Mourkas as described in *Enclosed Vertical Axis Wind Turbines* can be seen in Figure 9.



Figure 9: Enclosure setup used by Holak and Mourkas

Holak and Mourkas found that these shrouds have been shown to have a positive effect on drag type VAWT efficiency. A sample of their results can be seen in Figure 10.

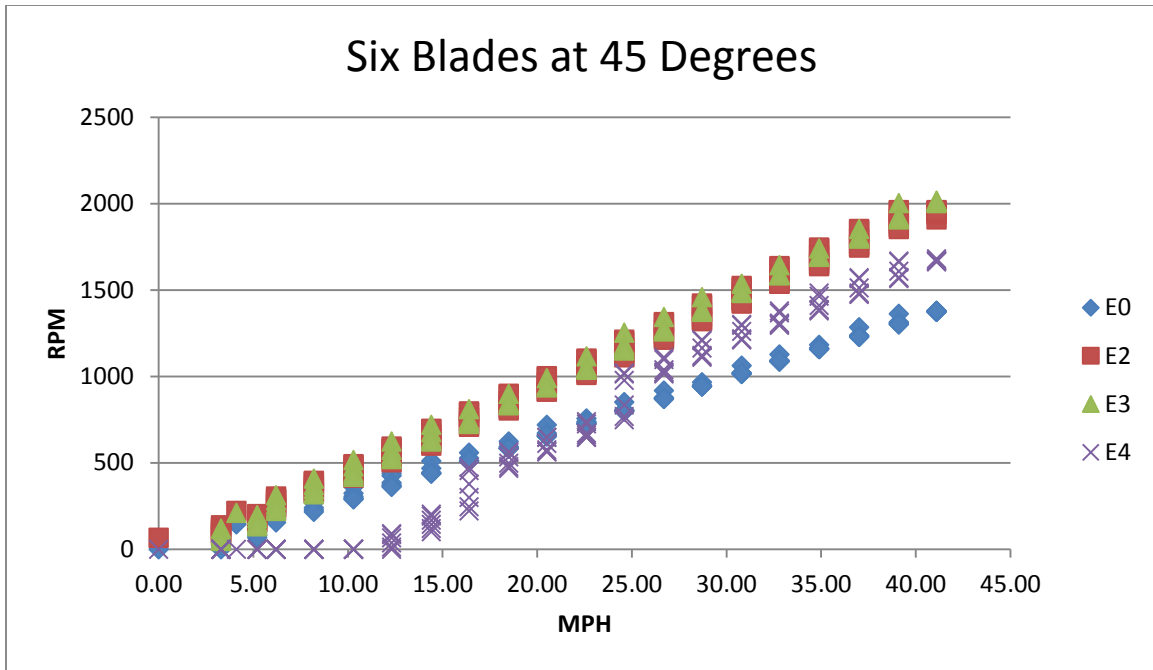


Figure 10: Sample results from Holak and Mourkas: Six-blade turbine with four different enclosures

Here, E0 represents the results when no enclosure was used, and E2, E3, and E4 represent results obtained from using shrouds number 2, 3, and 4 respectively (pictures of these shrouds can be found in Appendix B-1). Although the enclosures did not have a major effect at lower wind speeds, as wind speed increased the enclosures had a noticeable effect.

3. Methodology

The goal of this project was to design and develop a vertical axis wind turbine (VAWT) for urban residential use. The VAWT was designed to operate in conditions with wind patterns found in urban settings, and needed to be sufficiently mechanically efficient to be a viable option for consumers. While optimizing the VAWT for urban settings, special attention was paid to the type of turbine used and then to the design of the blades for that turbine. In order to accomplish this goal, the following objectives were addressed:

1. Analyze wind patterns and characteristics in an urban environment. By gathering data from anemometers atop three campus buildings in various locations.
2. Evaluate various turbine designs to predict which would be best for urban households based largely on efficiency but also on the following factors: vibrations, noise, aesthetics, reliability, manufacturability and cost to build.
3. Determine the efficiency of the best turbine design by manufacturing it, creating an experimental setup, and performing testing.

3.1 Analyzing Wind Patterns

For this project, data were collected from anemometers located on the roofs of three WPI buildings, and analyzed using Microsoft Excel and WASP (wind analysis software package). Excel was used to analyze basic data such as wind speed averages, time graphs, and Reynolds numbers. The WASP software provided information on variation of wind with direction and it provided basic wind information over different types of areas. These data were also used to more accurately predict how different blades would perform in the chosen area, thereby increasing the odds of coming up with an efficient turbine and blade

design. Another program that was used was ArcGIS. The main map used for establishing what wind power potential was available around WPI was entitled “Wind Power Availability” and was retrieved from arcGIS’s online data base. This map represented the annual average wind resource potential for the United States. Wind power class is an indicator of likely resource strength, with a higher wind power class representing higher wind resource levels. The classification information is for utility-scale application was at a 50 meter height.

3.2 Comparing Turbine Types

Three different types of turbines were investigated; drag, lift, and hybrid. The advantages and disadvantages of each turbine type and corresponding blade type (Savonius and Darrieus) were considered. The results from the wind analysis were used to determine which attributes were of greatest concern in the design, and a turbine type was chosen based on that. A specific design was modeled using two Computed Aided Design programs, Solidworks and Creo, with consideration of the estimated performance in the predicted wind conditions as well as the manufacturability of the design. In the end, the turbine was designed to utilize both lift and drag dynamics, which meant that airfoils were used (see section 3.3) and new shroud designs were investigated (see section 3.4).

3.2.1 Manufacturing the Turbine

Since this turbine was a custom design, the major parts were built from raw materials. Aluminum was bought from suppliers such as McMaster-Carr and Metals Depot. These materials were cut and then machined and/or welded to make the major components of the turbine. Haas CNC machines (VM2 and VF4) owned by WPI were used to mill out specific shapes for some components. Various bearings and standard fasteners

were used to hold the turbine together and allow it to spin. More details about the manufacturing and assembly can be found in sections 4.2.4 and 4.2.5, respectively.

3.3 Analyzing Blades

In order to quickly analyze a large amount of airfoils, a program called QFils was created by the team. QFils is based off of the program xflr32 and is available for download at <https://sourceforge.net/projects/qfils/>. This program imports multiple airfoil geometries and for each airfoil it then computes the coefficient of lift over the coefficient of drag (C_l/C_d) for the set range of angle of attacks (AoAs) at each given Reynolds number. Using these calculations it then computes an expected C_l/C_d score (the C_l/C_d at each Re multiplied by the probability that the wind speed will result in that Re) and a bucket score (the arithmetic mean of the C_l/C_d at the optimum angle of attack ± 2 deviations). From these two scores an overall score is calculated (the mean of the expected C_l/C_d score and the bucket score), which is treated as the final score for the airfoil. A results file for each airfoil is created with all of the calculated C_l/C_d ratios and the C_l/C_d score, bucket score, and overall score. It also creates a deviation score which is the sum of the change of the optimum angle of attacks between sequential Reynolds numbers. Part of the QFils package then takes the results and creates a spreadsheet that has all of the airfoils in descending order by score and for each also shows the deviation score. From those results, 12 candidates were chosen by prioritizing the highest score while taking into account the deviation score, blade thickness, and the overall ease of manufacturability. Each of these airfoils was then placed into QBlade and graphs were generated displaying the C_l/C_d vs. AoA, C_m vs. AoA, and the C_l vs. C_d . After combining this information with the blades'

geometry, manufacturability, best angles of attack, and deviation scores, an optimal airfoil was chosen for this application.

3.3.1 Airfoil Stall

An important aspect to take into account in the design of an airfoil is its performance in high winds. As wind speed increases, the rotation speed will increase, and if no precautions are taken then the wind turbine can spin out of control and be destroyed. No mechanical or electrical systems were included, so a design point stall was created to prevent such an event. This was done by choosing an airfoil that would reach a point where an increase in Reynolds number would only result in a small increase in C_l/C_d . This can be seen in Figure 11.

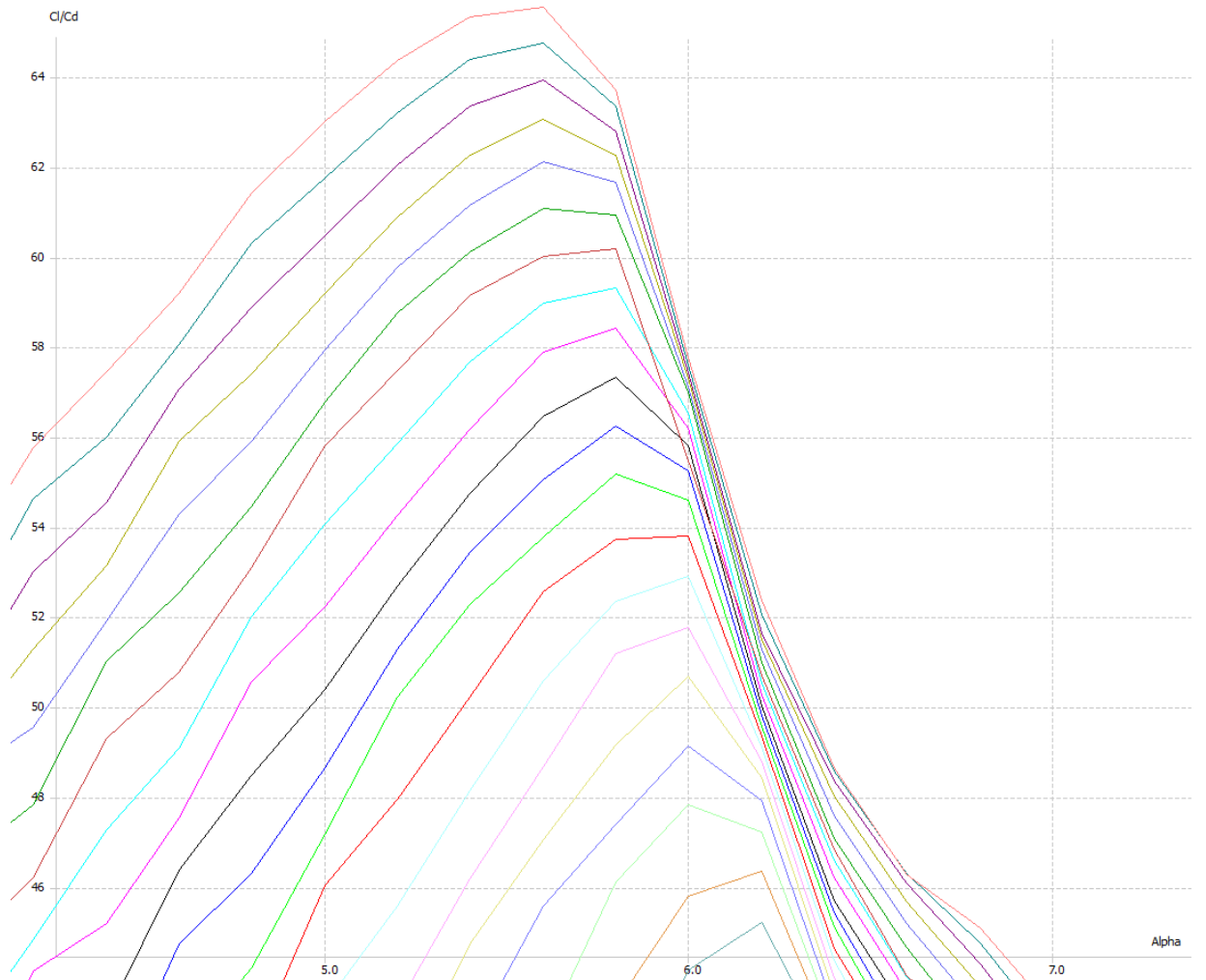


Figure 11: Airfoil design stall

In this figure, alpha represents the angle of attack and each line represents a different Reynolds number (with lines with higher peaks generally representing higher Reynolds's numbers). If a constant angle of attack was chosen to be approximately 6.0° , then once the Reynolds number reaches a certain point, the C_l/C_d will nearly be constant. This means that in high wind speeds, the wind turbine speed would depend more on the drag side, and less on the lift side, and would be rotating slower overall.

3.3.2 Manufacturing the Blades

The blades were created out of sheets of extruded polystyrene (XPS) housing insulation. The chosen airfoil design was first shaped out of glass to provide a stencil for cutting the blades. The foam was then cut to rectangular size and then the glass pieces were placed on the top and bottom for cutting. Approximately 400W was connected to a nichrome wire to heat it up to a point where it could cut through the foam. The foam was slowly pushed through to allow the wire to cut the shape from the stencils. Once for blades were fully cut they were then spackled to fill in any imperfections, and sanded to smooth out the overall design. Each blade was then covered in fiberglass cloth and epoxied to provide a rigid structure that will allow air to flow smoothly over the entire surface.

3.4 Design of the Shroud

Due to the mixing of lift and drag in the turbine, a unique shroud needed to be developed. The shrouds that were researched had been designed for drag type VAWTs, and therefore had one area in which they focused the air flow. The shroud needed to direct airflow to both the lift and the drag sides of the turbine. In addition, it needed to reduce air flow in the center of the inlet to block high winds from reaching the blades while they were transitioning between lift and drag angles. Several designs were developed in SolidWorks, and each had openings of different sizes and orientations. The designs were then tested using Fluent, a Computational Fluid Dynamics software, to develop velocity flow fields. Examples of these figures can be seen in section 7.1. The flow fields were analyzed to predict which shroud was going to be most beneficial to the chosen turbine. This shroud was chosen to be built and tested with the turbine.

3.4.1 Manufacturing the Shroud

The shroud was constructed from aluminum sheets. To save money, scrap metal in the form of old printing plates were used. These sheets were cut into sections and sealed at the seams to allow them to hold in their bent structure.

3.5 Testing the Chosen Turbine

The chosen turbine and airfoil combination was manufactured and tested in a lab both with and without a shroud. Air flow was generated from a fan and from a leaf blower. During the experiments, the wind speed and direction was monitored by an anemometer. In addition, the rotational speed of the turbine was recorded. These results were then used to determine the performance of the turbine in different wind environments.

4. Results

This section details the results from the analysis of wind data, the design and manufacturing of the turbine, and the testing of the turbine. The wind results include analysis on wind speed data from anemometers on three buildings, as well as some wind direction data. The design results begin with the decision on the type of turbine to be built, and continue with details on specific components of that turbine, such as the cam track, airfoils, and shroud. The assembly and manufacturing of the turbine is then discussed, followed by the results of the testing.

4.1 Wind Analysis Results

The wind analysis was an important part of this project because it allowed for perspective locations for the designed wind turbine to be discovered. Through analyses done using different programs, all the data can be combined to see what potential lies around the Worcester area. Using WAsP, a large amount of data was able to be looked at in an organized manner. The program provided wind roses for the directional data that was collected, these wind roses can be seen in Figure 16 and Figure 17. Also provided were the bin numbers for the frequency of wind speed values. These helped to show how often certain wind speeds occurred and not just what the overall average was for each location.

Figure 12 helps to show the wind potential directly surrounding the Worcester area. The magenta area of the map shows poor wind potential while the turquoise section of the map shows slightly better wind potential. This map was created in ArcGIS and used data gathered from online systems and monitoring programs that covered the New England area.



Figure 12: Wind Potential surrounding WPI, scale 1:15,000m

Figure 13 shows a map of buildings that were pertinent to this project along with color coding wind potential locations immediately surrounding WPI. Labeled are the three buildings that have the anemometers atop them (Daniels Hall, East Hall, and the Campus Center) that have provided the data for this project. Surrounding the Campus Center are three equally as tall, if not taller buildings. By both Daniel Hall and East Hall, there are no buildings that are close in height. Greater wind speeds were found at these two locations.

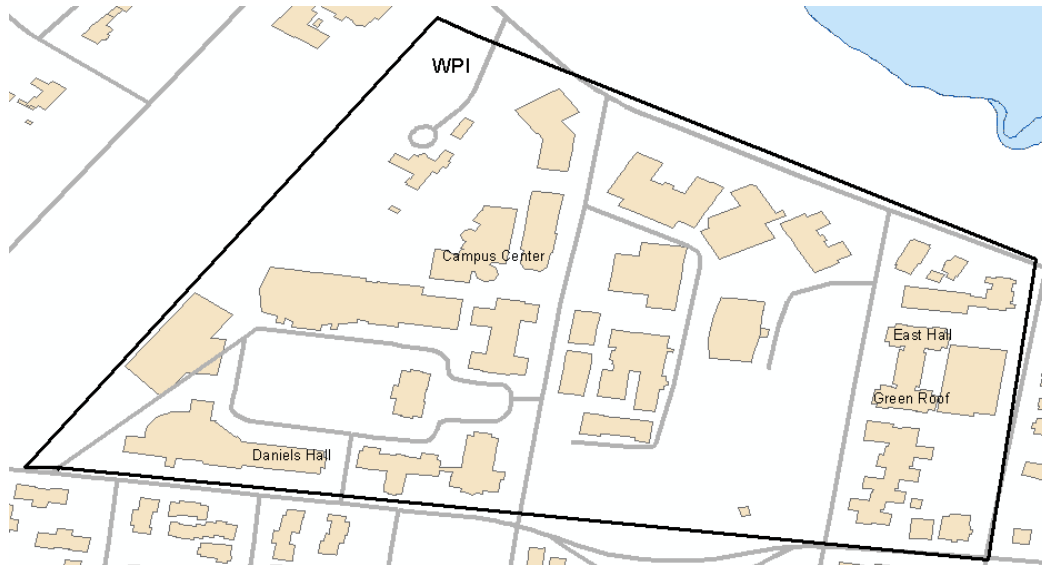


Figure 13: Locations of WPI buildings with anemometers

Figure 14 shows a scatter plot of the yearlong data collected along with a linear trend line to show the average speeds throughout the year. The average wind speed determined for the Campus Center anemometer was 3.27 MPH, with a standard deviation of 1.72. This velocity covers data collect over one year from December 2012 to December 2013. This average was calculated using 36,109 data points. This is the lowest average speed of the three locations.

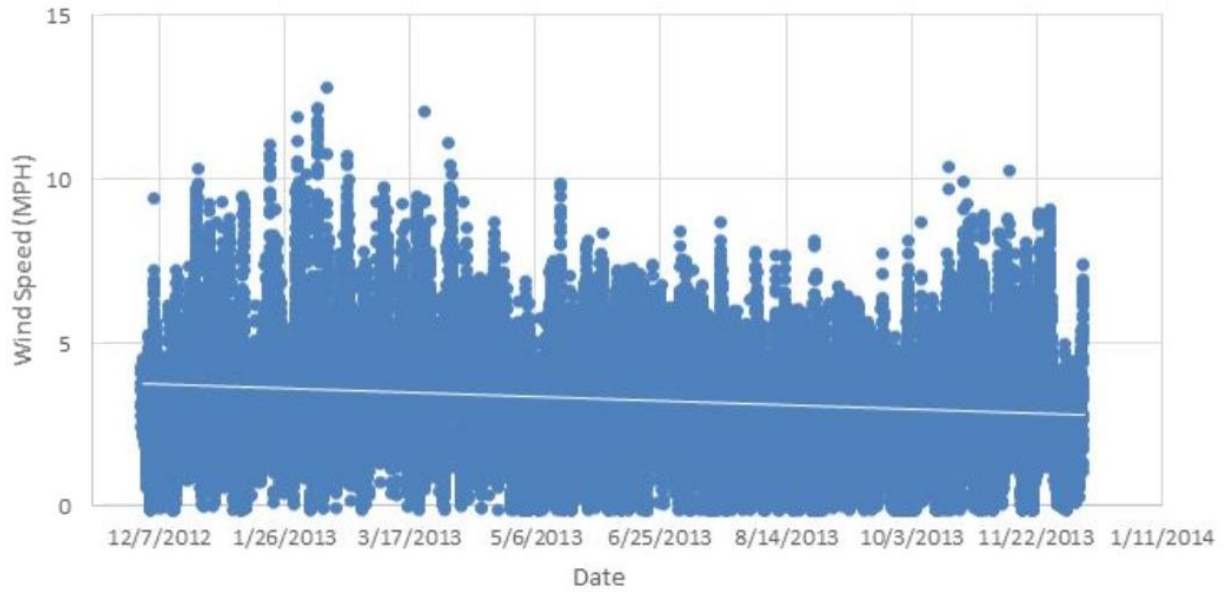


Figure 14: Campus Center Wind Speed Data

The average wind speed from the East Hall anemometer was 3.85 MPH, with a standard deviation of 1.93. This average is a combination of averages from all of the various data that has been collected from 2011-2013. This is because there was no consecutive year or data for this anemometer as it has not always been functional. Figure 15 shows this data compiled into one consecutive set of points.

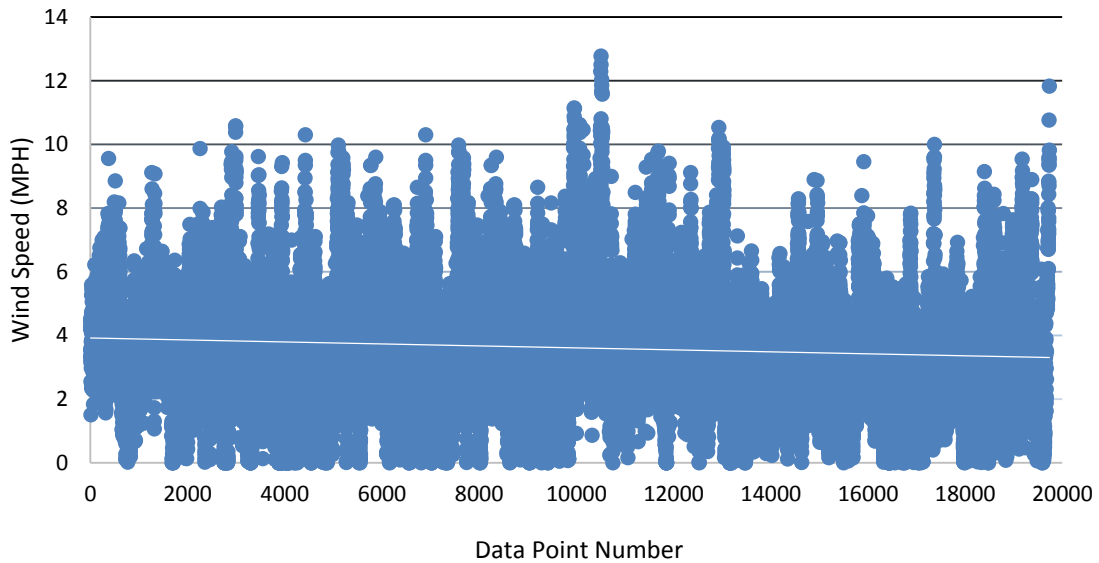


Figure 15: East Hall Data from 2011-2013 over varying months

Figure 16 shows a wind rose, which is split up into 12 sections, each representing 30°. The section representing 210° is the largest, showing that most of the wind that the anemometer received came from the Southwest. However, that is only about 20 percent of all of the data, therefore the distribution is quite variable. This supports the concept that wind comes from many directions and not just one. To the right of the wind rose in Figure 16 is a bar graph with a bell curve overlay. This graph shows the overall velocities for all of the collected data versus the frequency of their occurrence.

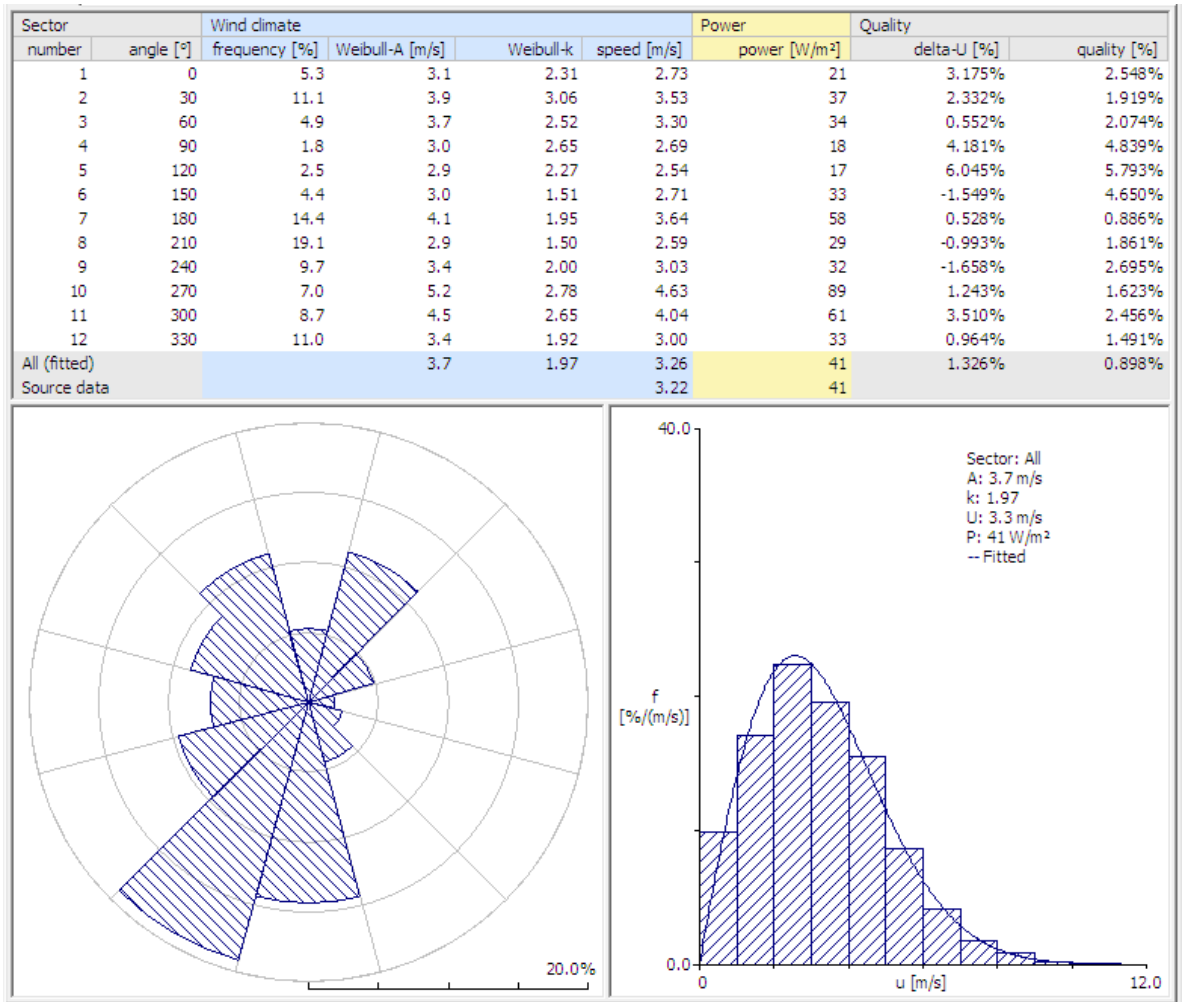


Figure 16: Wind Rose of Green Roof Data from September to October 2013

Figure 17 provides the same data as Figure 16 but this wind rose provides only data for the Southwest wind direction (210°). Even though the wind speeds coming from this direction are often lower than average, the most wind power comes from there.

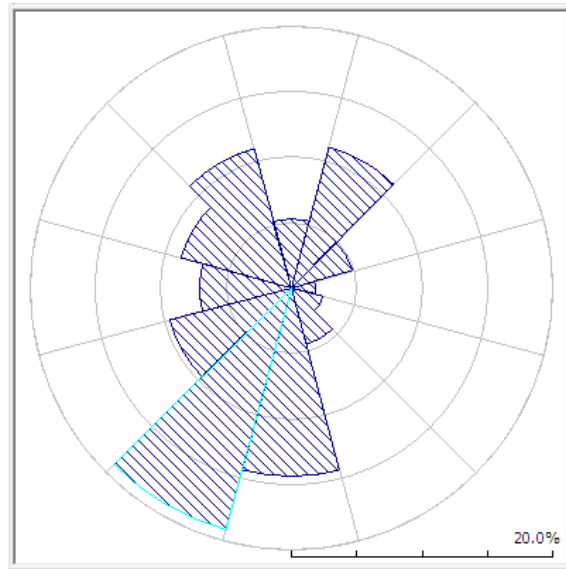


Figure 17: Wind rose for 210°

Figure 18 depicts a scatter plot for Daniels Hall of the wind speed data collected over one year along with a linear trend line to show the average. The average wind speed from the anemometer on top of Daniels Hall was 5.31 MPH. This average covers a year from December 2013 to December 2013 and was calculated using 35,136 data points. This average was the highest of the three locations and was used for further calculations since it is assumed that the turbine would be placed strategically in order to capitalize on high wind speed locations like this one.

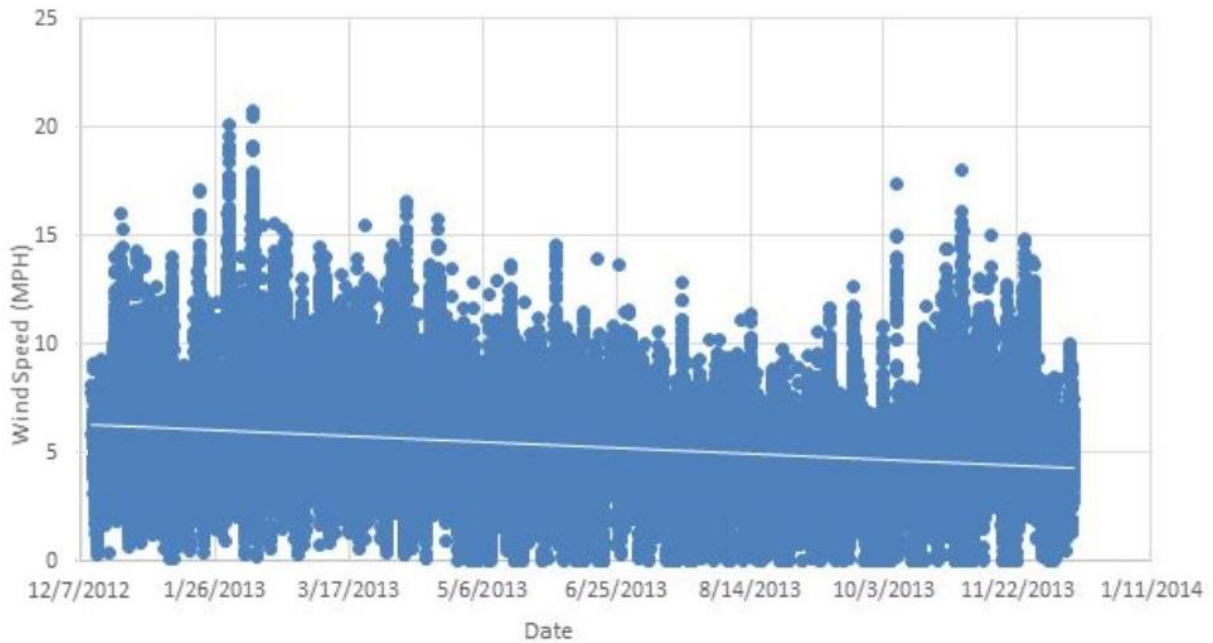


Figure 18: Daniels Hall Wind Speed Data

The anemometer on top of Daniels Hall lies at an elevation of 554 feet above sea level and 604 feet at roof height. The wind analyzed from Daniels had the greatest average speeds of 5.31 miles per hour, with a standard deviation of 2.72. The reasons behind this observation include the fact that this building has an unobstructed roof top, with no other structures close enough to impede the wind flow to this area. The higher elevation is also a factor that allows for faster wind speeds. Although the average speed was 5.31 miles per hour the highest recorded speed was around 20.78 miles per hour, this was an out-lying data point that fell well outside the average. Figure 19 provides a histogram of the collected data from Daniels Hall and Figure 20 shows the same analysis of Campus Center data.

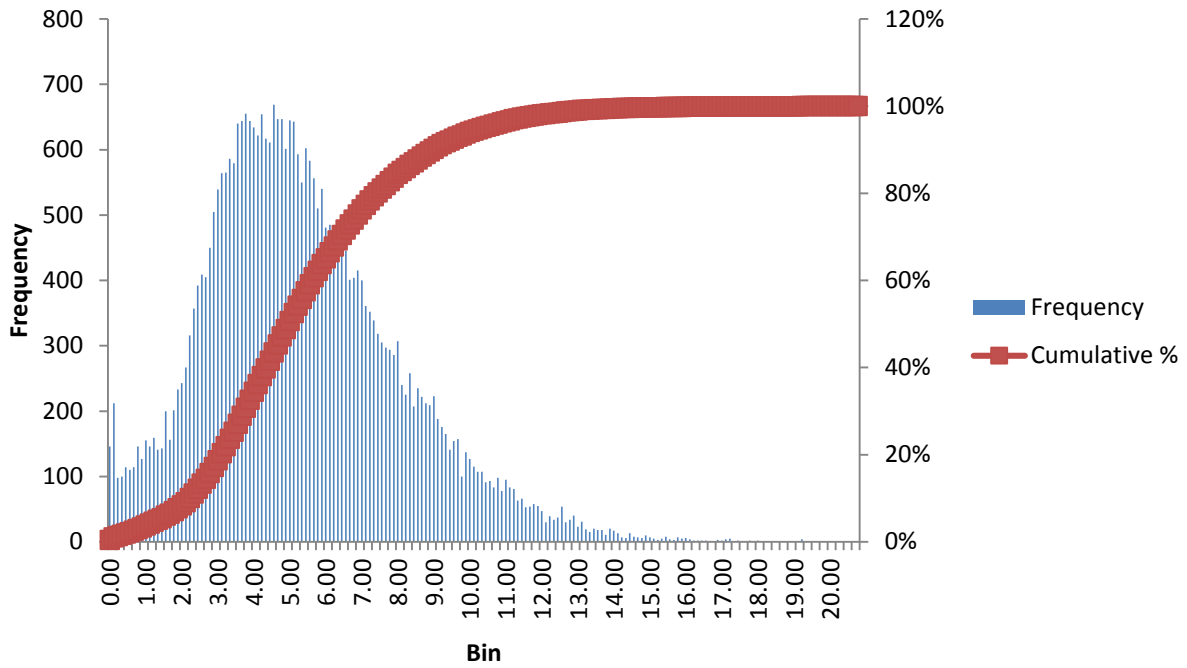


Figure 19: Daniels Hall Wind Speed Histogram

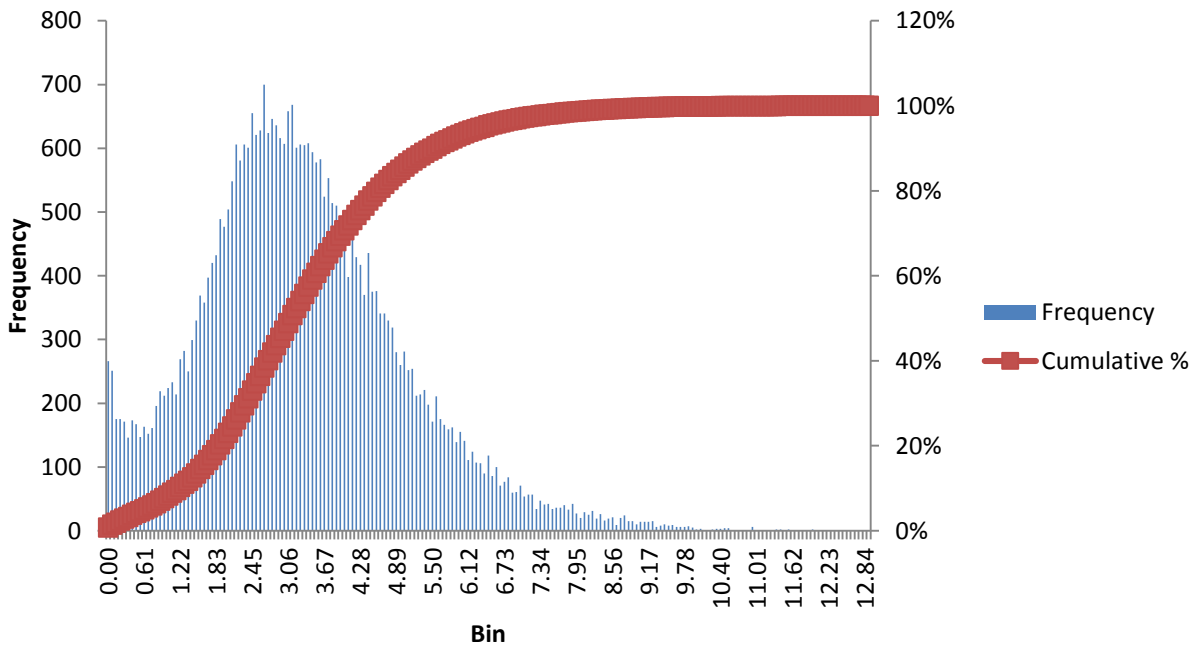


Figure 20: Campus Center Wind Speed Histogram

As Figure 20 shows, there is a faster rise in cumulative percentage of the Campus Center wind speeds than of the Daniels Hall wind speeds. This means that the data is more closely grouped than that of Daniels Hall. The maximum of each graph lies around the average wind speed which is to be expected. The data show that the highest recorded wind speed on the Campus Center was only 12.91 miles per hour which is much lower than wind speed for Daniels Hall which was at 20.78 mph.

With an elevation of 549 feet above sea level and 579 feet at roof height, the Campus Center has the least desirable wind speeds averaging 3.27 miles per hour. Factors that contribute to this low average wind speed include the tall surrounding buildings and the fact that this building has the lowest elevation of the three buildings on which anemometers were located.

The roof of East Hall lies at an elevation of around 501 feet above sea level and 562 feet at roof height. Although this elevation is lower than the Daniels Hall, the roof on top of East Hall has a relatively unobstructed flow of air. The average wind flow found on the roof of East Hall was 3.85 miles per hour. This is because East hall is the tallest building in its immediate vicinity causing higher wind speeds to be observed by the anemometer.

Table 1 provides a summary of the basic findings of the wind speeds per building along with their heights.

Table 1: Wind Results Findings

	Average Wind Speed	Building Height	Standard Deviation
Daniels Hall	5.31 MPH	604 ft	2.72
Campus Center	3.27 MPH	579 ft	1.72
East Hall (Green Roof)	3.85 MPH	562 ft	1.93

Figure 21, Figure 22, and Figure 23 were used to determine the approximate probability of each of the Reynolds numbers occurring. This information was used in the design of the airfoils, by optimizing the airfoils for the most frequently occurring Reynolds numbers. The Reynolds numbers were calculated using the Reynolds number equation,

$$Re = \frac{Ul}{\nu} \quad (5)$$

where U represents the velocity of the fluid, l represents the chord length and ν represents the kinematic viscosity of the fluid. The fluid was assumed to be air at 20°C resulting in a kinematic viscosity of $\nu = 1.5111 * 10^{-7} \frac{m^2}{s}$.

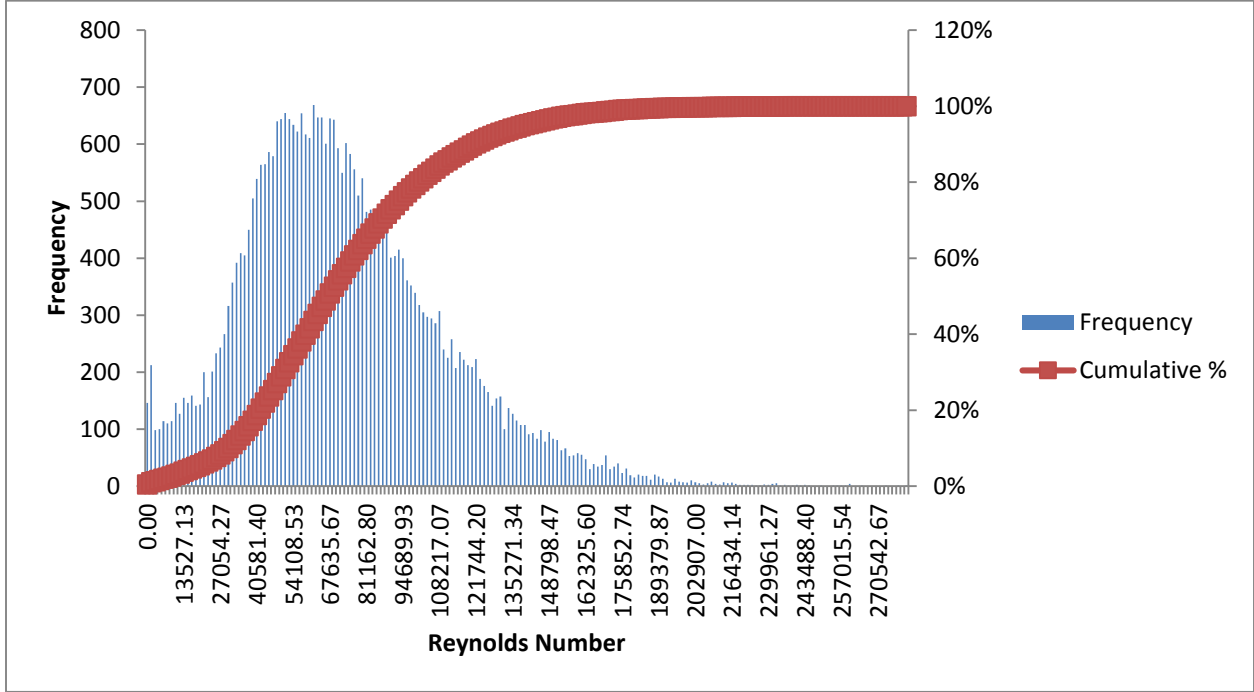


Figure 21: Daniels Hall Reynolds Number Histogram

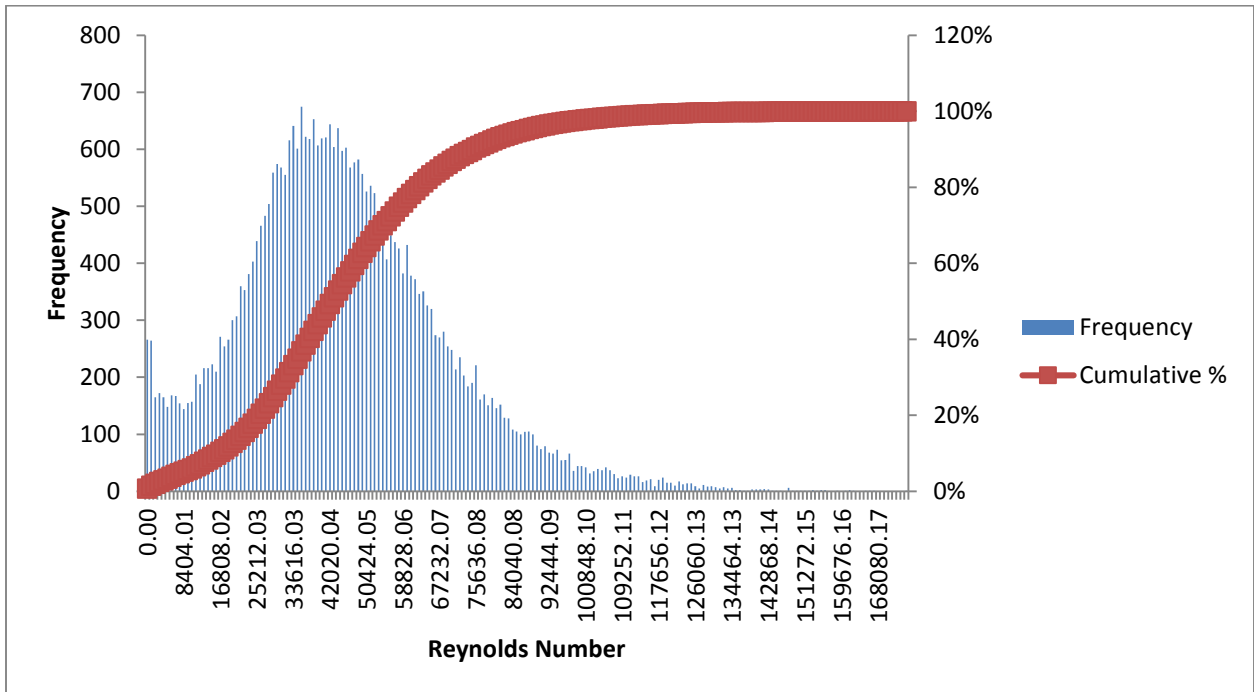


Figure 22: Campus Center Reynolds Number Histogram

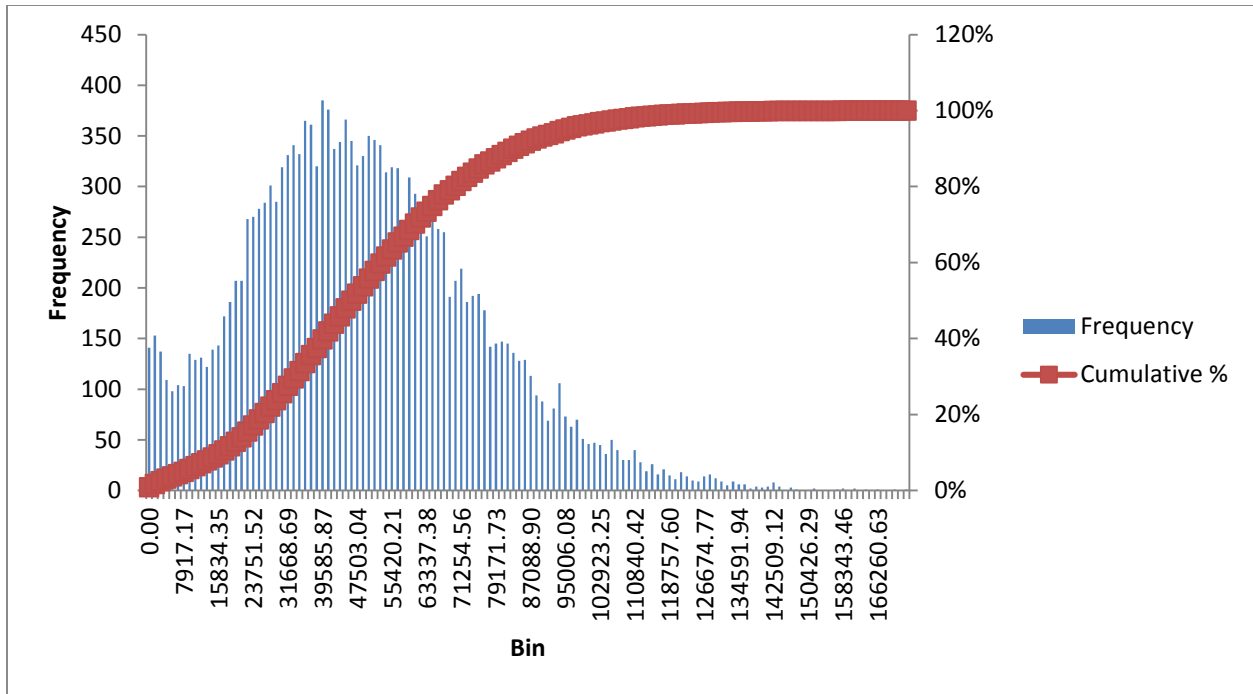


Figure 23: East Hall Reynolds Number Histogram

4.2 Turbine and Shroud Development

The purpose of developing a turbine and a shroud from scratch was to rethink all of the previous designs and try to improve on them. Design results include the analysis of three turbine types, the analysis of 1,548 airfoil profiles, and the design and analysis of several shrouds. By the end of each analysis cycle, a final design was chosen or developed for the component. Manufacturability was considered as a part of each decision, and after the entire system had been modeled, a detailed manufacturing plan was laid out.

4.2.1 Turbine Design

In order to design the turbine, each general type of VAWT was considered, one was chosen, and then the specific design was developed. To begin the design, the advantages and disadvantages of the two main types of VAWTs were explored: lift turbines and drag turbines.

4.2.1.1 Evaluation of existing turbine types

The major advantage of a lift type turbine is that it is very efficient. As discussed in section 2.10.2, an airfoil rotates due to the pressure difference created by the air traveling along the outside and inside of the blade. Since the airfoils travel into the wind in this way, they can move at a greater speed than the incident wind, allowing for a greater angular velocity of the turbine.

The high efficiency of lift type turbines comes at a price. They will not self-start at low wind speeds, and therefore would require a motor to restart whenever the wind speed drops and the turbine stops rotating. This electrical input would significantly decrease the net output of the turbine in the variable wind conditions experienced in urban locations. In addition to this, the airfoils used in lift type turbines are much more difficult to manufacture than the simple cup shaped blades used for drag types. Since the airfoils are thin and the accuracy of their shape has a strong effect on their performance, more sophisticated, and usually more expensive, techniques must be used. There are also some mechanical downfalls of lift type turbines. The standard Darrieus type has high stress at its outer extents, which can lead to premature mechanical failures. Also, each blade stalls at one point in the turbine's rotation, which could lead to vibrations which cause mechanical problems and nuisance noise.

Drag type turbines have the opposite attributes of lift type in most cases. They are self-starting, simple and inexpensive to manufacture, and generally mechanically reliable. However, their efficiency is much lower than the lift type, which means that in urban environments with relatively low wind speeds, a drag type turbine would create very little power.

After determining that neither of these types would be ideal for the urban environment, a hybrid type was considered which combines lift and drag into one turbine. They are normally constructed as a Darrieus with a drag type blade in the middle, as seen in Figure 24³⁸. These can normally self-start, but after they have started, they are less efficient than a normal lift type due to the middle creating negative drag.



Figure 24: Hybrid VAWT

4.2.1.2 Chosen turbine type

A new hybrid type was created for this project, which will be referred to as a mixed type. This was done in order to eliminate as many cons of the hybrid turbine as possible, while keeping as many pros. Instead of having separate sets of blades, the mixed type used the same blades to produce both lift and drag. As the blades rotate into the wind, they create lift, and then as they travel away from the wind, they create drag. A model of this

³⁸ (Blade Wind Tech 2013)

turbine, with one rectangular blade representing the airfoil positions, is shown in Figure 25.

4.2.1.2.1 Advantages and disadvantages

This turbine should self-start due to the drag aspect; yet it will have high efficiency due to the airfoils creating lift. In addition, the turbine will have an enclosure to direct the wind and increase its velocity. The shroud will also help to keep foreign objects out of the turbine, decreasing the likelihood of damage from such an event.

This mixed design still has some disadvantages. Due to the complexity of the design, there are lots of moving parts which could result in vibrations, noise, and a low mechanical reliability. There is also a loss of efficiency due to friction in the cam and the rotation of the blades from the lift to the drag position.

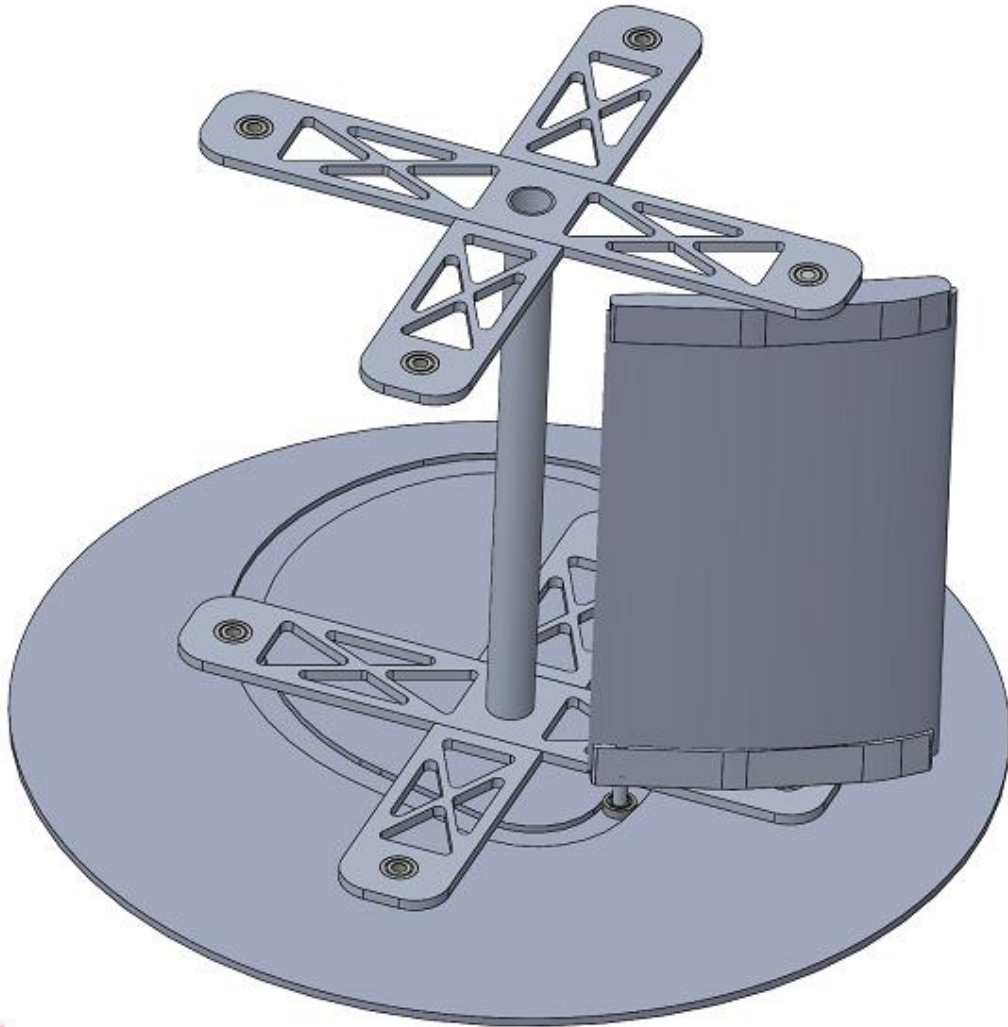


Figure 25: Model of the mixed design without airfoils

4.2.1.2.2 Design considerations

Several particular design aspects were considered when developing the design shown in Figure 25. One problem for lift type VAWTs is that the blade rotates relative to the wind, which makes it have varying angles of attack. This creates stall situations that lead to lower performance, vibrations, and noise. In the mixed design, this problem was limited by keeping a constant angle of attack along the lift side. The particular angle depended on the airfoil shape. For the drag side, the angle of attack needed to produce

maximum drag. Since drag is produced by a surface area normal to the wind, the drag area of the blade would be the total area multiplied by the sin of the angle of attack. Therefore, the angle which produces maximum drag is 90° , and so the drag side was designed to stay at that angle. Another method which was used to increase drag was orientating the blade in such a way that when it is on the drag side, it hits the underside of the airfoil, which is curved like traditional cupped savonius blades.

4.2.1.2.3 Controlling the angle of attack

Two methods were considered for controlling the angle of attack of the blade. The first method is a system with two resting positions determined by springs. This would work by having a central cam in the middle, with each blade having a cam follower connected to the blade via a spring. The central cam would likely look something similar to Figure 26.

The other method, which was chosen over the spring system due to its simplicity and relative ease of manufacturing, was a cam track with a follower attached to each blade. As seen in Figure 27, the follower was offset to one side of the axis on which the blade was rotating. Therefore, the radial distance between the blade's axis and the follower controlled the angle of attack of the blade. The follower was placed on the back side of the blade as opposed to the front so that it would be dragged along the track, creating less resistance than if it were pushed.

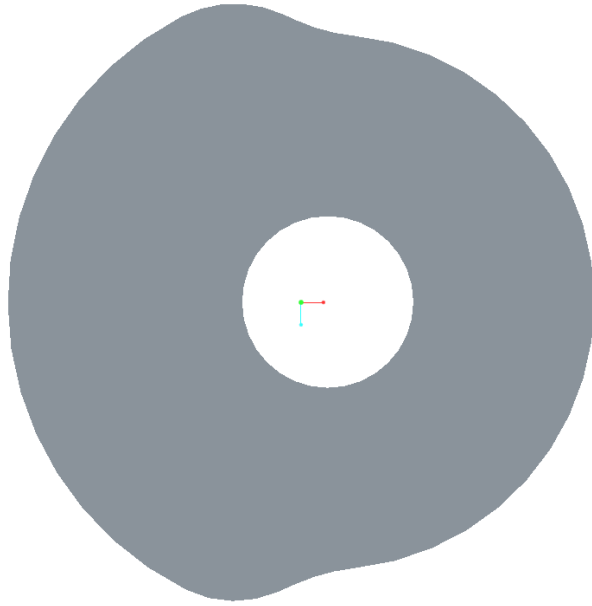


Figure 26: Spring loaded cam concept

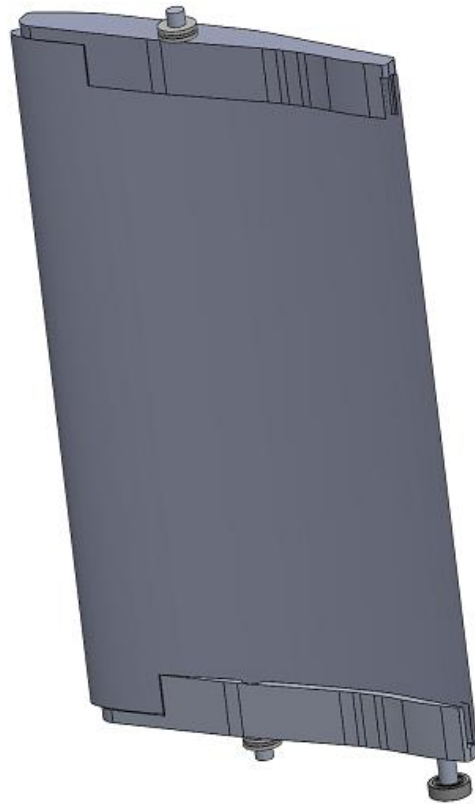


Figure 27: Blade with cam follower

In order to determine where to place the track, two expressions for its radius were first created: one which would position the blades for lift, and one which would position them for drag. Equations (6) and (8) show formulas for the (x,y) position of the center of the follower for lift and for drag, respectively. Definitions for each of the variables can be found in Table 2. Using the relationship $r^2 = x^2 + y^2$, an expression for the radius of the path was then determined. Equation (7) defines the radius of the track that would put the blade in the lift position, while Equation (9) defines the same for the drag position.

$$(x, y) = (R_{rod}\cos\theta + L\sin\alpha, R_{rod}\sin\theta - L\cos\alpha) \quad (6)$$

$$R_{lift} = \sqrt{(R_{rod}\cos\theta + L\sin\alpha)^2 + (R_{rod}\sin\theta - L\cos\alpha)^2} \quad (7)$$

$$(x, y) = (R_{rod}\cos\theta + L, R_{rod}\sin\theta) \quad (8)$$

$$R_{drag} = \sqrt{(R_{rod}\cos\theta + L)^2 + (R_{rod}\sin\theta)^2} \quad (9)$$

Table 2: Variables and Definitions for the CAM Track

Variable	Definition
$(x,y) = (0,0)$	The center of the turbine's rotational axis
R_{rod}	The distance from the center of the turbine to the center of the rod which attaches the blade to the turbine
θ	The angle of the R_{rod} vector
L	The radius of the follower
α	The ideal angle of attack for lift (angle between the blade and the incident wind)

The drag and lift equations were inputted into Creo in order to begin creating the complete path. The equation for the drag path was adjusted slightly in order to keep the angle just below 90 degrees. This is because at 90 degrees, a blade could get stuck in a

statically indeterminate state which would cause extra stress in the system that could lead to failure. Once both of these tracks, seen in Figures Figure 28 Figure 29, were in Creo, a complete track needed to be created based on them. This path would need to follow the lift path while the blades travel into the wind, and then follow the drag path away from the wind. On both the front and back of the turbine, there would be transition sections which brought the follower smoothly from one path to the other. Figure 30 shows the full path which was created, with the wind entering from above.

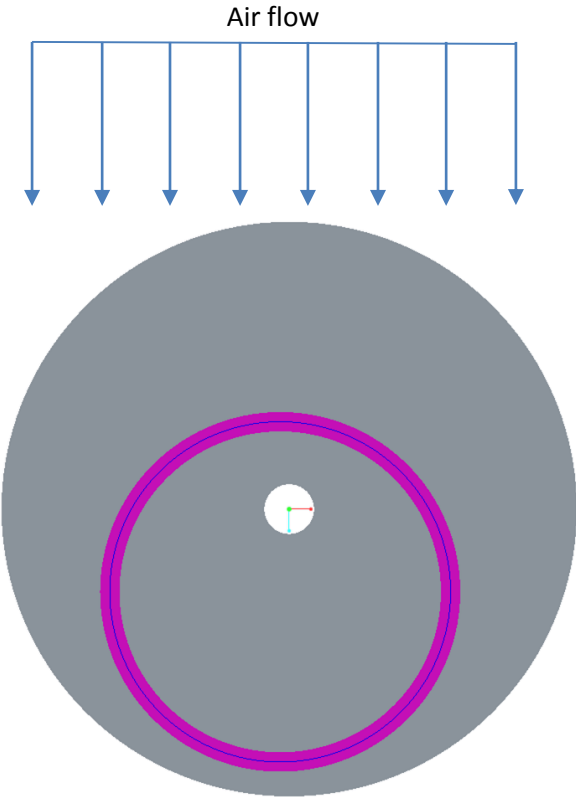


Figure 28: Lift Path

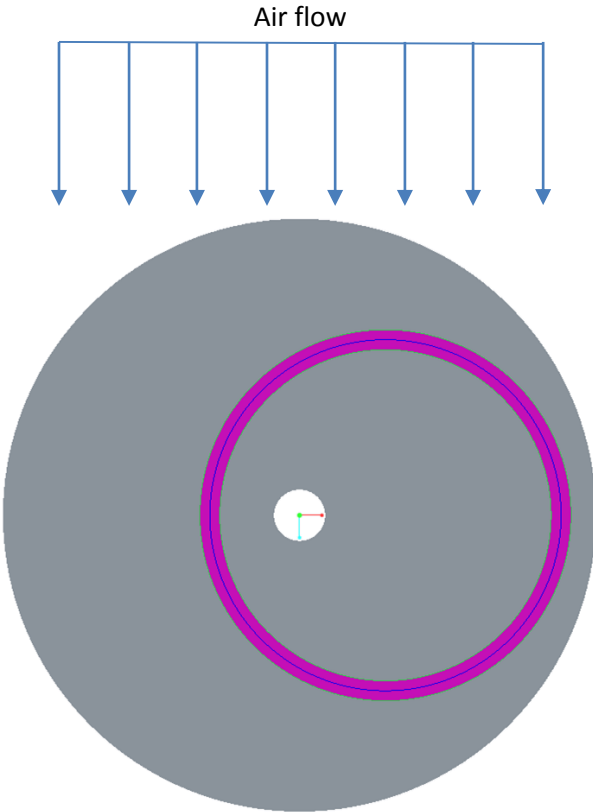


Figure 29: Drag Path

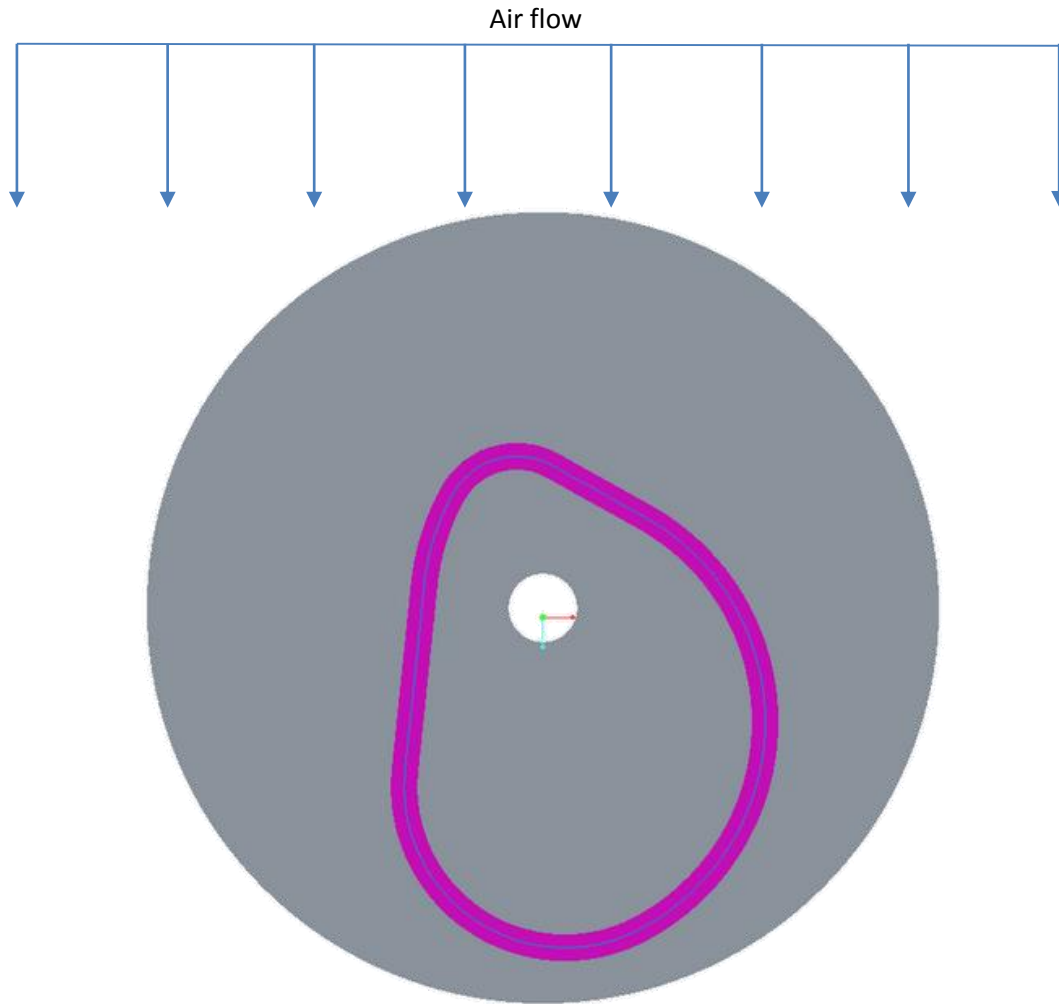


Figure 30: Full Path

As the follower travels around the track in Figure 30, the angle of the blade changes from α to 90° and back again. Figure 31 shows the blade's angle for one full rotation. The solid blue line labeled AoA represents the angle of attack of the blade, or the angle of the blade with respect to an outside non-rotating coordinate system. The lift angle dashed line and the drag angle dashed line represent the ideal angle of the blade during the lift phase and the drag phase respectively. The sloped sections of the AoA show where the blade is transitioning from one phase to the other, which occurs along the front and the back of the turbine.

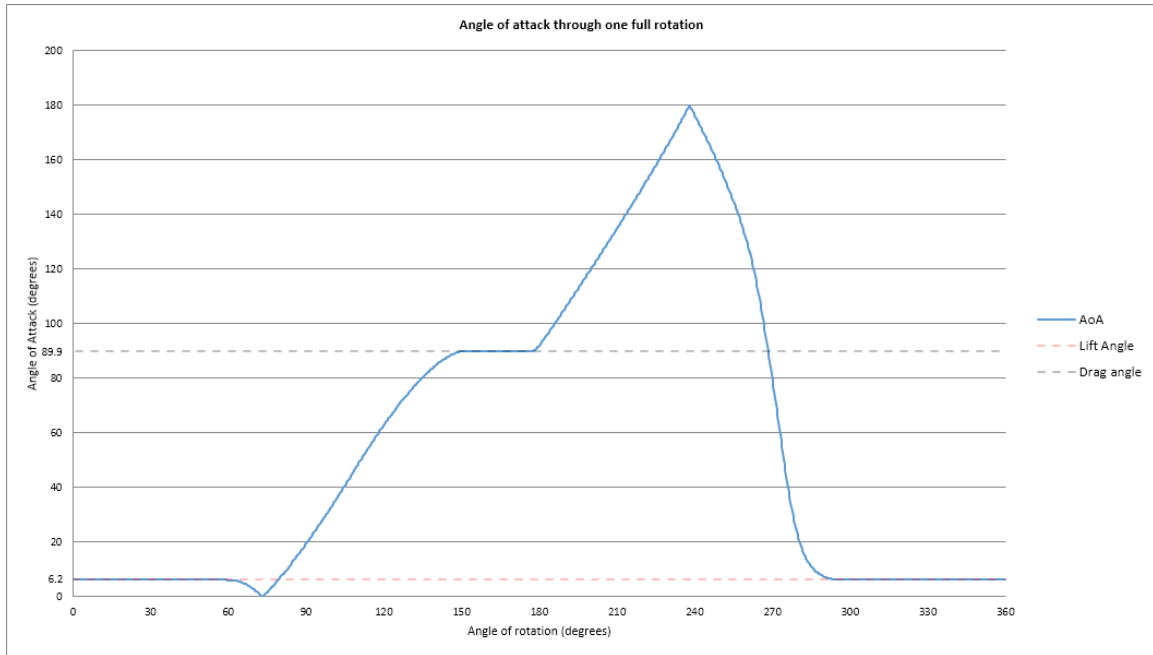


Figure 31: Graph of the angle of attack of the blade through one rotation

4.2.2 Airfoil Design

After completing the analysis described in section 3.3, a table of candidate airfoils was produced. Explanations of the different result categories were given in section 3.3, and here, the results are discussed in the context of deciding between the top airfoils. The top six airfoils (bacj, du86137, e874, giiid, giiiig, and naca 64209) were disqualified due to abnormalities in their results (such as having an artificial peak, or a divide by zero error resulting in an infinite L/D value). The remaining top 10 airfoils as indicated by the program are displayed in Table 3.

Table 3: QFils Top 10 Airfoils

Foil Name	Overall Results	Angle Results	Ratio Results	Bucket Results	Deviation Results
e63	42.7	5.4	46.3	39.1	0.97
arad6	42.2	5.7	43.3	41.2	0.32
as5045	42.2	5.7	43.3	41.2	0.32
as5046	42.2	5.7	43.3	41.2	0.32
as5048	42.2	5.7	43.3	41.2	0.32
e62	41.8	6.2	44.8	38.8	0.49
s1091	41.2	5.4	41.7	40.6	1.08
a18sm	41.0	6.1	42.8	39.1	0.23
oaf095	40.5	6.1	42.2	38.8	0.21
ma409sm	40.3	5.6	42.0	38.5	0.21

As the ratio results were relatively close to each other, other factors were taken into account over the ratio and bucket results. The e63 airfoil was attractive due to its higher L/D ratio, but it was very thin (with a thickness of only 4.27 percent of its chord length) and had a very small bucket, meaning any manufacturing defects, or if the wind did not hit it correctly to achieve an angle of attack of 5.4 it could perform poorly. Out of the remaining airfoils, oaf095 was chosen. This was due to the fact that it had a very small deviation, but most importantly it was very thick compared to the others (with a thickness of 9.48 percent of the chord length) meaning it would be easier to manufacture, and would be stronger than the other airfoils. The final airfoil was a modification of oaf095, which is shown in Figure 32. The original oaf095 was smoothed, and the trailing edge was closed. To close the trailing edge, nineteen different airfoils were generated with varying positions of initial taper. After looking at the drag polars for the 19 airfoils, the best candidate was chosen for manufacturing.

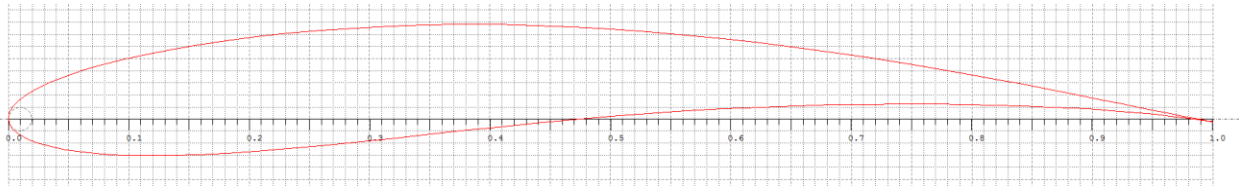


Figure 32: Modified OAF095 airfoil used

4.2.3 Shroud Design

Some shroud designs that were considered included:

- 1- A cylinder with 2 inlets and 2 outlets
- 2- A cylinder with 2 inlets and 1 outlet; the thought being that air would curve along the drag side
- 3- A cylinder with 2 inlets and 3 outlets in order to released air that gets stuck
- 4- A cylinder with 2 inlets and walls only on the sides (1 very large outlet)
- 5- A funnel toward 2 inlets with varying outlet configurations
- 6- A funnel toward 2 angled inlets with various outlets
- 7- A funnel with varying angles and lengths toward 2 inlets and 2 outlets

After looking at simple cylindrical shrouds with two inlets and two outlets, and at the flow fields produced by these type of shrouds, such as the one in Figure 33, it was decided that a funnel should be added to the inlet to increase the wind velocity inside the shroud. The flow field produced by one of the funneled designs can be seen in Figure 34. By adding the funnel, the air velocity contacting the blades can be increased by almost 200 percent from the incident wind velocity.

Once it was decided that a funneled shroud would be most beneficial to the performance of the turbine, several different models were created (as seen in the appendix). The sizes and positions of the openings were varied along with the angles and lengths of the funnel.

To analyze the different shrouds, the computational fluid dynamics package Fluent was used. Operating conditions were assumed to be air at standard temperature and

pressure (STP), with an inlet velocity of $2.46 \frac{m}{s}$. To speed up computation and allow for more shrouds to be analyzed, some simplifications were made to the model. The model was assumed to be 2-D, as the blades would not span the entire height of the airflow, so the vertical boundaries were not of concern. The model was also assumed to be steady state, and was not modeled with the turbine in the center of it. If each turbine was modeled in a transient state with moving airfoils, it would not be feasible to analyze the number of shrouds that needed to be analyzed in the time provided. As the design of the turbine was not finished by the time that the shroud analysis was started (as necessitated by time constraints), it was decided to not include a turbine in the middle of the shroud in case that including an incorrect design could later invalidate some or all of our analysis.

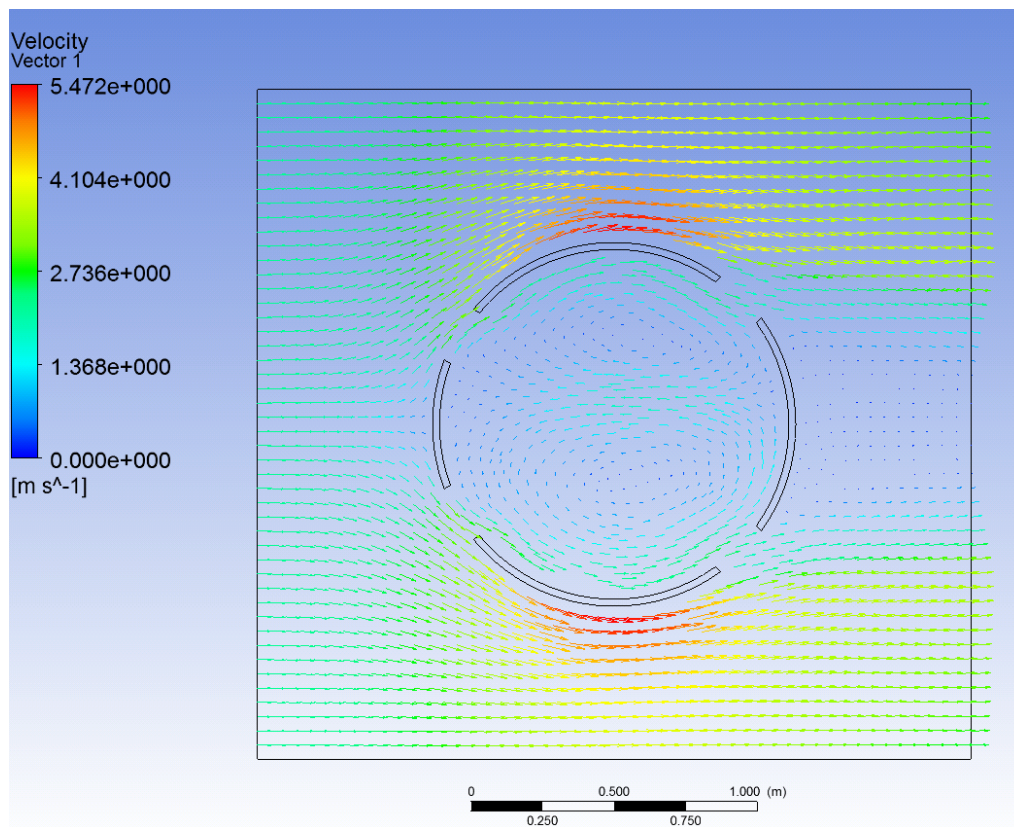


Figure 33: Preliminary Shroud Design

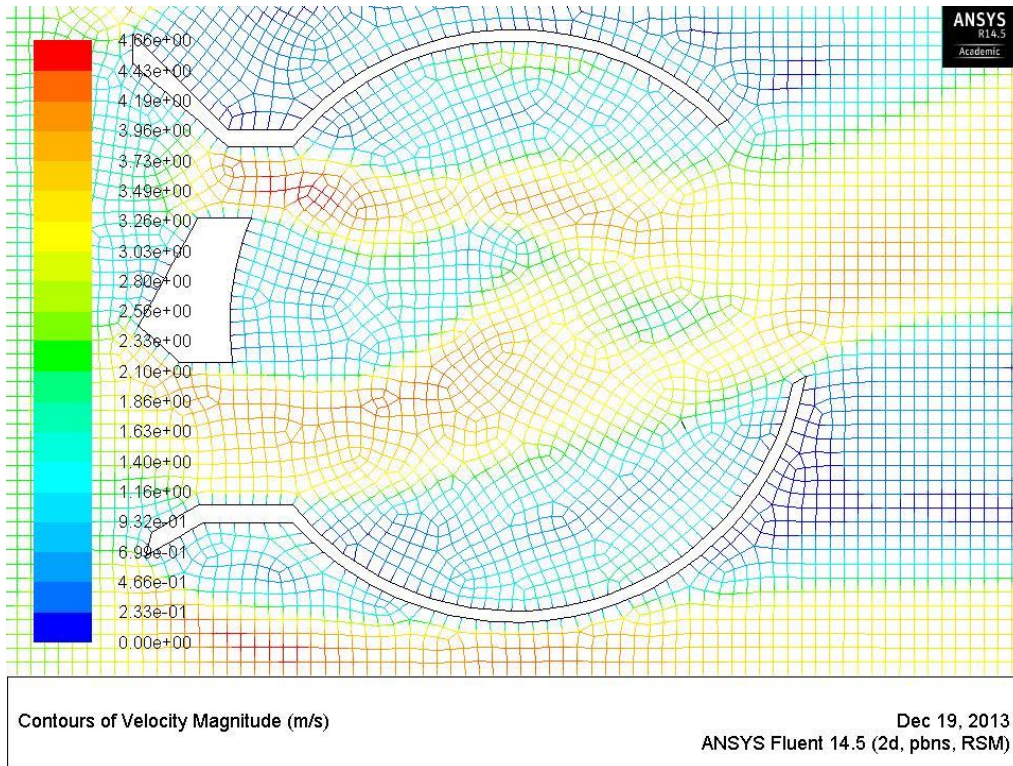


Figure 34: Funneled Shroud Design

The final shroud used was Shroud #26, as seen in Figure 35. This shroud used two outlets, with two funneled inlets, one of which (the lift side) was angled.

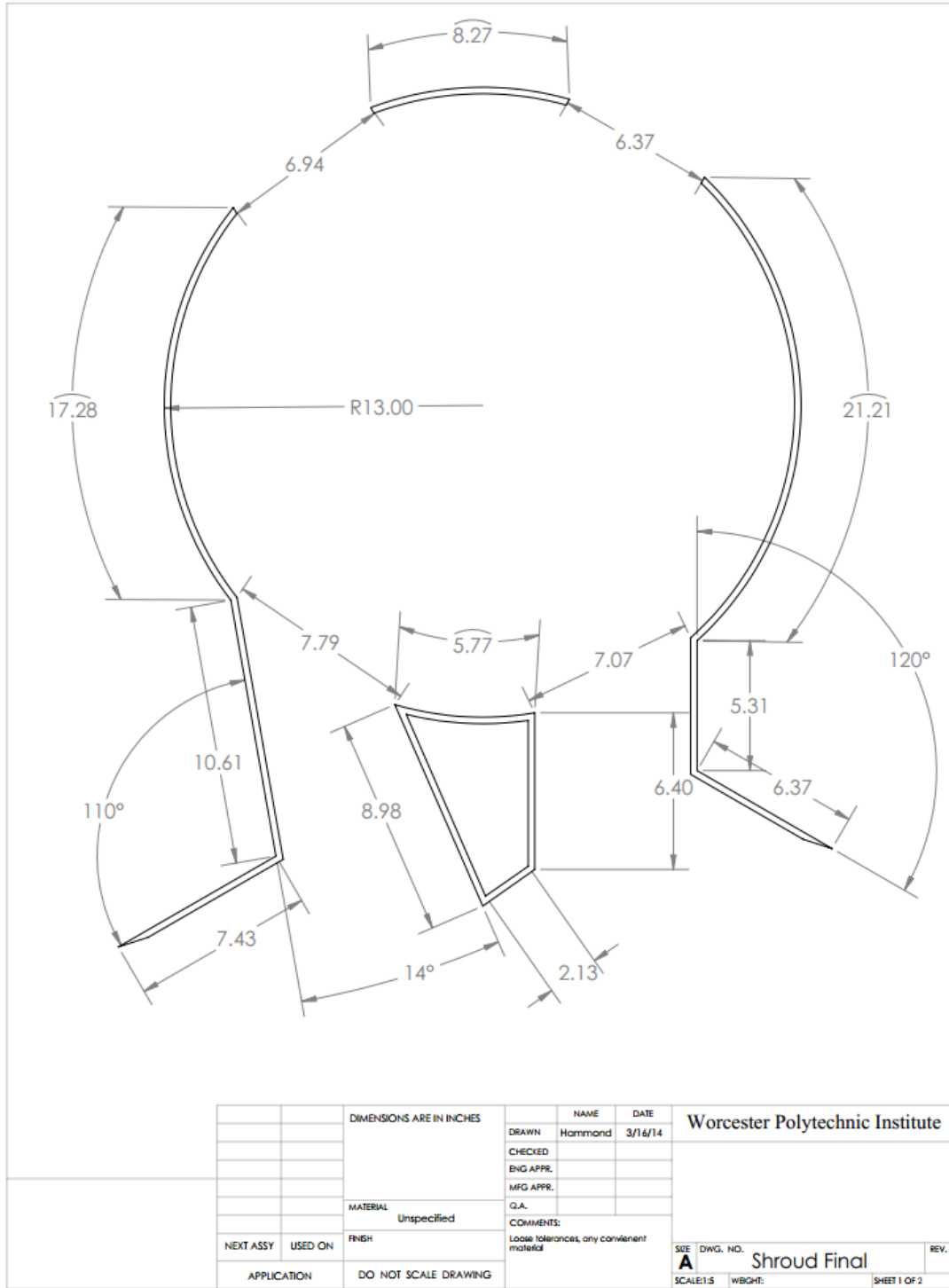


Figure 35: Drawing of the final shroud design

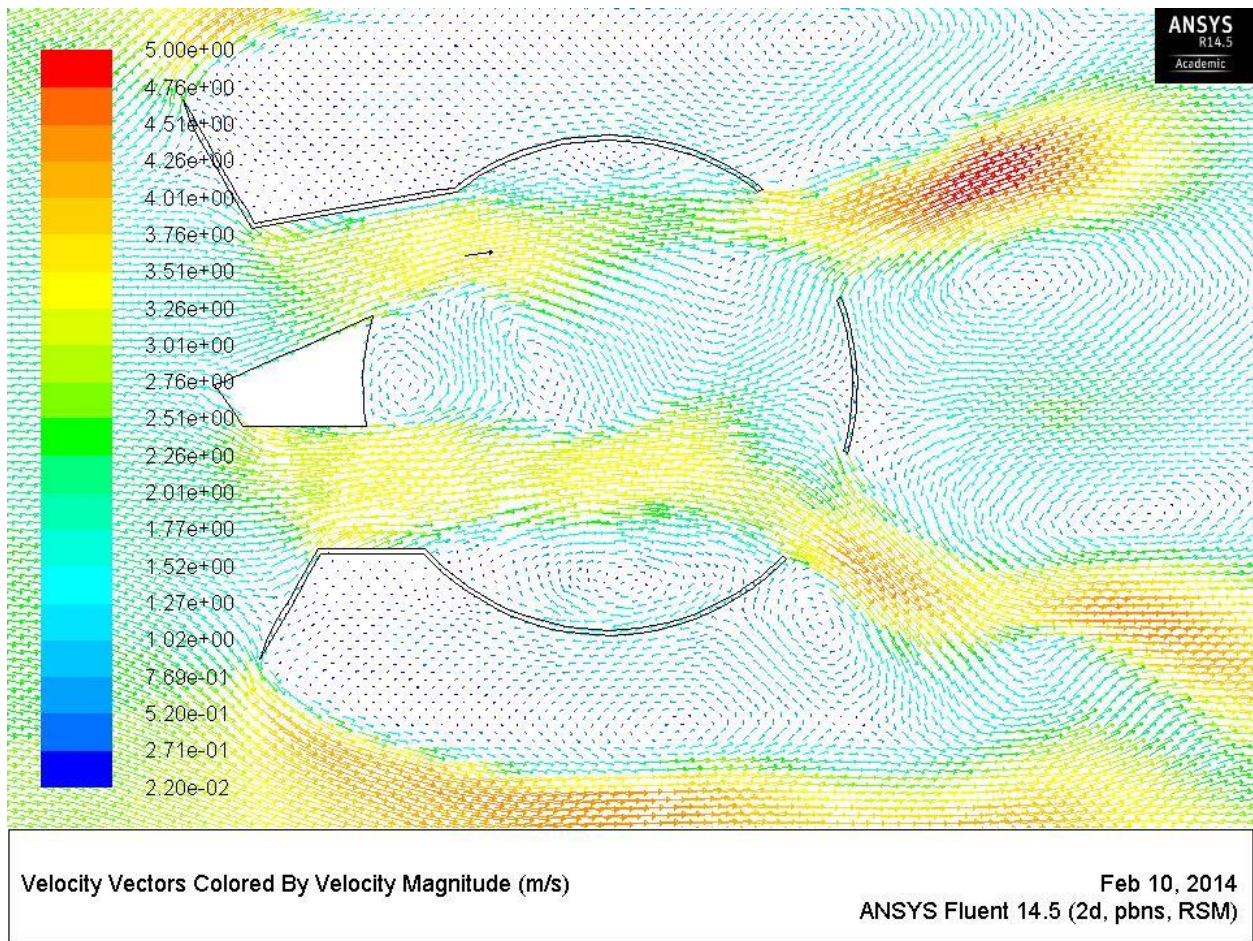


Figure 36: CFD results for the final shroud design (shroud #26)

Shroud #26 was chosen for a few reasons. Looking at the Fluent analysis for it, shown in Figure 36, one can see that it provides a good stream for the drag side (it breaks off towards the end, but the blade is also rotating at that point so it does not make as big of an impact), and more importantly a good stream for the lift side. As the actual turbine resides in the middle of the shroud and was not modeled in Fluent, this analysis is not exact. This design was chosen in hopes that the presence of the turbine will decrease the interference the drag side stream has on the lift side stream, as seen towards the trailing end of the lift side stream.

4.2.4 Final Assembly

After the turbine type, airfoil profile, and shroud design had been determined, the turbine was then designed for manufacturing and assembly. This design was completed in Solidworks, and it included a combination of custom parts and stock bearings. The complete design is shown in Figure 37. This figure, like all of the others in this section, is shown without the shroud so that the components are visible.

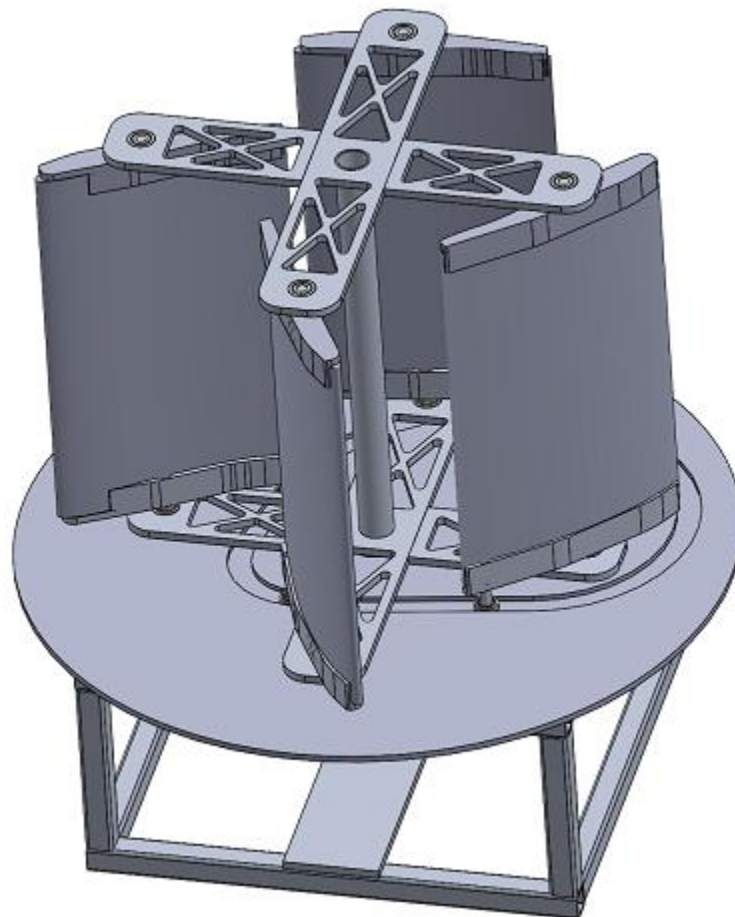


Figure 37: Complete turbine model

The exploded view in Figure 38 shows how the turbine and shaft rotate within the base. The blades are supported by two x shaped plates above and below, which are welded onto the shaft. The shaft, x plates, and blades, are supported vertically by a thrust bearing

between the bottom x plate and the large plate with the cam track in it. They are kept straight and allowed to rotate due to the two large bearings; one in the cam plate and one in a support plate welded to the bottom tube of the base frame.



Figure 38: Exploded view of the mounting system

In addition to the rotation of the shaft, the blades also needed to rotate within the x plates and follow the cam track. The rotation was achieved by placing small cylinders at the center of the top and bottom of the blade, and placing them in bearings in the x plates.

The cylinders were welded on the blade holders and were threaded on the other end so they could be secured in the bearings with bolts. Thrust bearings were placed between the blade holders and the x plates to ease rotation and keep the blades at consistent heights. The cam follower was constructed from the same cylindrical aluminum stock and steel ball bearings as the components just described. Figure 39 shows how all of these parts fit together.

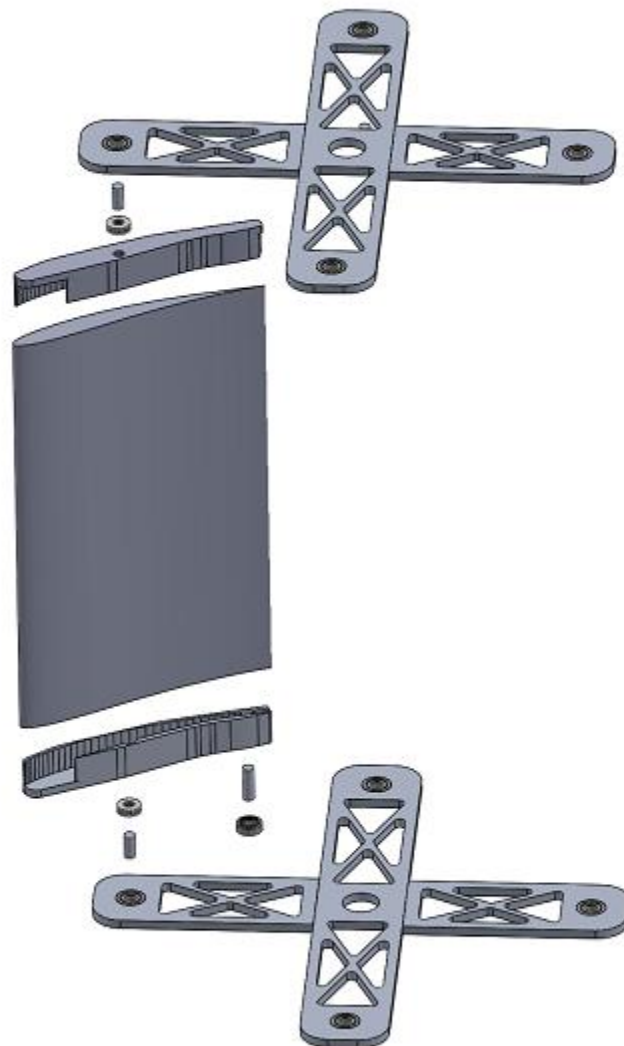


Figure 39: Exploded view of the components for blade rotation

Important dimensions of the components in Figure 39 are shown in the drawing in Figure 40. The most notable of these are the height of the blades, which was about 15 inches, and the height of the blade holders. About 1 inch of the total 1.2 inch height of the holders was milled out to contact the blade.

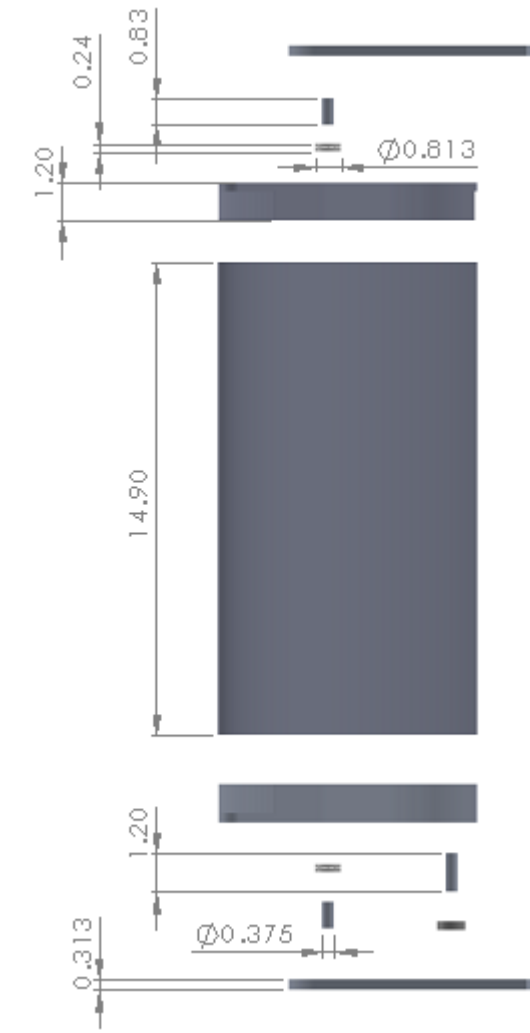


Figure 40: Drawing of parts relating to blade rotation

The entire system, including the base frame, was 26 inches tall and about 26 inches in diameter. Figure 41 and Figure 42 show these dimensions and others that may be of interest.

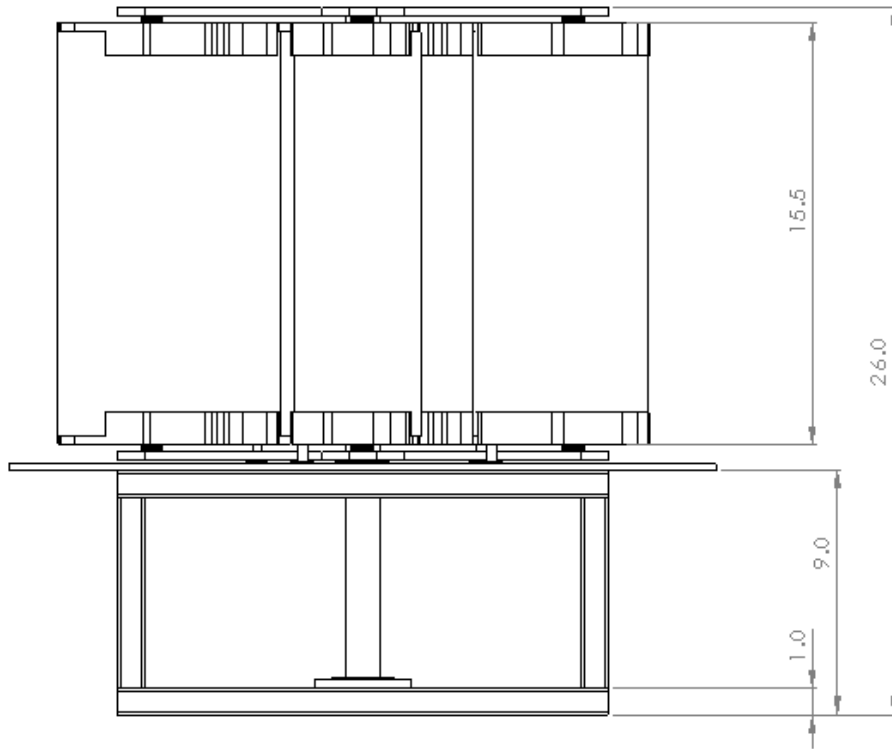


Figure 41: Profile view of the turbine showing height

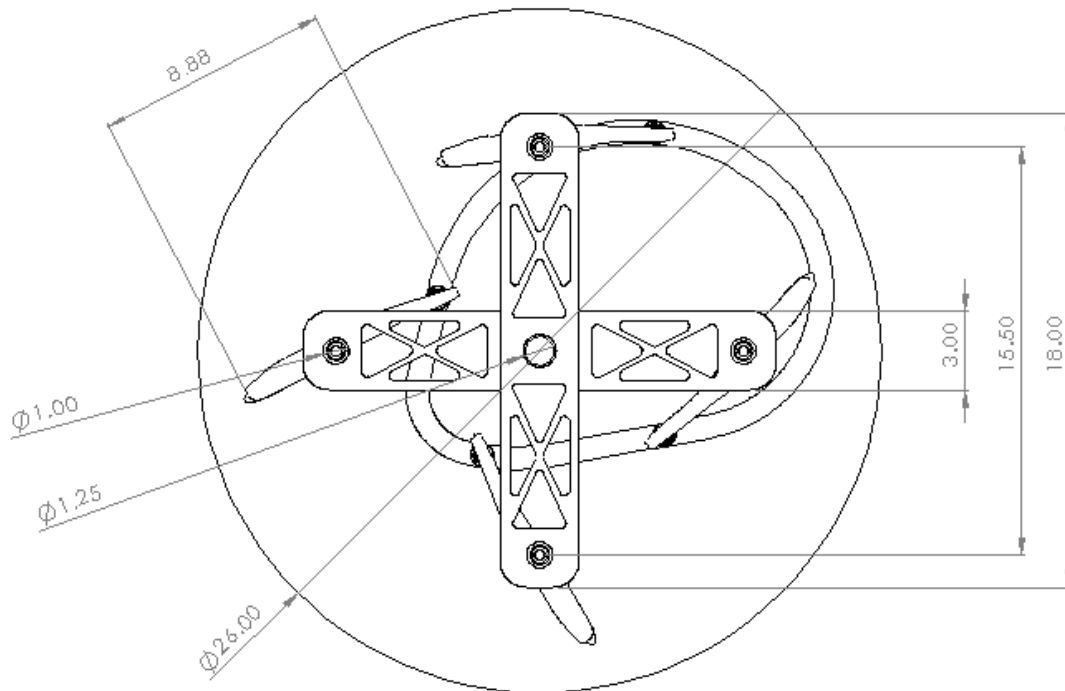


Figure 42: Plan view of the turbine with dimensions

4.2.5 Manufacturing

Since this turbine was much larger than those built by previous MQPs, different materials and manufacturing methods were used. Most of the manufactured parts were machined from raw aluminum using CNC machines. One exception to this was the airfoils, which were the most complicated part to manufacture. Table 4 below details the manufacturing options considered for the blades. The foam and fiberglass method was chosen because it was inexpensive and it allowed for a relatively thin and therefore more efficient blade to be made. The other exception to the machining method was the shroud, which was constructed from aluminum sheets by the method explained in section 3.4.1.

Table 4: Airfoil Manufacturing Options

Manufacturing Method	Advantages	Disadvantages	Approximate Cost
3D printing	Precise and easy	Expensive	\$2000-4000
Laser cutting: laser cut several identical sections, glue them together, coat blade in fiberglass	Inexpensive, DIY	Not precise, labor intensive, and time consuming	\$400
Foam: cut polystyrene foam with hot wire; glass with fiberglass cloth and epoxy resin	Inexpensive, DIY	Not precise, may or may not work as planned	\$250
Milling: mill each blade out of aluminum using WPI's CNC machines	Inexpensive, DIY	Blades would have to be thicker (less efficient) to hold up to milling	\$300

A cost report is shown in Table 5 which includes all raw materials, manufacturing supplies, and standard parts that were purchased. Some materials were acquired through other means, such as the sheet metal for the shroud and the various bolts and washers used in the assembly.

Table 5: Materials Costs

Part	Quantity	Individual price	Total price
shaft bearings	2	12.38	24.76
shaft thrust bearing	2	3.12	6.24
washers for thrust bearing	4	1.53	6.12
blade bearings	8	4.56	36.48
blade thrust bearings	8	2.47	19.76
rollers	4	7.60	30.40
cam plate	1	150.00	150.00
base frame tubing	1	99.00	99.00
shaft	1	27.41	27.41
top and bottom x plates and base frame bearing support	2	37.32	74.64
upper & lower blade holders	2	66.49	132.98
cam follower extenders	1	8.18	8.18
shaft collars	2	10.07	20.14
epoxy resin	1	136.00	136.00
extruded polystyrene (2 inch)	1	35.65	35.65
fiberglass cloth	4	6.98	27.92
sandpaper (400 wet/dry)	2	3.97	7.94
random orbit sandpaper	3	7.98	23.94
nickel chromium wire	1000ft	23.12	23.12
		TOTAL	890.68

4.3 Testing Results

When testing the turbine, it was discovered that there was an unexpectedly large amount of friction. This proved to be a problem and completely stopped the turbine from rotating in the fan. The turbine was then taken apart and each of the posts that held the rollers in the cam was filed down so that they did not touch and rub against the track at any point. Once the turbine was reassembled, WD40 was added to the track to further reduce the friction in the cam. While testing it was determined that the large floor fan that was being used gave out wind radially. The wind speed in the center was close to zero, but at 45° out to the side of the fan was giving out 13.4 mph of wind. When the turbine was adjusted to receive the maximum amount of wind it still did not turn. Since the wind speeds found on the top of WPI buildings were comparable to the speeds produced by the fan, the results showed that if something was not changed on the turbine, it would not operate in the wind conditions surrounding WPI.

Another test was performed as a last option to see if extremely high wind speeds would move the turbine even with all of the friction. A leaf blower that operates at 150 mph was pointed directly at the center of the blades along the drag side of the turbine from about 1 foot away. This caused the turbine to rotate extremely well providing about 70 rpm.

Several other problems that may have been contributing to the turbine's resistance to rotation were identified. One was that not all of the bearings were aligned directly perpendicular to the track, which was causing only the edges of some of the bearings, rather than the entire height of the outside of them, to be contacting the track. Since bearings are designed to rotate most freely in the perpendicular position, this irregular

contact pattern may have led to much more friction in the rotation of these bearings than there should have been. Another problem was the width of the cam track. In some places along the track, particularly in the places with smaller radius curves, the bearings were observed to scrape along both sides. If there had been more time, the track would have been widened slightly to eliminate this issue. One last observation about the rotational resistance was that the shaft was not perfectly straight. When the shaft was spun without the airfoils, there seemed to be a variation in the resistance in the bearings depending on the angular position. Such an effect created a small area of high resistance during each revolution. If time allowed, the shaft would have been substituted for a different one with a higher tolerance to diminish this problem.

The shroud proved to be ineffective using the floor fan. The wind provided was so variably distributed that the shroud had no effect other than blocking some of the wind that was coming at the turbine. It was unable to be tested with the leaf blower because it was not built to withstand such strong winds, and therefore it is unclear if it would have had the desired effect of increasing the wind speed at the inlet to the turbine.

5. Conclusions and Recommendations

For this project, a vertical axis wind turbine which combined both lift and drag aerodynamics was designed in order to theoretically be efficient in an urban setting. The urban wind environment surrounding WPI was analyzed along with the data from anemometers that had previously been installed on the roofs of some of the on-campus buildings. These data were used to conclude that in order to have an efficient small scale urban VAWT, the turbine needs to be placed on a rooftop with unobstructed airflow, giving it the greatest power generation potential. It also needs to have a low cut-in wind speed, and have its highest efficiency in relatively low winds. A recommendation for future projects would be to analyze a different urban environment and its wind data and to provide power potential outputs for various turbines for these locations.

Different types of turbines were evaluated to determine which would complement the wind conditions from the gathered information. It was concluded that creating a turbine that combined lift and drag would be the best option. A turbine of this nature was then designed, along with an airfoil that would be efficient and manufacturable, and a shroud that would increase the air velocity where it contacts the blades. This turbine was built, and the testing completed on it led to the conclusion that both the scale of the model and certain design aspects needed to be adjusted in order for it to be successful.

Overall there are many recommendations for this project going forward. The first recommendations relate to the manufacturing of the turbine. For the shaft of the turbine, a lighter material with a higher tolerance should be used. Also, a larger baseplate should be used to allow for room to attach the shroud to it, instead of having it be placed directly on the ground. This would also be beneficial in the future if the shroud and/or turbine are self-

aligning. Lastly, the friction on the turbine needs to be carefully taken into consideration. Too much friction causes the turbine to require more force than can be reasonably expected from the wind in order to rotate it. It is also recommended that the track be widened and lined with some form of lubricant to allow for smooth rolling around the pathway. A suggestion for lining the track with a different material would be to use brass or Teflon, as these materials have less rubbing friction with the steel bearings than aluminum³⁹.

In future projects, the overall size of this model would need to be increased to allow for the blades to gain more surface area and pick up more wind. When doing a test with a leaf blower to see if the turbine would actually work on its own it was proven that it would in fact rotate at about 70 rpm with 150mph winds directed on the center of each blade. Other things that should be considered include eventually testing outdoors in a real wind scenario instead of indoors with a fan or a wind tunnel. Another important thing that needs to be measured is the torque of the turbine. This could be done with a Prony Brake or with a motor or generator. In addition, a self-aligning and rotating shroud could greatly increase the amount of wind captured, thereby increasing the power potential and marketability of this product.

The concept for this turbine is still considered to be valid, and if adjustments were made to mitigate the issues found during the testing, this could be a viable design.

³⁹ (Rubbing Metal-Metal Combinations n.d.)

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7. Appendix

7.1 Additional Figures from Shroud Analysis

It should be noted that for Shrouds #10, #11, and #12 displayed, the shroud is mirrored across the x axis.

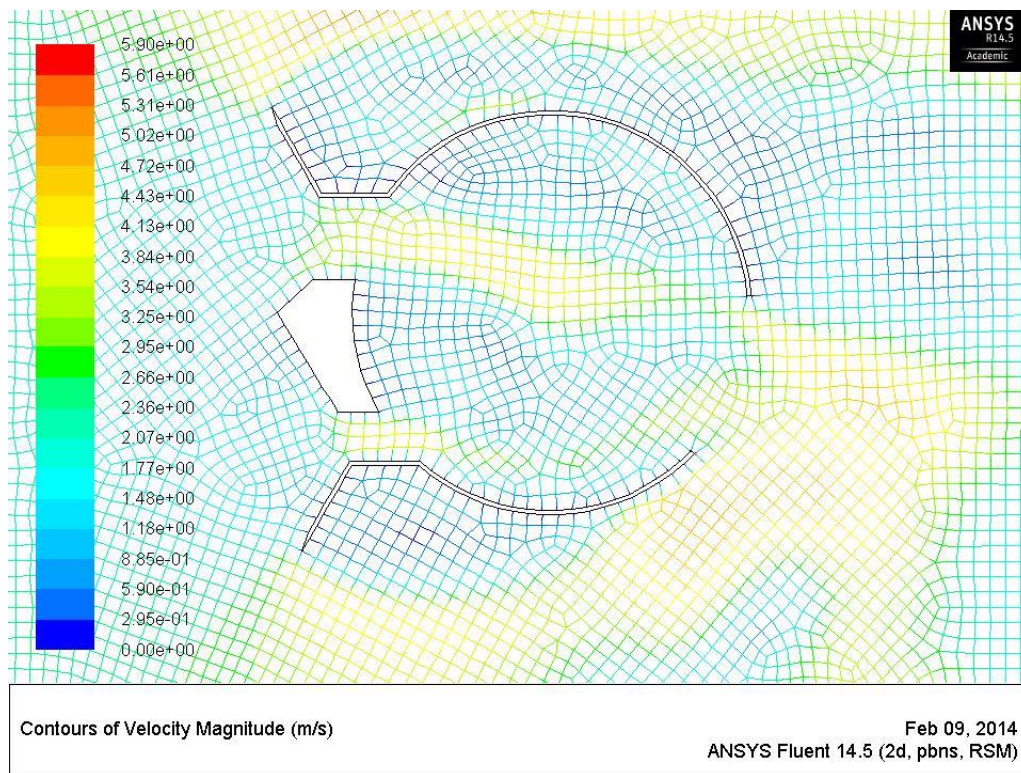


Figure 43: Shroud #10 Fluent Analysis

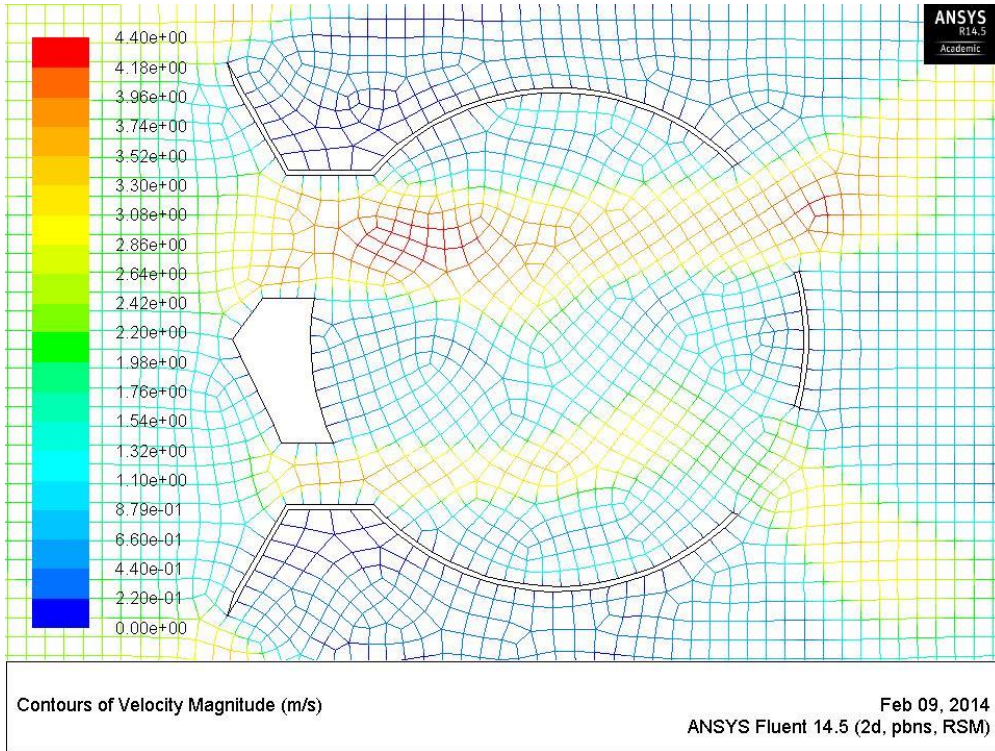


Figure 44: Shroud #11 Fluent Analysis

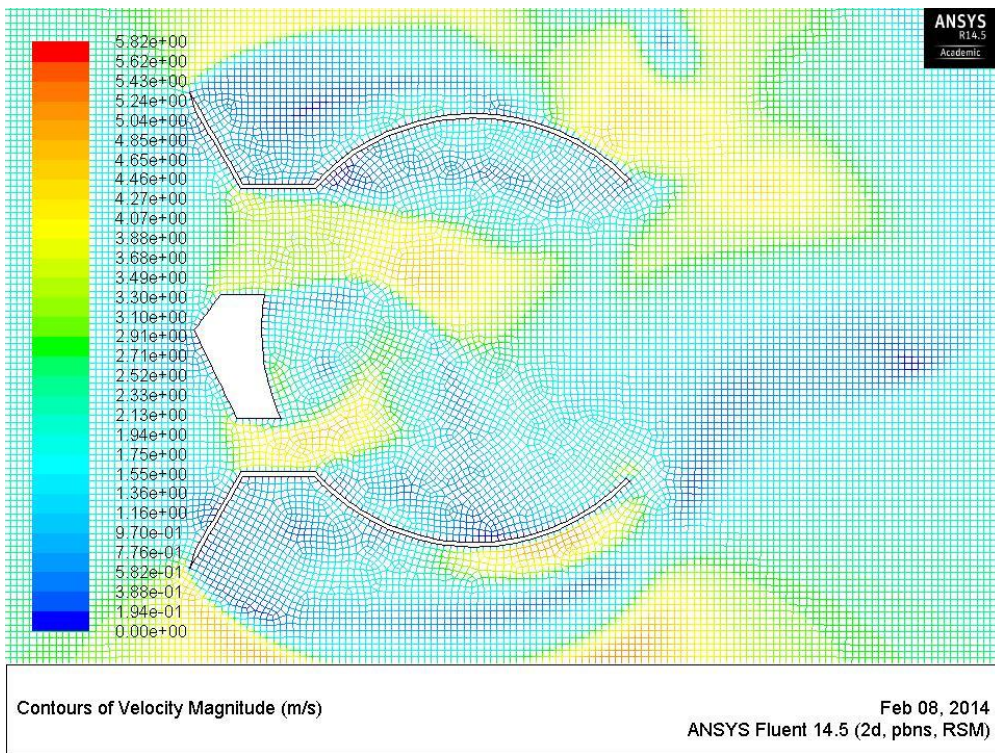


Figure 45: Shroud #12 Fluent Analysis

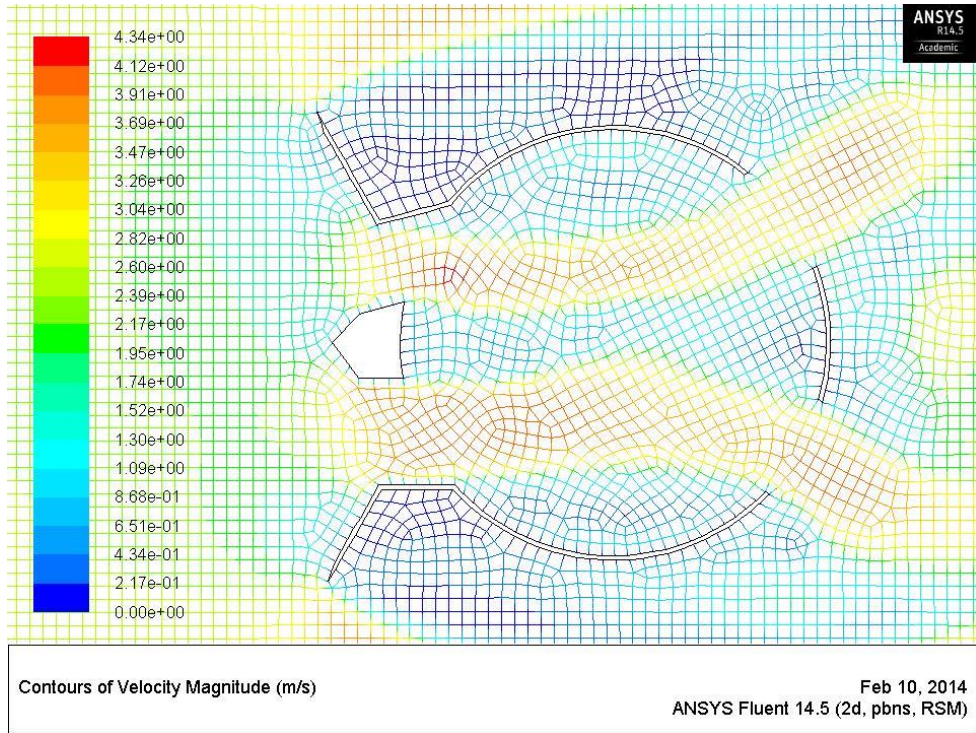


Figure 46: Shroud #17 Fluent Analysis

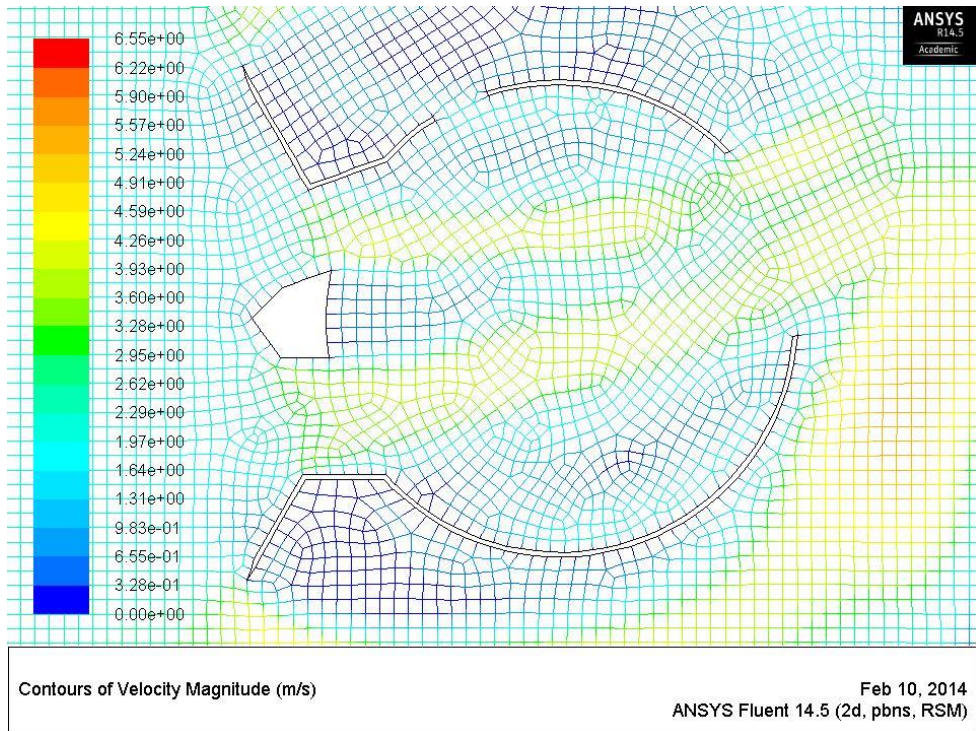


Figure 47: Shroud #22 Fluent Analysis

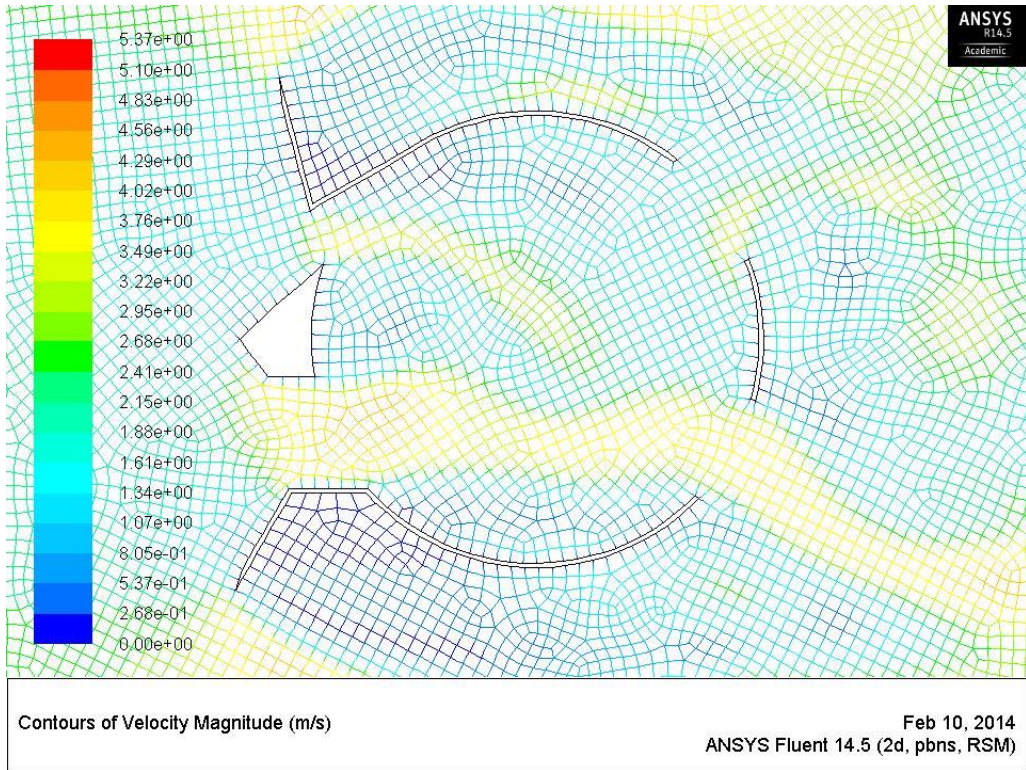


Figure 48: Shroud #23 Fluent Analysis

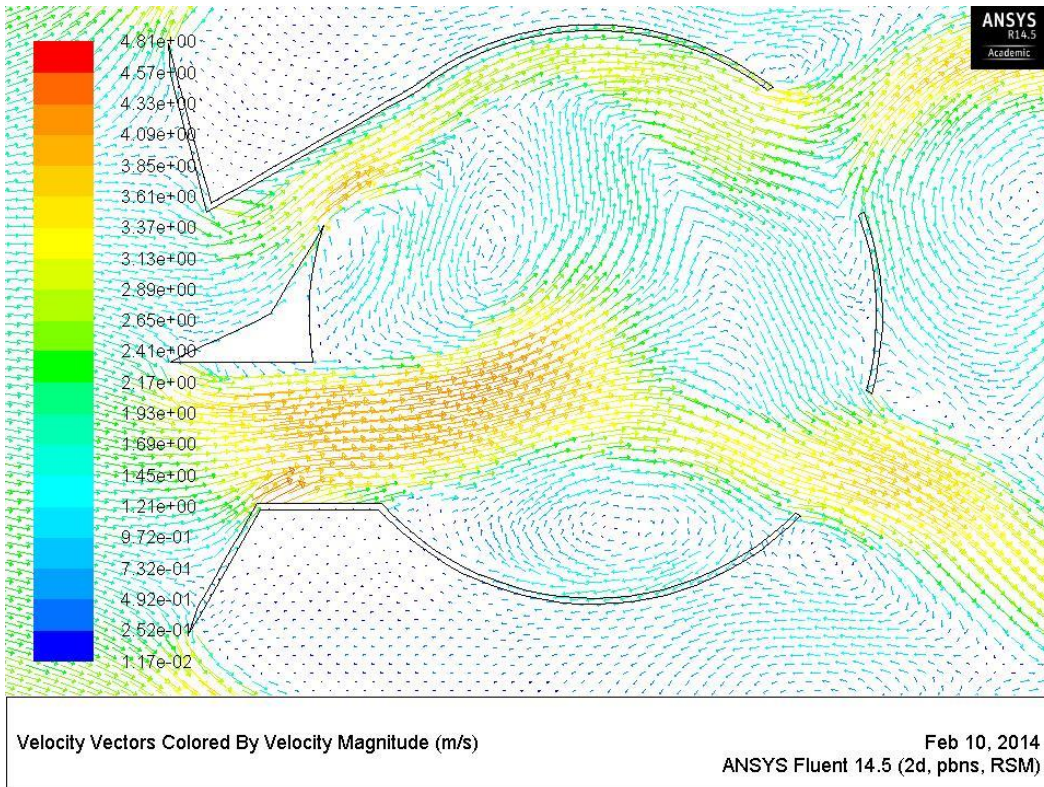


Figure 49: Shroud #25 Fluent Analysis

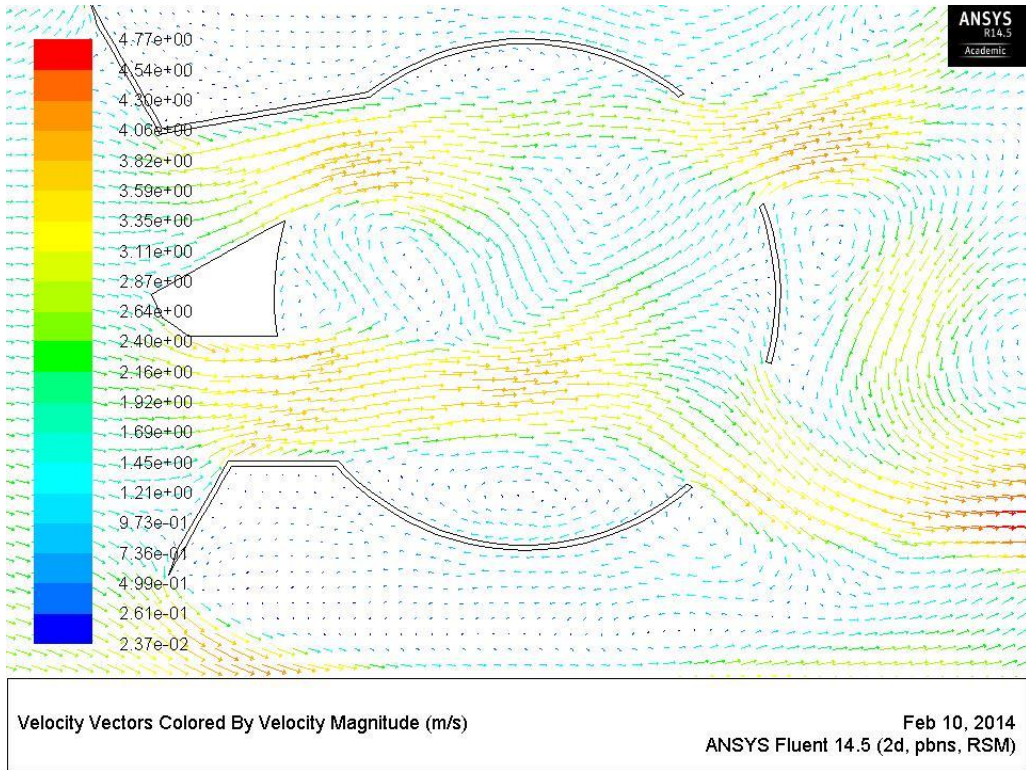


Figure 50: Shroud #27 Fluent Analysis

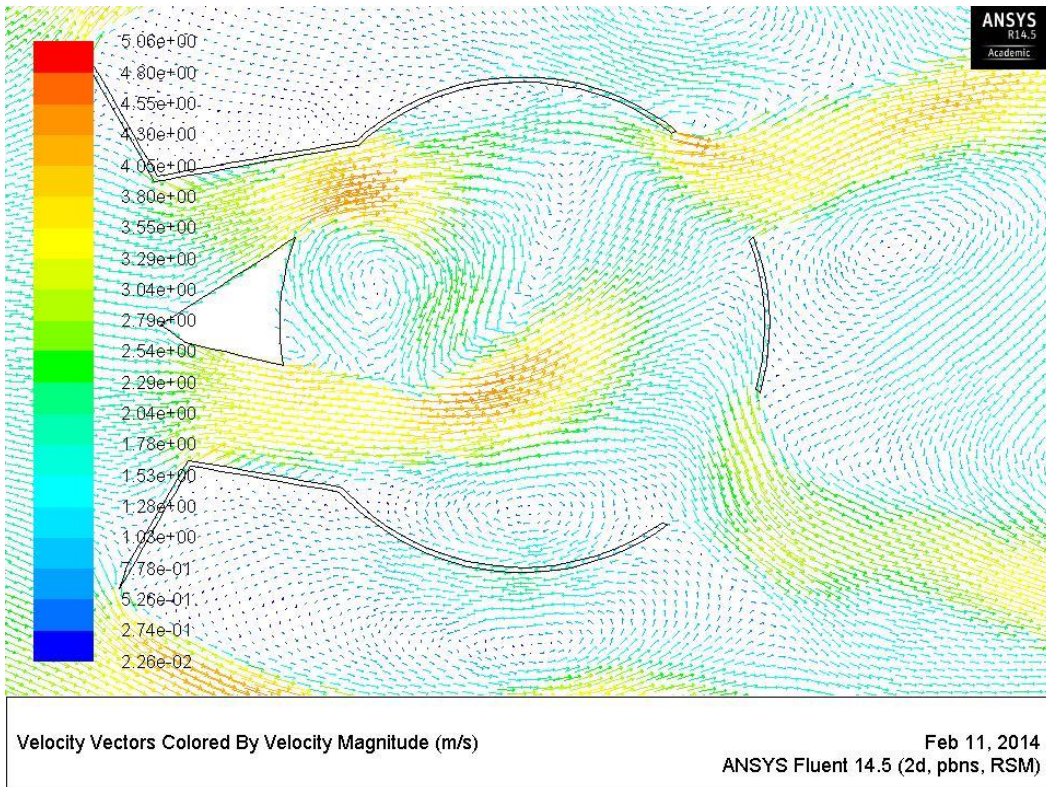


Figure 51: Shroud #28 Fluent Analysis

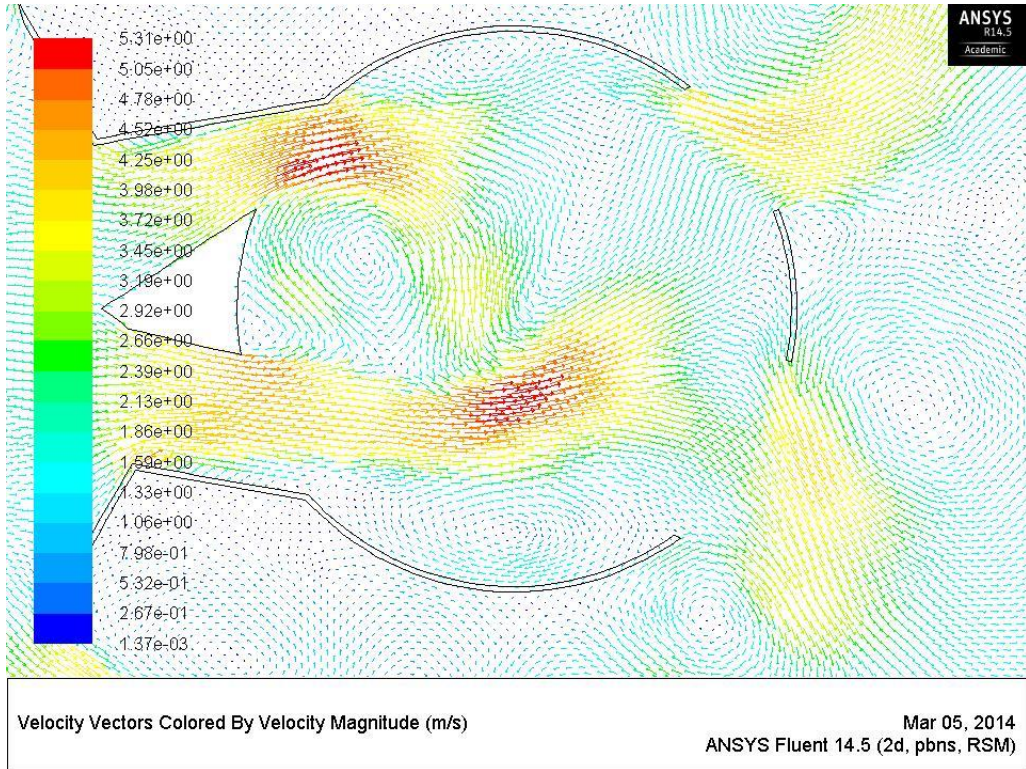


Figure 52: Shroud #30 Fluent Analysis

7.2 Photos of the Turbine

