NAU Collegiate Wind Competition 2016 Tunnel Team ME

Final Report

Randon Allen
Jessica Bauer
Nathan Ceniceros
Jeremy Cook
James Melton
Tyler Richards

2015-16

Project Sponsor: The U.S. Department of Energy (DOE) & the National Renewable Energy Laboratory (NREL)
Faculty Advisor: David Willy and Karin Wadsack
Instructor: Dr. Sarah Oman

Contents

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

1 – Background

The US Department of Energy's (DOE's) Collegiate Wind Competition (CWC) involves 12 colleges around the United States, and is designed to give students a better understanding of wind energy. The competition also gives students real-world experience in the design, construction, and testing of a wind turbine generator and related turbine components (e.g. turbine controls). These aspects are coupled with drafting a business plan of a turbine that mathematically corresponds to a proof-of-concept small scale model. Employers attending the competition will be interested in the experience attained by students and competition attendees. While the CWC final report will contain the details of the business and marketing plans designed to showcase small wind, this report focuses on the mechanical aspects of the small scale build. The sections of this report have been broken up into sub-groups to more clearly identify the different aspects of the mechanical systems: blade design, structural design, and generator selection.

1.1 – Introduction

Northern Arizona University (NAU) was given a place in the DOE's CWC for the 2016 academic year. The competition involved three separate aspects: a business and marketing plan, a conceptual design that coincides with the business and marketing plan, and a small scale wind turbine for testing in a wind tunnel. The three aspects are integrated with each other; the business and marketing plan are based on the conceptual design. The conceptual design is directly scalable (i.e., the dimensions can be changed to meet a required output or physical dimension) from the competition prototype that was constructed by the tunnel team. This distribution of efforts coupled with the interdisciplinary nature of the design and manufacturing of the small scale build emulated an industry setting for designing, marketing, and developing a business plan for a product. The experience gained by the competitors was invaluable for transitioning to industry.

1.2 – Project Description

The purpose of the Tunnel Team was to design a highly competitive wind turbine, which fulfilled the requirements outlined by the faculty sponsors and the DOE. The turbine was taken to competition in New Orleans and tested against turbines designed by other colleges. The Tunnel Team followed the guidelines that were given by the DOE to be eligible to compete in the competition. The turbine was built to the specific size, design, and safety requirements. Care was taken to create a turbine that had a competitive advantage when compared to the turbines from previous years at NAU.

> "Now in its third year, the Collegiate Wind Competition challenges undergraduate student teams to design, build, test, and develop the business plan for a small wind turbine, and to represent their business idea and turbine concept at a national event competing with teams from top universities across the country. NAU was again selected for the 2015-2016 year to field a team of students in this prestigious competition. Mechanical and electrical engineering students on this team will collaborate with business students in developing a viable technical concept and design for an off-grid wind turbine. Off-grid turbines are those that generate electricity or do other mechanical work in a situation where there is no access to the electricity grid. Engineering students will design and build the turbine tested at the competition, and the business students will develop the business plan and collaborate on the turbine deployment strategy. The competition will take place in New Orleans May 23-26, 2016 at the National Wind-Power Conference, which is the largest American wind industry conference. Several students from the team will attend the competition, giving a presentation on the business plan and technical design, assisting with the performance testing, giving a 'public pitch' for the turbine concept, and meeting with industry and government representatives attending this annual event. The student team(s) working on this project in ME 476/486 will meet outside of class with business students and project managers who are faculty and staff at NAU. The design report draft will be completed in the fall semester, and in

the spring semester, some FCB [Franke College of Business] students will be selected to stay on and work with the engineering students to develop a combined business plan, technical report and deployment strategy. Iterations on the design and business plan may take place in the spring. The project will be documented in news outlets, photos and videos, and will receive national attention through promotion by the U.S. Department of Energy [1]."

1.3 – Previous Competition Turbines

The NAU wind turbine Tunnel Team had the ability to look back at the turbines designed from the 2014 and 2015 competitions. By reviewing methods used previously the current team was able to learn from these designs and improve upon the previous team's builds to iterate the next generation design. Along with having the previous turbines to glean information from, the team had contact with participants and clients from previous years. For consistency with the information detailed within the report, only the sub-systems that Tunnel Team ME was responsible for will be discussed.

1.3.1 – 2014 Competition Year Turbine

The 2014 team chose a down-wind horizontal design, which allowed for passive yaw control. The blades selected were an S834 airfoil. These were able to be scaled down to meet the size required for the competition. The original blades were fabricated from carbon fiber; however, there was an issue with testing prior to the competition, and the blades were damaged when the rotor came off the nacelle. The replacement blades were 3D-printed. The material used was not listed in the report that was referenced for the information. A complex mounting system was used to attach the generator components to the nacelle, which was comprised of a 3D-printed skin that was placed over a steel housing. The complexity of the attachment caused some issues with the set-up at the competition, which is why a less complex system was designed for the 2016 competition. The generator was pre-determined by the DOE, which was a Rimfire .32. The rendered design for the 2014 competition turbine can be seen in Figure 1 [2].

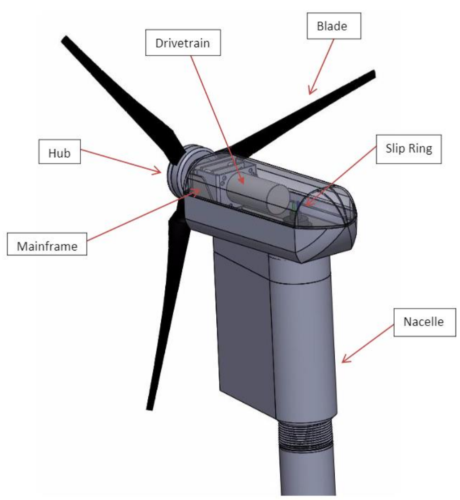


Figure 1: 2014 NAU Competition Turbine

1.3.2 – 2015 Competition Year Turbine

The 2015 competition turbine was built by mechanical engineering students at NAU and electrical engineering students at Kansas State University (KSU). The available report contained the mechanical aspects that were reviewed prior to additional research for the development of the 2016 competition build. The blade style chosen was a S822 airfoil. The pre-designed shape was scaled down to meet the size requirements imposed for that competition year. The blade featured the appropriate contours required for generating the necessary lift to allow the turbine to operate as designed. The structure was broken into two sections, the mainframe and the support. The mainframe was constructed of 1018 steel and attached to the support structure with a snap ring. The support structure was built of the same steel and utilized a slip-ring to allow for it to adjust its alignment to the wind. The generator selected was a Mystery 5010 400kV motor. This specific model is an out-runner design, which designates that the input shaft for the motor is on the outside of the coils. The 2015 wind turbine design can be seen in Figure 2 [3].

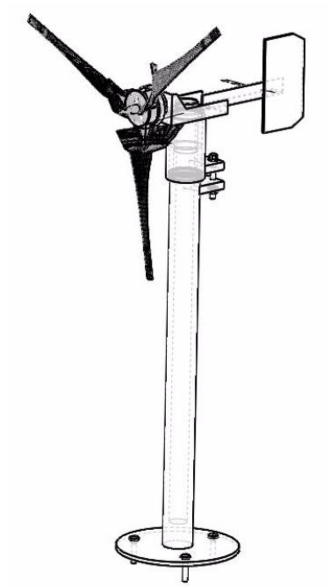


Figure 2: 2015 NAU Competition Turbine

2 – Requirements

This section gives a more in-depth analysis of the requirements for the CWC, based on the rules and regulations issued by the DOE. The input from the faculty mentors assisted in deriving the engineering and customer requirements. These include aspects related to turbine blade design, mainframe and structural support, and generator selection. The team created a House of Quality that rates the importance of each of these customer requirements related to the validity in the project.

2.1 – Customer Requirements

The customer requirements were derived from the rules and regulations document that was provided by the DOE. The requirements discussed in this section were given a rating based on each requirement's level of importance. Table 1 contains the weights for these requirements, based on a total value of 250 points.

Table 1: Customer requirements and weightings

Customer Requirement	Rating (250 Points Total)
Power Curve Performance	50
Control of Power	25
Control of Rotor Speed	25
Load System	25
Wiring and Electrical Connections	25
Cut-in Wind Speed	25
Durability	15
Safety	35
Mounting System	10
Small Scale	15

2.1.1 Power Curve Performance

The highest rated customer requirement in the House of Quality was power curve performance with a rating of 50. The performance was rated the highest due to the performance aspect containing maximum number of points for the DOE competition, when compared to the other tests. The team designed a turbine that can produce its optimal power within the range of 5 to 11 m/s.

2.1.2 Control of Power and Rotor Speed

It is required by the DOE that the turbine will slow itself down when wind speeds higher than 11 m/s are present. The ideal case for competition grading purposes was to design the turbine so optimal power output occurred at 11 m/s. Ratings of 25 were given to both categories due to the competition safety requirements. This allowed the team to control the power and speed to the DOE's requested specification.

2.1.3 Load System

The load system supplied was rated at 25 points. The high point rating of this load was put in place because the DOE grades the load on safety and creativity. Successfully achieving both goals, the design of the load gave the team a major advantage at competition.

2.1.4 Wiring and Electrical Connections

Throughout the project, wiring and electrical connections were essential to ensuring a successful test, safe operation, and clean wiring design. Due to these aspects, the wiring and connections requirement were given a rating of 25.

2.1.5 Cut-in Wind Speed

The cut-in wind speed requirement was rated at 25. While the performance is graded on the 5 to 11 m/s range, bonus points are awarded for power production at slower wind speeds. Emphasis was placed on designing blades that were able to overcome inertial forces and cogging torque near the 5 m/s mark. The blade designed allowed for the most points to be earned at the competition.

2.1.6 Durability

The turbine was built so it was durable enough to withstand testing in the tunnel, transportation, and multiple set-ups. Although this has some importance, the team rated this requirement at 15/250. Along with durability, the safety of the turbine was considered.

2.1.7 Safety

The aspect of safety was rated at 35 points. If the turbine has safety concerns, it will not be able to compete. An emergency braking system was required to ensure that the turbine will stop completely if an issue arises. The turbine must also be stopped by the brake system if the turbine experiences a loss of connection to the load. If there are unseen hazards or a faulty braking system, injury or property damage could result.

2.1.8 Mounting System

The mounting system for the turbine was specified by the DOE. Although it was a simple issue, having mounting hardware not properly aligned with the DOE's testing facility will require-last minute modifications that could delay testing and potentially reduce the overall score. The mounting system has a customer requirement rating of 10.

2.1.9 Small Scale

The size of the design was rated at 15 points. To qualify for the competition, the turbine met the requirements of being sized within a 45cm cube.

The turbine being the appropriate size was required to meet all parameters for testing purposes. Care was placed to ensure that any revisions of size requirements were met and properly adapted to the control system requirements.

2.2 – Engineering Requirements

This section detailed the engineering requirements that were derived to satisfy the customer requirements. The engineering requirements are the technical aspects that show the scientific and mathematical analysis required to determine the feasibility of the project.

2.2.1 – Number of Blades

The number of blades on the rotor affected different performance aspects of the turbine. Based on the blade design used, 3 blades optimized the system. The number of blades affects the tip speed ratio (TSR) of the turbine. The TSR dictates the maximum revolutions per minute (RPM) of the rotor, which affected the amount of power that can be captured from the wind.

2.2.2 – Rotor Inertia

Rotor inertia is a measurement of weight, which is the mass of the object multiplied by the forces exerted on the object. Maintaining a low rotor inertia lowered the cut-in wind speed and allowed the turbine to generate power with lower wind speed availability. The rotor designed was optimized to reduce overall weight and was below the 1Kg maximum.

2.2.3 – Swept Area

The swept area is the rotational area that the blade covers. It has a radius equal to the length of the blade measured from the center of the hub, and was calculated using the area of a circle. The amount of power captured by the blades uses the swept area as a crucial part of the power calculation, which converted wind energy into mechanical energy for use by the generator. The swept area maximum is defined by the DOE and the blade and hub design are within those constraints.

2.2.4 – Cogging Torque

Cogging torque is a phenomenon that occurs in motors and generators when the permanent magnets align with the coils on the stator. A low cogging torque allows for smaller applied forces from the blades to overcome the inertial resistance. The motor selected for the competition had an overall cogging torque of 0.019 N-m ± 0.002 N-m at 95% confidence.

2.2.5 – Efficiency

The efficiency of the wind turbine was most affected by the blade design and the generator selection. The efficiency is a ratio of the energy that is captured and put into the generator and the energy that is converted from mechanical energy to electrical energy.

2.2.6 – Aerodynamic

The aerodynamics analyzed the lift the blades generated. Lift was important because it affected the overall coefficient of power. With a higher coefficient of power (C_P), the blades had a greater ability to capture power from the wind and convert it into mechanical energy. Dividing the coefficient of lift (C_l) by the coefficient of drag (C_d) describes the aerodynamic properties of the airfoils. The higher the C_l/C_d results in more lift generation, which returned a higher C_P.

2.2.7 – Scales to Full Size

Scalability was a requirement for the DOE CWC competition. This was met by having the Deployment Team’s turbine linked to the Tunnel Turbine mathematically.

2.2.8 – Quick Assembly

Due to DOE requirements for the CWC competition, the entirety of the testing must be completed within 30 minutes. To gain the maximum timeframe for testing, the assembly was simple so assembly was quick in the wind tunnel.

2.3 – Testing Procedures

The testing procedures describe the tests that were planned and carried out for the discussed aspects contained within this report. Each engineering requirement was linked to one or more testing procedures to ensure the engineering requirements adequately satisfied the customer requirements. The detailed testing procedures, and the engineering requirements they link to are discussed below.

2.3.1 – Physical Parameter Testing

Testing the rotor inertia and the swept area of the components required using standard measurement equipment to determine the values necessary for comparison with the targeted tolerances. A scale was used to weigh the entire hub and blade assembly once it had been manufactured. This allowed comparisons with the desired inertial weight. To determine the swept area, the diameter of the assembled hub was measured and the area calculated using the formula for an area of a circle.

2.3.2 – Motor Torque Testing

To test the cogging torque on the generator selected, a testing apparatus was designed and constructed. The apparatus held the motor stationary while a lever arm was placed onto the input shaft of the motor. The lever arm was leveled with the horizontal axis and weights were added to a specific point on the arm. When enough weight was added, the cogging torque was overcome and an estimate of the force necessary for overcoming the cogging torque was calculated. To lower uncertainties and errors within the experiment, a low resolution weight was used and multiple trial results were recorded. This data was analyzed statistically to determine the forces required and the tolerances of those forces.

2.3.3 – Motor Efficiency Testing

To test the efficiency of the motor, a dynamometer was used that was designed and assembled for the specific purpose of testing small scale motors as generators. Two different electrical tests were performed, an open circuit voltage test (OCV) and a loaded current test (LCT). The OCV tested the motor at various revolutions per minute (RPM) and provided a no load voltage with the output leads open. By testing at different RPM, established a voltage versus RPM curve. The LCT loaded the motor with a variable resistor and a shunt. The resistance of the resistor was measured disconnected from the circuit and recorded. Based on the voltage drop across the shunt, the current through the circuit was calculated. Using the voltage and current curves, an optimal power output RPM was determined.

2.3.4 – Aerodynamic Testing

The aerodynamic testing took place in the local wind tunnel once the turbine construction was completed. This allowed for estimations of the C_l/C_d and establishing how much energy was being captured from the wind.

2.3.5 – Point Load Testing

Testing the integrity of the structure and the base plate welds involved mounting the plate and tower horizontally with the motor mount facing up. To simulate a point load, a weight was placed on the motor mount surface. Initially a weight of 5Kg was used because it was equivalent to the amount of force that would be created for having a solid plate the size of the swept area of the turbine blades in a wind of 24m/s.

2.3.6 – Timed Testing

Once the components of the turbine were manufactured, timed testing involved using a stopwatch and measuring the time required to assemble the turbine. As expected, the amount of time necessary for assembly lowered with practice.

2.4 – Design Links

The design links show how the design of the project satisfied the engineering requirements derived to meet the customer's needs. A brief overview of the design links are in the sections below. The actual design is discussed further in Chapter 5.

2.4.1 – Rotor

The blade design satisfied the engineering requirements by using three blades. The rotor supported the blades and helped optimize rated power and cut-in speed. The swept area was set by competition conditions, the rotor designed took full advantage of the limitations imposed. The rotor overcame the rotor inertia by having the blades twisted to match the Betz optimal twist angle at each blade section except the root where an added twist was included to compensate for the low Reynolds numbers the rotor operated at. The rotor's aerodynamics were met as the blade shape and airfoils achieves a lift to drag ratio greater than 25.

2.4.2 – Motor Selection

The motor selection directly affected the efficiency and the amount of cogging torque that was experienced by the wind turbine. The generator selected has an optimal pole to stator coil ratio. The poles are on the armature ring, which rotates when the mechanical energy is put into the system. The stator coils are on the interior of the motor and do not move. The electrical energy is generated through magnetic induction, when the magnets pass over the coils.

2.4.3 – Scalability

The requirements for the DOE were met, the small scale turbine that was designed was linked to the Deployment Team's turbine design mathematically. This allowed for the design to be directly scaled up meeting the CWC requirements.

2.4.4 – Structure

The structural design affected the integrity and the assembly time of the turbine. By combining the nacelle and tower into one component, it reduced the amount of time required to assemble and the number of failure points. The streamline profile of the airfoil structure and the lack of nacelle increased the overall aerodynamics of the wind turbine

2.5 – House of Quality (QFD)

The following House of Quality, Table 2, was laid out to prioritize the customer requirements, which are connected to each of the engineering requirements listed along the top of the chart. It was used by the team to properly characterize the level of importance for each aspect of the design and how it pertained to the customer requirements.

Table 2: CWC Tunnel Team ME QFD

		Engineering Requirements								
Customer Requirement	**Weight**	**# of Blades**	**Rotor Inertia**	**Swept Area**	**Cogging Torque**	**Efficiency**	**Aerodynamic**	**Scales to full size**	**Structural integrity**	**Quick Assembly**
Rated Power > 10W	50	9	3	9		9	9	6		
Power Curve Performance	50	9	3	9		9	9			
Control of Rated Power	25	6	6	3	6		6			
Control of Rotor Speed	25	6	9	6	9		6			
Cut-in Wind Speed	25	9	9	9	9		9			
Cut-out Wind Speed	25		9		9					
Durable	15								9	6
Mounting System	15								9	9
Small Scale	20							9	3	6
	250									
Target(s), with Tolerance(s)		3	>1kg	0.16m²≥	>1Nm	40% ± 5%	L/D>25	LTE	FoS>5	5 Min≥
Testing Procedures		-	1	1	2	3	4	-	5	6
Design Links		1	1	1	2	1,2	1	3	4	4

3 – Existing Designs

The existing designs showcase the research gathered and the methods used, which ensured a successful design for the mechanical aspect of the small scale build. The information gathered was used to compare the designs with the previous competition years' builds. The details available allowed replication of the things that were done well and to improve upon the areas which experienced issues. Due to the scale of the competition turbine, which produced 30 Watts at maximum output, no commercially available products were comparable to gather information for development of this turbine.

3.1 – Design Research

Researching appropriate topics for the development of the mechanical turbine involved using readily available materials from courses that members of the team took. Wind Energy Engineering was a course that was comprised of information and materials that were necessary for the development of the turbine blades. Ranging from the calculations that were made to determine power harvesting and torque development of the blades used, to the theory on how wind power was captured were gone over in depth within the course.

Another course that members of the team took was Power Systems, which gave an overview of how electrical power is transmitted from the power plant to the consumer. This course gave insight into how to most efficiently transfer the power generated to the components that needed the power to function appropriately during the competition.

The information gained from this coursework, coupled with the research performed at the sub-system level allowed for the development of a competitive turbine for the DOE competition.

3.2 – System Level Research

The system level research performed involved reverse-engineering the 2014 and 2015 competition turbines and an analysis was performed on an older Whisper that was developed by Southwest Wind Power. The research yielded a baseline for the development of the turbine that was used for the DOE competition.

3.2.1 – 2014 Competition Turbine Reverse Engineering

The analysis performed on this design yielded information that was invaluable for the turbine that was developed. The use of carbon fiber blades was desirable, due to the strength characteristics of the material. The down-wind design was considered and rejected due to reliability issues that arose during the analysis, namely the rotor came loose during testing and caused a catastrophic failure of the system. The complexity of the assembly required excessive time to disassemble and reassemble, just shy of 15 minutes when timed. Considering the requirements of the DOE competition, where only 30 minutes was allowed for assembly and testing, an easier to assemble turbine was built [2].

3.2.2 – 2015 Competition Turbine Reverse Engineering

The 2015 competition turbine featured an up-wind design, which removed the major failure point experienced by the 2014 competition year. This turbine also featured a different style of generator from the 2014 competition year, which yielded a higher power output for the competition [3]. Given the successes that were achieved for this competition year, the turbine provided a baseline for the necessary research on the mechanical sub-systems.

3.2.3 – AirBreeze Analysis

The AirBreeze that was analyzed was obtained specifically for the purpose of disassembly to see how the different components of the turbine interacted with each other. Some of the information obtained assisted in the starting point for the various sub-systems that were researched. The competition turbine was not required to have a yaw system in place, so those portions of the AirBreeze design were ignored for the development of the 2016 turbine. The AirBreeze utilized a Permanent Magnet Induction Generator (PMIG) which was too large for use in the DOE competition; however, it provided an ideal ratio of stator coils to magnets for the selection of the generator for the small scale build.

3.3 – Subsystem Research

Research and testing allowed the Tunnel Team to look for ways to improve upon the designs created by the 2014 and 2015 competition teams. With the limited information available regarding these designs, pursuing other options was a requirement to ensure a successful build for the 2016 CWC turbine. The following sections outline the additional research that was performed by the individual sub-groups to supplement the available information from the previous years' turbine builds. The research involved looking through technical reports and journal articles for more information as well as market research to see what products were currently available.

3.3.1 – Blade

The blades of a wind turbine use lift forces created by a pressure gradient to rotate. This pressure gradient is created by the shape of the airfoil, which accelerates wind on top of the blade. This causes a low pressure zone while the air under the blade travels at the original speed, creating a high pressure zone. The resulting lift force causes the blades of the wind turbine to rotate. Figure 3 shows a visual representation of lift force generation.

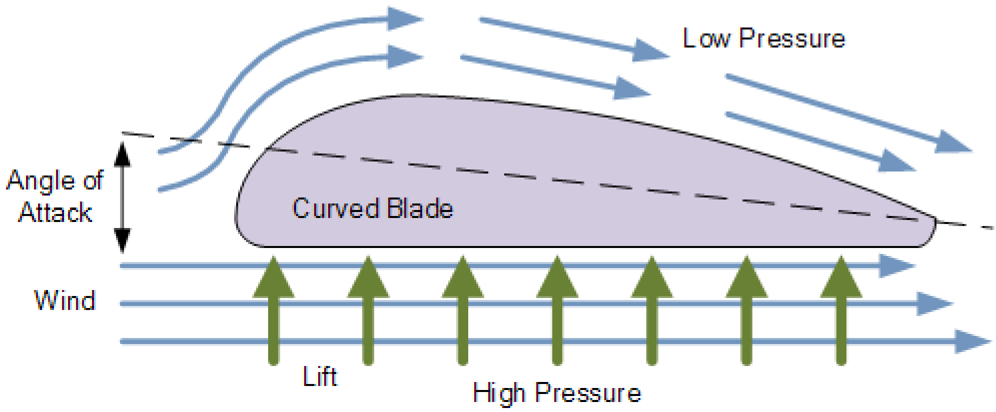


Figure 3: Mechanics of a Wind Turbine Blade [4]

As the competition rules stated, the rotor must have a diameter no larger than 45 cm [5]. The blades should begin rotating when the wind speed is 5 m/s to begin power production. There are many different airfoil designs being used in the market, with each one having its own range of cut-in speeds and optimum running speeds.

The NAU CWC team from 2015 used a S822 airfoil, shown in Figure 4, and the NAU CWC team from 2014 used a combination of S834 and CP-080-050-GN airfoils, shown in Figure 5.

Figure 4: geometry for airfoil S822 with average error in inches [5]

Figure 5: geometry for airfoil S834 with error in inches [5]

Designing the blade was a complex process because the blade must be lightweight but also have high strength rigidity. The top half of the blade experiences compression-compression loading in high winds, while the bottom half experienced tension-tension loading. So the blade needed to be made of a material that has a high compression and fatigue strength [7]. The blade root experienced the most stress during operation; therefore, a finite element analysis (FEA) was performed on the blade root using the computer program SOLIDWORKS. This analysis identified any weak points on the blade root that were vulnerable to failure.

Carbon fiber was the material chosen for the blades due to its high tensile and compressive strengths and because of its lightweight composition. One drawback to using carbon fiber was anticipated cost and in commercial applications, it is used in high stress areas of the blades, such as the spar, which is a stiffening support attached on both sides of the blade. Aside from cost, the challenges that were experienced by using carbon fiber were the time required for curing and the intricacy of the finishing process [7].

E-glass is a common type of fiberglass used to construct wind turbine blades. Being heavier and weaker than carbon fiber, E-glass is not an optimal material to make wind turbines blades, but it is less expensive than carbon fiber [7].

Dielectric polymers generate power when they are deformed. Although dielectric polymers have been used to generate power or used as an actuator, our idea is to use them as a sensor in the blade that would allow wind turbine operators to see stress in the blades by measuring the electrical output. This would give wind turbine operators another tool to monitor the condition of the wind turbine's components [8].

3.3.2 – Structure

The structural system for the wind turbine was broken down into three components: the nacelle or mainframe, the base, and the tower. The nacelle is the portion at the top of the turbine that contains the generator and the blade mounting apparatus. Depending on the configuration, the electrical control systems may be in the nacelle as well. The base or baseplate of the turbine is the structure that supports the weight of the nacelle and the tower. Its purpose was to provide a stable surface for the other components to rest on. For the purposes of the competition, a base plate was used that allowed the turbine to be semi-permanently attached to the testing apparatus via bolts. The tower is the support structure that connects the nacelle and the base plate. Depending on the parameters for the design, the tower can be adjusted in length to allow the turbine to achieve a target height to take advantage of stronger wind currents. For the competition, limitations were in place that determined the length of the tower.

The nacelle was removed from the design so that it did not interfere with the downwind flow from the turbine blades. The material for the mainframe was a steel square tube to mount the generator to the tower.

The connection between the mainframe and the tower will be fixed. This will eliminate the need for the turbine to have a tail piece, which allows for yaw control. The hub was made of 6061-T6 aluminum and was balanced with the blades installed to prevent errant vibrations at high RPMs.

The previous years' competition turbines used cylindrical steel pipes for the tower. This allowed for the installation of a slip-ring, a component that allowed for full rotation, but did not bind the electrical wiring running from the nacelle to the base. The benefits of using a pipe for the central support: high strength, low cost, durability, and easy fabrication. Mild steel pipe is abundant at many hardware stores and can be easily welded to the baseplate and nacelle/main frame.

Other possibilities for the support tower were researched as alternatives to the previous years' choices. They include utilizing square tubing or using a carbon fiber airfoil for the support structures. The benefit of a square or rectangular tube is that it would have a high bending moment, making it structurally sound. The shape allows for easy fabrication and mounting of components to the tower. A drawback to a tower design using square tubing is that it creates more turbulent airflow that would interfere with the function of the turbine blades. The use of an airfoil shape resulted in lower drag forces from the wind acting on the tower. Figure 6 contains examples of different structure materials.

The DOE provided some specific structural requirements and needs for the wind competition. The structure was created to hold the rotor within 2.54 cm of the center of the wind tunnel. The base plate met the specified dimensions to mount to the testing stand [6]. The base plate schematic is shown in Figure 7.

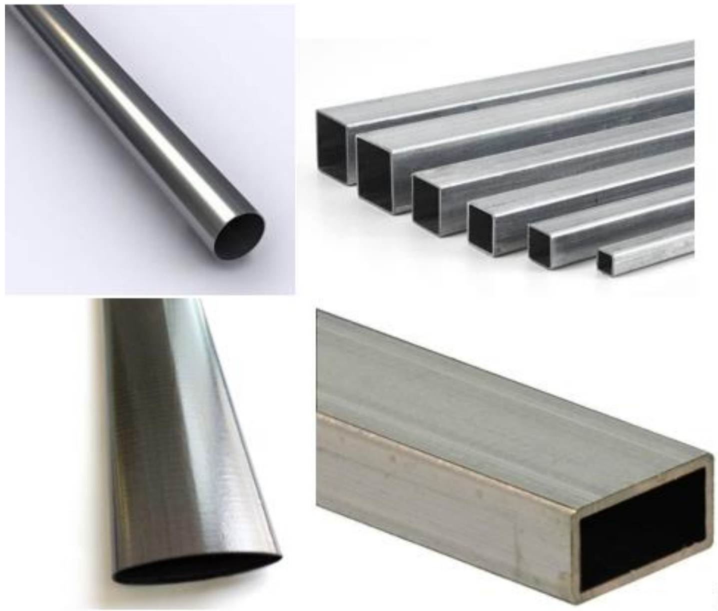


Figure 6: Steel pipe, square and rectangular tubing, and a carbon fiber airfoil

The base plate can be made from many different materials and thicknesses. However, due to the simplicity of the part, eighth inch A36 Mild steel was used to keep the price down and maintain strength.

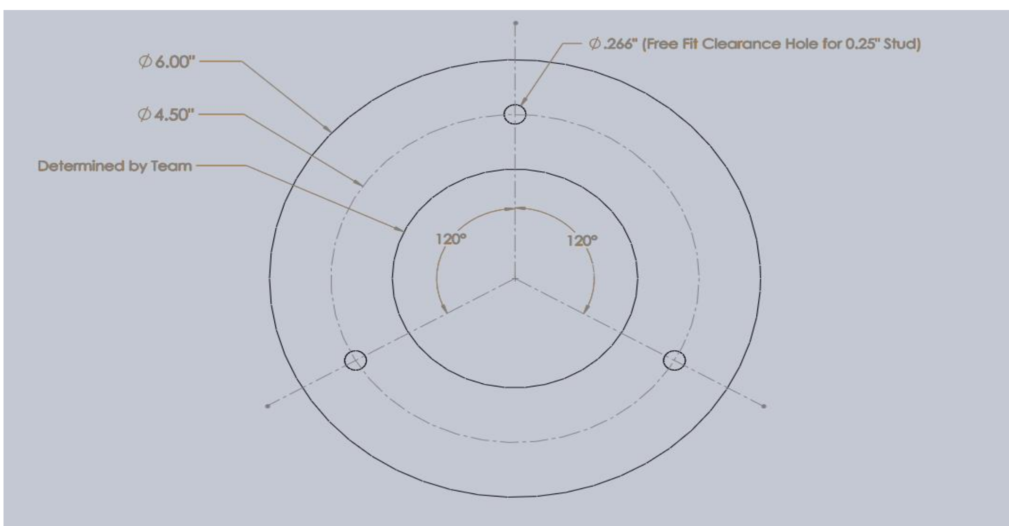


Figure 7: Base plate dimension requirements [1]

The testing for the structural system was broken into three separate pieces: the mainframe, tower, and mounting plate. Each section of the structure had different requirements for strength, durability, and rigidity. The initial force analysis of the pieces, general forces of an area and point forces were used to determine an appropriate material. After the material was selected, the computer program SOLIDWORKS was used to perform FEA on each part to determine any potential design weaknesses.

The design chosen for the tower determined the necessary test parameters. An airfoil was chosen for the tower; a full FEA was completed before material selection. With an airfoil, the forces are unevenly dispersed and have higher stress concentration factors, but provide less downwind flow interruption. To ensure a factor of safety above 10, 4130 Chromoly steel was selected for use in the construction of the tower.

The mounting plate had very little design room because the DOE supplied the measurement and material specifications. The mounting plate cannot be thicker than half an inch and must be able to withstand a force of ten N-m. In addition, the mounting plate must have three quarter-inch holes spaced at 120 degrees apart spanning a diameter of four and a half inches. Due to the success of the previous years' mounting plates, a similar design was used.

3.3.3 – Generator

The generator of the turbine utilizes properties of magnetic induction to produce an electrical current. Due to the requirements of the competition, which restrict overall size of the turbine, the generators researched were manufactured for small model applications. The market research showed the differences in motors designed for model remote controlled airplanes and model electric trains.

Small scale motors/generators are used for miniature, remote controlled, battery powered models. Model airplanes and model electric trains were used for research purposes to meet the size restrictions imposed by the CWC rules and regulations. Another aspect of generator design was to determine the type of electrical power that needed to be generated. Consistency with current practices in industry limits this to the following: three-phase alternating current (3-AC), single phase alternating current (AC), or direct current (DC). There are advantages to all forms of power generation; however, which type is used is determined by the circumstances of the power transmission. For maximum output of the generator for the turbine, 3-AC produced the most power per RPM compared to the other two commonly used power types [6].

Cogging torque was another aspect considered for generator selection. Cogging torque is a force that needs to be overcome before the generator can start spinning and producing power. This force is caused by the interaction between the generator magnets and the generator coils. Options were considered to reduce the cogging torque. Lowering cogging torque increased the cost of the generator and reduced its maximum power output.

The state of the art technology included changing the electrical and magnetic properties of the motor to increase efficiency. By removing the spaces between the permanent magnets on the rotor, the cogging torque is lowered, but this process is expensive and lowered the overall power output of the generator. Using an air-cored motor can increase power generation by increasing heat dissipation within the generator coils, which allows for a higher RPM to be achieved by the generator before failure occurs. Using a brushless motor removes wearing components that have been standard to motors/generators since their conception. A brushless motor rotates a permanent magnet rotor by switching the polarities of electromagnets within the stator.

The faculty sponsor for this project required that the generators from the previous competition turbines be tested prior to testing additional generator options. The testing procedure included using a dynamometer that ran the generator, allowing for the testing of power output at various speeds. This test provided the necessary data to generate a plot for the power curve, which will gave a baseline for outputs to meet or exceed for future motors to be tested.

4 – Designs Considered

Tunnel Team ME went through concept generation to develop solutions for the different sub-systems of the wind turbine. In addition to sub-system solutions, different layouts for the overall design were weighed which determined the most appropriate style of turbine used for the CWC. By considering the different options available, it was determined which solutions were the most feasible for the design considered.

4.1 – Full System Design

The team considered three designs for the complete turbine. The designs were: a vertical axis wind turbine (VAWT), a downwind horizontal axis wind turbine (HAWT), and an upwind HAWT. The three designs have aspects that contributed to increased wind generation, but some designs lowerd the overall efficiency of the system.

4.1.1 – Vertical Axis Wind Turbine

Vertical axis wind turbines use blades attached to a shaft that is perpendicular to the ground to catch the wind. The drag that the wind imparts on the blades forces the shaft to rotate. The rotating shaft can be attached to multiple generators to produce power. These generators are considered more aesthetic than the horizontal counterparts; however, they are more costly to maintain, and manufacture. They have a lower overall power output.

4.1.2 – Downwind Horizontal Axis Wind Turbine

The downwind HAWT utilizes a passive yaw system, which means that the turbine blades are designed to force the turbine to align itself with the direction of the wind that generated the most power. These systems have a lower efficiency than their upwind counterparts due to the wind shade that the nacelle casts onto the turbine blades. This effectively lowers the overall cross sectional area that is available to capture wind to generate power. The lower stresses applied to the blades are desirable in higher wind areas, where the wind shade has a lower effect on the system's ability to generate power.

4.1.3 – Upwind Horizontal Axis Wind Turbine

Upwind HAWTs are designed to have their turbine blades at the front of the nacelle. The system utilizes a tail to adjust the yaw as the wind changes direction. These systems are generally heavier due to more rigid blades and the tail on the end of the nacelle. Due to no wind shade from the nacelle, the upwind systems have a higher overall efficiency than their downwind counterparts. The drawbacks are that there are higher forces applied to the turbine blades, which required them to have a more rigid construction.

4.2 – Sub-system Design

4.2.1 – Blade Design

The turbine blades fulfilled a specific need for the wind turbine. Being the only source of power to the generator, the blades needed to provide the maximum efficiency possible in converting the energy of the wind to mechanical energy going into the generator. Nature provided an insight to look into the design further.

The first design considered was modeled from the flight feathers of a bird. Having a surface area and shape conducive to generating lift was applied to the wind turbine. A number of pre-existing airfoil shapes were available to use as a reference for the slight re-design which met the specifications required. By modeling the blade from the shape of a flight feather, it gave an advantage in certain ranges of wind speeds.

Utilizing the pre-existing blades selected by the 2014 and 2015 CWC teams were also considered as an option. The S882 and S834 airfoil shapes were efficient at allowing the small scale turbine to capture wind to generate rotational motion.

The shape of the body of a fish swimming upstream was also considered for a profile. Fish have evolved to be capable of swimming upstream expending as little energy as possible. Utilizing this design which evolved and was optimized in a denser fluid than air had potential as a possibility for the turbine blades if the differences between the fluid flows were minimal. A rough sketch can be seen in Figure 8.

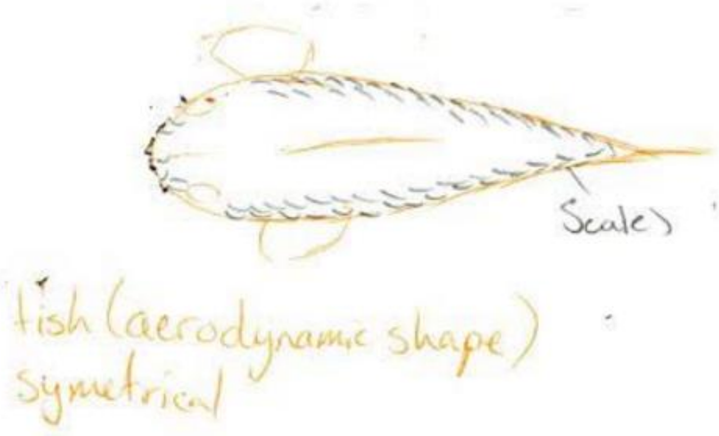


Figure 8: fish body sketch

A pine seed was another option considered for the initial blade profile. Having the ability to travel long distances via wind currents gave the pine seed the ability to find places away from its parent to grow. The profile offered the advantage of a higher lift to drag ratio, which allowed for a larger mechanical advantage introduced to the wind turbine from the blades.

The last option considered was flower petals. Flower petals have evolved to maximize their surface area while maintaining a minimal amount of material required for their development. This aspect assisted in allowing for a lower volume turbine blade that was capable of capturing the flow of the wind more efficiently. The sketch for the design can be seen in Figure 9.

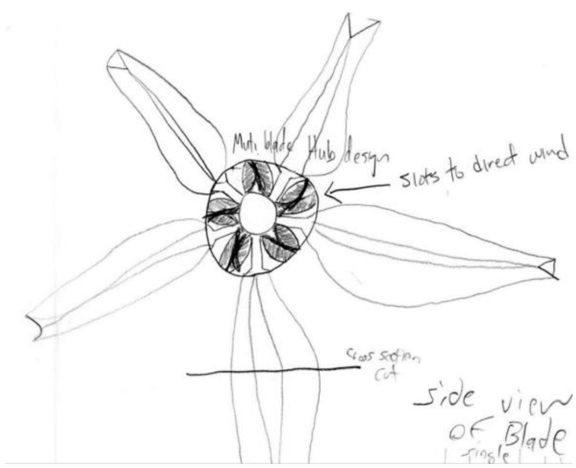


Figure 9: sketch of flower petal design

4.2.2 – Structural Design

The structural system contains the mainframe, tower, and base plate. These parts meshed well and adequately supported the rest of the wind turbine structure. The first design considered for the tower was a straight, half-inch diameter circular pipe welded to the mounting plate. This design was simple to fabricate and inexpensive. The drawbacks were: pipe is not very aerodynamic and would cause downwind disturbances. When using a pipe design, attaching the nacelle would be difficult, requiring welding or some other mechanism to secure the nacelle. This overall design increased weak points within the system.

The second design considered was a 3D printed airfoil. This allowed for the nacelle to be integrated seamlessly into the tower. The 3D printed tower/nacelle had streamlined aerodynamics to decrease the downwind disturbances. The drawbacks of 3D printed materials, they are weaker and have directional properties. This would have caused safety issues and structural failures to occur at points of high stress concentrations. Additional analysis determined the plastics available would not be sufficient to meet the requirements for the competition.

A carbon fiber airfoil was also considered and would provide streamlined aerodynamics downwind of the turbine. This reduced the downwind disturbances caused by the turbine as well as allowed for a higher efficiency due to decreased blowback onto the turbine blades. Carbon fiber provided adequate structural strength and offered a lightweight option for the tower support. The problems with carbon fiber were its high cost and difficulty to work with for intricate fabrication.

Two designs were considered for the nacelle shape. The first was using the body of a small bird in flight. A bird's aerodynamic properties and capability to travel long distances using minimal energy offered an excellent solution for drag reduction and shear forces onto the turbine from the wind. A teardrop shape, like a rain drop in free fall, was also considered. This shape forms naturally and has a low drag due to the nature of its formation. Figure 10 shows the initial sketch of the nacelle design.

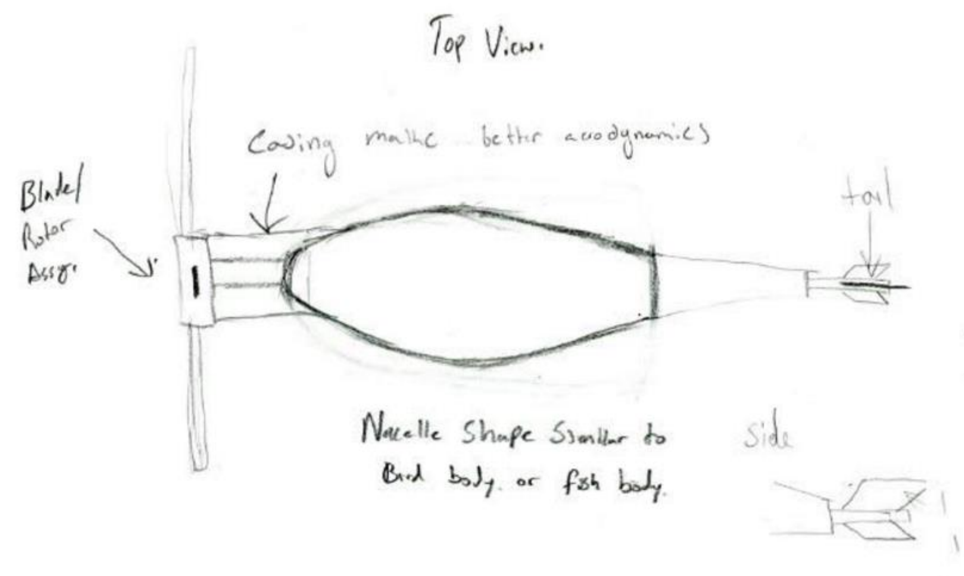


Figure 10: bird body nacelle sketch

4.2.3 – Generator Design

The Generator team applied the generator requirements to industry models in order to select proper ideas for the tunnel wind turbine design. In order to select a proper design, certain criteria had to be met. These included low cogging torque, a range of motor revolutions per volt (K_v) of less than 500 K_v, and the ability to easily mount and change generators during testing.

The first design idea was to locate an off the shelf out-runner motor which would be disassembled to reconfigure the windings, stators, and armatures. This process was done to try to reduce the air gap between armatures and would also reduce the cogging torque of the motor.

The second design idea would be to purchase a Turnigy 4114 370K_v brushless motor. This motor was designed for quadcopter applications, costs $60-70 and has positive qualities for the wind turbine application. The motor has 24 poles, which reduced the amount of cogging torque when compared to competition motors from the past with only 12 or 14 poles. The Turnigy motor was designed with mounting holes that were used for easy fastening to the nacelle. By adding additional poles and being designed as an out-runner, this model may be exceptional for the application [11].

The third option discussed was the SunnySky X4108S 480K_v brushless out-runner motor which costs $40-50. The SunnySky motor has 24 poles, similar to the Turnigy. This motor also has mounting holes similar to the Turnigy 4114 design. Along with these qualities, the websites that sell the product provide tables with information necessary for selection [12].

Using a traditional brushed motor was discussed. These motors have been in production for a long time and are readily available. The drawbacks to them are the decreased efficiency due to the brush and commutator requirement for operation, electrical excitation is required for them to generate power in the ranges necessary for the competition, and they have more wearing parts, which means increased failure points.

5 – Design Selected

The selected design that performed the best in the CWC, Tunnel Team ME selected an overall style for the wind turbine as the first step. With the overall design selected, the sub-teams chose the designs that scored the highest with a decision matrix which were used in the final design. Selecting individual system designs allowed for the technical expertise of each team to be best utilized and generated an overall design that is more suitable for the competition in the spring.

5.1 – Full System Design

Collaboration between teams was required in selecting the overall turbine design due to the competition requirements. Table 3 shows the Pugh chart for the final design selections. A Pugh chart utilizes a datum that is randomly selected to compare against the other design options. The options are scored in a manner as better than, worse than, or same as. This allowed for a quick determination of which designs will not be viable as the final option.

Using the data from the Pugh chart, a decision matrix was built to score each system to determine which would be selected for the final design. The decision matrix for the overall design can be seen in Table 4.

Table 3: Full System Pugh Chart

Criteria	Downwind HAWT	VAWT	Upwind HAWT
Complexity of design	D	-	+
Aesthetics		+	s
Rated power	A	-	s
Maintenance	T	-	s
Cut-In wind speed	U	+	s
Rated wind speed		-	s
Size/Weight	M	-	+
Noise		-	+
Sum of +		2	3
Sum of -		6	0
Sum of s		0	5

Table 4: Full System Decision matrix

Criteria	Weight	Vertical Axis Wind Turbine	Downwind Horizontal Wind Turbine	Upwind Horizontal Wind Turbine
Efficiency	.20	4	8	8
Cut-In wind speed	.15	9	7	6
Rated wind speed	.15	5	7	9
Rated power	.15	5	7	8
Aesthetics	.05	9	5	5
Noise	.05	4	6	9
Reliability	.15	3	9	9
Manufacturing	.10	3	5	8
Total	1	5.05	7.15	7.9

The results of the decision matrix led the team to the conclusion that the upwind HAWT would be the best design to meet the competition's criteria. Figure 11 shows the preliminary design for the full system.

Figure 11: Preliminary System Design

5.2 – Sub-system Design

The selection process for the following sections contains the decision making criteria for the individual sub-systems. The decision matrices follow the Pugh charts and contain a scoring out of 10 to determine which option scores best for the specific system.

5.2.1 – Blade

For the blade profile, or airfoil selection, the use of a Pugh chart eliminated the flower petal and flat plate designs. The decision matrix showed that the benefits of a feather design were the best, but the fish design also merits further consideration. The elimination of the pine seed was determined from its lower scores in tooling and controllability. The final airfoil selection will combine the fish body and bird feather design, using the desirable aspects of the fish body for the base of the blade and the bird feather contour for the tip section. The Pugh chart and decision matrix can be seen in Tables 5 and 6.

Table 5: Pugh chart for airfoil type

Criteria	Flat plate	Feather	Fish	Flower Petal	Pine Seed
Tooling	D	-	-	-	-
Aero Efficiency		+	+	+	+
Rated Power	A	+	+	s	+
Rotor Inertia		+	+	s	+
Rated Wind Speed	T	+	+	+	+
Sum of +	U	4	4	2	4
Sum of -		1	1	1	1
Sum of S	M	0	0	2	0

Table 6: Decision matrix for airfoil type

Criteria	Weight	Feather	Fish	Pine Seed
Tooling	.35	6	8	4
Aero Efficiency	.15	8	5	7
Rated Power	.15	8	5	7
Rotor Inertia	.15	7	6	7
Controllability	.20	5	9	5
Total	1	6.55	7.00	5.55

The material chosen to construct the blades for the competition was carbon fiber. Carbon fiber offered a high strength to weight ratio, and was ideal for the construction of the blades. Novakinetics has generously donated the carbon fiber material and time to teach the team how to work with carbon fiber to develop the blades for the competition. The blade consisted of 4 airfoils along the length of the blade. At the root of the blade, the airfoil was cambered 12 percent to assist in start-up. The rest of the blade used S835, S833, and S834 airfoils respectively from the bottom to top. These airfoils reflected the change in the airfoil profile from a fish body to a bird's feather in shape. The blade geometry and shape are shown in Figure 12.

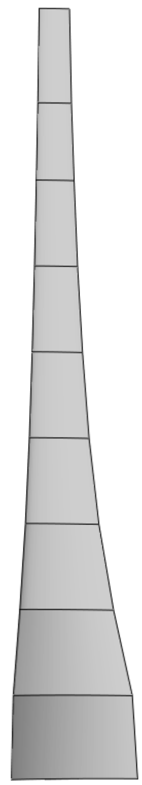


Figure 12: Blade shape and geometry

5.2.2 – Structure

For the tower, a steel airfoil was used. While carbon fiber would have been an ideal choice, the material's inability to be appropriately attached to the steel chosen for the baseplate would compromise the integrity of the structural design. Steel was chosen due to its ability to be welded to other steel components.

The design of the nacelle was integrated into the tower and was fabricated at the same time to create a seamless shape that offered the most aerodynamic efficiency possible. The construction material chosen was the same as the material for the tower to allow for easier, more reliable attachment.

The base plate design used in the 2015 CWC competition was used again for 2016. This was due to DOE requirements on the base plate construction and the simplicity and effectiveness of the design.

The initial hub design was a circular, aluminum disk that had inserts milled which the blades fit into. The final design of the hub was not determined until it was decided how the blades will fit into the hub.

The decision matrix and the Pugh chart for the structural selections can be seen in Tables 7 and 8. The steel pipe, leaning tower, square, and rectangular tubes were removed from the final decision matrix.

Table 7: Structural Pugh charts for design concepts

Criteria	Steel Pipe	Steel Airfoil	Square Tube	Carbon Fiber Airfoil	Leaning Tower
Manufacturing cost	D	-	-	-	s
Strength		-	+	+	s
Aerodynamic Efficiency	A	+	-	+	+
Innovation		+	+	+	s
Tooling	T	-	s	-	-
Sum of +	U	2	2	3	1
Sum of -		3	2	2	1
Sum of S	M	0	1	0	3

Table 8: Decision matrix for structural systems

Criteria	Weight	Airfoil	Carbon Fiber Airfoil	Square Tube
Manufacturing cost	.25	6	4	5
Strength	.2	9	8	8
Aerodynamic Efficiency	.2	8	9	3
Innovation	.15	7	8	3
Tooling	.2	6	5	7
Total	1	7.15	6.6	5.3

5.2.3 – Generator

After considering the initial options, the team chose to attempt to reconfigure a motor to reduce cogging torque and increase the efficiency of the generator. The process of reconfiguring a motor was very labor intensive and had room for potential issues during testing and operation. Due to this concern, a back-up motor was selected, the SunnySky X4108S. This selection was made in order to maintain a high pole count, low cogging torque, easy method of mounting and unmounting, and adequate information for implementing the generator into the turbine design. Even though the Turnigy 4114 and the SunnySkyX4108S were very similar, the advantages of the SunnySky X4130S are low cost and availability of generator specifications. As the project continued, further research was conducted regarding what industry improvements have been made and if these motors were beneficial to the wind turbine design [12]. Figure 13 shows the stock picture for the SunnySky X4130S brushless motor.

Table 9 contains the Pugh chart for the generator team. It agrees with the initial determination that the out-runner style motor had a higher performance potential than the in-runners. For the process of using the decision matrix, the in-runners were discarded due to extremely low scores. The decision matrix can be seen in Table 10.

Figure 13: SunnySky X4130S 480kv brushless motor [12]

Table 9: Pugh chart for generator selection

Criteria	22:24 Armature to Rotor Ratio (Out-runner)	Team rebuilt slot-less core (In-runner)	Team rebuilt slot-less core (Out-runner)	22:24 Armature to Rotor Ratio (In-runner)	12:14 Armature to Rotor Ratio (Out-runner)	12:14 Armature to Rotor Ratio (In-runner)
Durability	D	-	-	s	s	s
Aesthetics		s	s	s	s	s
Easy installation	A	-	+	-	+	-
Rapid Change-out		-	-	s	s	s
Cut in wind speed	T	+	+	s	-	-
Cogging Torque		+	+	s	-	-
Efficiency	U	+	+	s	-	-
Rated Power		+	+	s	-	-
Braking Torque	M	-	-	s	+	+
Sum of +		4	5	0	2	1
Sum of -		4	3	1	4	5
Sum of S		1	1	8	3	3

Table 10: Generator decision matrix

Criteria	Weight	22:24 Armature to Rotor Ratio (Out-runner)	Team rebuilt slot-less core (Out-runner)	12:14 Armature to Rotor Ratio (Out-runner)
Durability	.15	7	4	7
Aesthetics	.05	8	8	8
Easy installation	.15	10	10	10
Cogging Torque	.25	6	9	4
Efficiency	.25	8	8	6
Rated Power	.15	8	9	5
Total	1	7.65	8.1	6.2

In conclusion, the final design was determined for optimized power production, dependability, and safety. By using the SunnySky X4108S in conjunction with the current blade design the 10 watt minimum was met when testing was completed. The tower, base, and nacelle will work together to allow for easy mounting of the turbine in the tunnel and provide a safe support structure for testing procedures.

6 – Implementation

This section outlines the general progress of the project. By evaluating what changes need to be made to the design of the wind turbine, it will determine where the actual progress is when compared to the outlined schedule. The manufacturing process is overviewed in detail for the different pieces that need to be constructed for the project to be completed.

6.1 – Design Updates

At the start of the semester, the team reviewed the designs submitted, which was detailed in Chapter 5, to progress toward the manufacturing process. Unfortunately, the blade design submitted did not meet the required specifications for the competition in May 2016; this was due to minor rule changes within the competition and the project sponsor adjusting power requirements to match the generator output post testing. This caused a setback due to the component needing to be redesigned. The following sections detail the two main components that needed to be redesigned, which include the turbine blade and the hub assembly.

6.1.1 – Blade Design Updates

The blade design that was submitted was reviewed to ensure it would be able to perform appropriately for the competition in May. Due to budget and time constraints, only one blade mold will be manufactured, so the design of the blade chosen will have to meet the requirements necessary when manufactured. The blade design chosen at the end of last semester met the power requirements for the competition, but it was not able to overcome the inertial forces and the cogging torque of the generator within the wind speed requirements. This was a setback due to the manufacturing process being halted until the blade was redesigned.

The blade geometry was changed two times before the final profile was selected. The changes made were to the twist off of the root, the total number of profiles used to compile the blade, and the airfoil used in the blade. Figures 14 and 15 illustrate the differences in the power production versus wind speed for the two different profiles. Blade Iteration 1 was able to achieve the 10 Watt minimum power requirement for the DOE competition at 10 m/s. This gave no additional factor of safety in regards to power losses through components, or power draws from the electrical controls that are attached to the turbine. The final blade iteration was able to harvest 30 Watts from the wind at 10 m/s. This gave a factor of safety of 3, which will accommodate power losses and draws from the electrical components. The figures below show the various power versus wind speed curves for the blade iterations, the simulation was run under different wind speeds to establish a general power curve for the blades. The final blade iteration performed better in torque production and power generation when compared to the Iteration 1 blade. Table 11 shows the twist angle differences for the iterations of the blade.

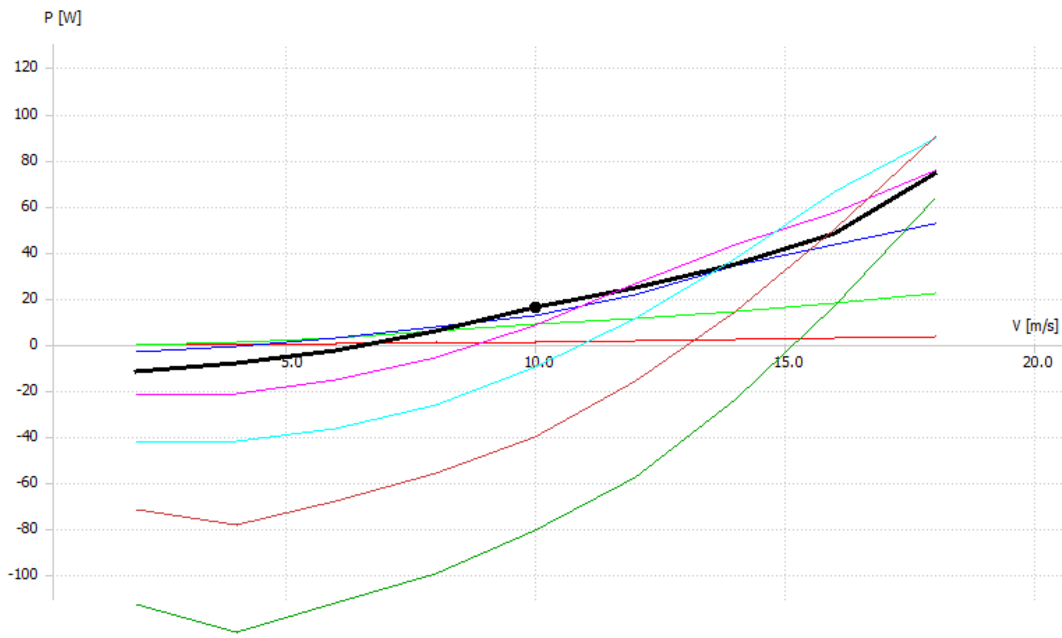


Figure 14: Power versus wind speed for blade iteration 1

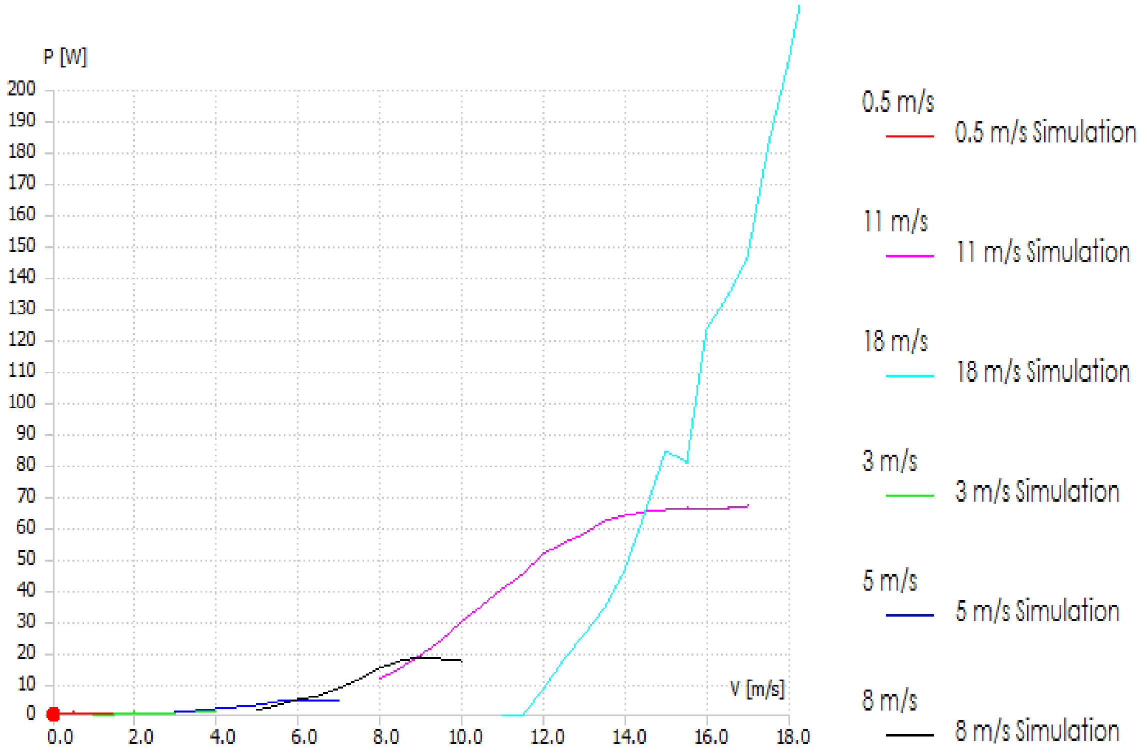


Figure 15: Power versus wind speed for final iteration

Table 11: Twist angle differences between the blade iterations

Blade Section	Iteration 1	Final Blade
1	53.64	42
2	34.14	35
3	23.65	25
4	17.22	17.22
5	13.04	13.04
6	10.12	10.12
7	7.99	7.99
8	6.37	6.37
9	5.09	5.09
10	4.06	4.06

The changes in the twist angle allowed for the power and torque production to be optimized for the scope of the competition. The final blade selected offered a greater factor of safety related to power production. For comparison, the final blade generates 40 watts at the 11 meter per second wind speed where the first iteration was only able to generate 20 watts. Figure 16 shows the final blade SOLIDWORKS model. The blade profiles for Iteration 1 and the final blade can be found in Appendix C – Figures C1 – C2.

Figure 16: Final blade CAD

6.1.2 – Hub Design Updates

The original hub design was adequate for the purposes of the competition. The hub was optimized to reduce weight and allow for easier start-up by reducing inertia on the rotor assembly. This required the original root shape of the blade to be adjusted to allow for more material to be removed from the hub without sacrificing strength. The changes to the hub included decreasing its thickness from 12mm to 10mm and removing approximately 40% additional material. The new hub was designed to place the blades at their optimum distance from the center of rotation for power and torque production. This required the new hub to be 12mm larger in diameter than the original hub design. The designs can be seen in Figures 17 – 18, and Figure 19 shows the proposed design for the thrust washer to be used with the new hub.

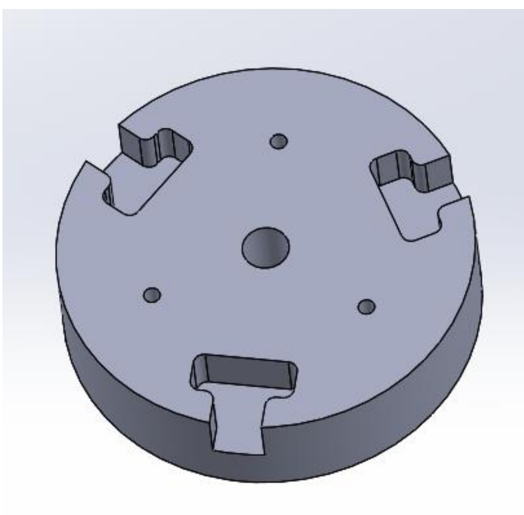


Figure 17: Initial Hub Design

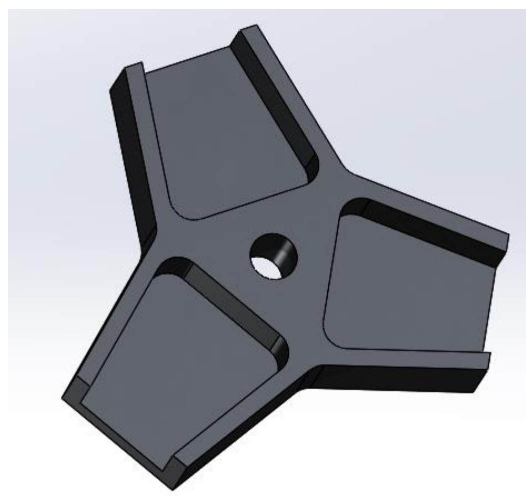


Figure 18: Final Hub Design

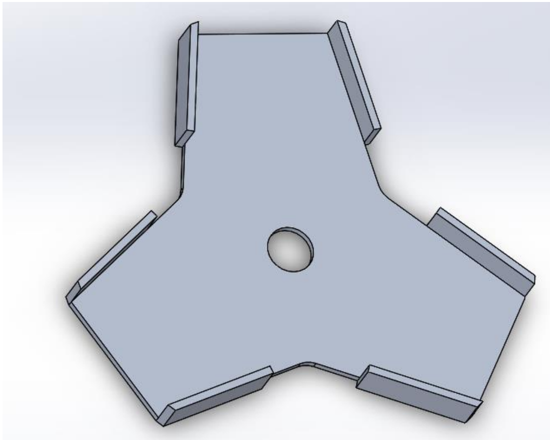


Figure 19: Thrust Washer

The final design of the wind turbine changed from the proposed design. The changes made to the blade design and the hub assembly allows for a larger factor of safety in terms of potential power generation and theoretical startup speeds. Making these changes, allows the team to be more competitive at the competition in May 2016. The updated final design can be seen in Figures 20 - 22.

Figure 20: Final design hub view

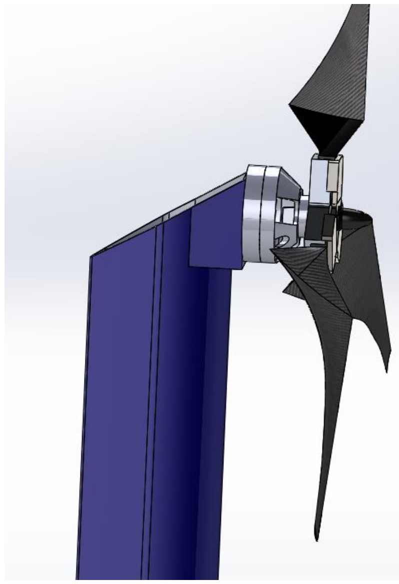


Figure 21: Final design side view

Figure 22: Final design – trimetric view

6.1.3 – Structural Design Updates

After the new FEA was done on the blades a higher deflection was calculated which resulted in an interference of the blades and the tower. The integrated nacelle was extended by a 25mm to allow for additional clearance so the blades would not strike the tower.

The mounting plate for the motor needed to be modified to distribute the forces over 4 fasteners instead of 2. This was due to a catastrophic failure that occurred during testing. To reduce failure points, the generator mounting plate was modified. To update the tower mounting plate to receive 4 fasteners the plate was widen by 12.5 mm to allow the 4 bolt pattern with enough space to access the fastener heads.

6.2 – Manufacturing

6.2.1 – Blade Manufacturing Process

To manufacture the blades, a mold must first be made. The mold will be milled out of aluminum from a CAD file. Novakinetics has generously allowed the use of their milling equipment, along with an employee to assist in manufacturing the blade mold. Once the mold has been manufactured, the process to make the blades begins by coating the mold with a nonstick wax. The nonstick wax will not bind to the resin used with the carbon fiber, which will allow the blades to be removed from the mold without potentially damaging them. Once the wax and initial resin have been laid down, carbon fiber sheets will be used to construct the blade. Alternating between carbon fiber mesh and resin to bind them together, the carbon fiber orientation will be altered by 45 degrees between layers. This allows for additional strength within the finished product by reducing shear lines that can be destructive to carbon fiber. Once the appropriate amount of material has been placed into the bottom half of the mold, a last layer of resin will be applied. The top half of the mold will be aligned and pinned into place and the mold will be placed into a C-clamp to apply pressure to the material inside. This pressure is necessary to ensure the resin penetrates the carbon fiber mesh, which will form the composite. A 24 hour cure period is necessary to allow the resin to harden and the bulk of the blade manufacturing process will be complete. Once the blade has been removed from the mold, the excess carbon fiber material will need to be trimmed and the surface will need to be sanded and polished to desired finish. Figure 23 shows the completed mold after manufacturing.

Figure 23: Completed blade mold

6.2.2 – Tower Manufacturing Process

The first step in manufacturing the tower is plasma cutting the base plate. The airfoil tubing will be cut to the specified length, orientated, and welded to the base plate. At the top of the tower, the mounting bracket for the generator will be welded in place and a 45 degree angle will be cut from the front of the mounting plate to the back of the tower. This will allow for access to the back of the bracket to mount the generator and electronics in the tower. A removable cap will be used to seal the tower and complete the aerodynamic profile. The drawings for the tower components can be seen in Appendix D, Figures D1 – D6.

6.2.3 – Hub and Hub Adaptor Manufacturing Process

The hub adaptor from the 2015 competition will be reused for the 2016 competition. This is due to schedule setbacks. Designing and analyzing one less part will allow for the team to get back on schedule. The hub will be manufactured using CNC technology to mill the component from 6061-T6 aluminum alloy. The thrust washer that completes the hub will be cut from aluminum sheet metal to match the hub profile. Tabs will be added to assist in the alignment of the component. The engineering drawing for the hub can be seen in Appendix D, Figure D7.

6.3 – Design of Experiments

6.3.1 – Proposed Experiment

After manufacturing has been completed, the wind turbine will be taken to Southwest Wind Power for testing and analysis. One of the tests to be performed is a Design of Experiments, which involves testing three separate components or systems simultaneously. The three systems will be given a minimum and maximum value, and the same experiment will be ran a total of eight times, to use all of the minimum/maximum combinations. To emulate the testing that will be performed by the DOE during the CWC, the design of experiments that was developed was for the power curve performance testing. By performing a design of experiments in this manner, the team will be able to assess any minor changes that will need to be made to optimize the power curve performance for the competition. The three aspects that will be tested for this power curve performance test are the generator type, whether or not to use a DC voltage boost converter and the type of load used for the test. To maintain consistency with the data collection, the minimum for the generator test will be the Turnigy 4114 and the maximum will be the SunnySky X4108S. The use of a DC voltage boost converter will be considered the maximum, and the absence of the boost converter will be considered the minimum. Using an absorbed glass mat battery will be considered the maximum, while the use of a resistive load will be considered the minimum.

The output parameters being observed are the output power, which will be calculated by use of a shunt within the load circuit, and the stability of the power produced. To consider the power output stable, the power fluctuation will have to be less than 10 percent of the average power output. This means that if the generator is producing 5 watts at the shunt, the fluctuations will need to be between 4.5 and 5.5 volts. The amount of power produced stably will be used with the spreadsheets provided for the calculations necessary to determine the systems that directly affect the performance of the wind turbine.

Some additional constraints have been put in place with this test to further emulate what will be experienced at the competition in May. Six different wind speeds will be used throughout the testing, in increments on one m/s, starting at 5 m/s and ending at 11 m/s. Each wind speed will be run for a maximum of one minute before moving to the next wind speed bin.

Unfortunately, due to a catastrophic failure of the turbine during testing, the proposed design of experiments had to be cancelled due to the amount of time required to source and receive replacement parts.

6.3.2 – Completed Design of Experiments

To complete the required testing for capstone, a second design of experiments was created to allow for some general testing with the turbine components. While the turbine blades will be unable to be changed for this year's competition due to time and budget constraints, the information yielded from the deflection testing would better prepare the next year's competition team and assist in determining the cause of the catastrophic failure that occurred.

There are three input parameters that are being evaluated for the design of experiments, the length of the blade, the construction material of the blade, and the thrust load being applied to the blade. Each testing parameter has a minimum and a maximum value for the design of experiments. For the length of the blade, the maximum will be 17cm long and the minimum will be 12 cm long. The maximum for the construction material will be a pure carbon fiber toe blade and the minimum will be a carbon fiber mesh blade. For the loading, the maximum will be a 25 Newton load (approximately 2.7 Kg) and the minimum will be a 1 Newton load (approximately 0.15 Kg). The reasoning behind the loading values are due to the thrust forces the blade experiences at the minimum and maximum wind speeds for the competition, 5 and 18 m/s respectively.

The output being observed is the total deflection of the blade at the point of loading, which will be 0.5 cm from the tip. This distance was put in place to prevent unnecessary damage to the blades during the testing. Table 11 shows the collected data in ascending order for clarity, while the experiments were run randomly to reduce random error within the results.

Table 11: Design of Experiments Results

Test Number	Blade Length	Blade Material	Load[N]	Average Deflection [cm]
1	-	-	-	0.2
2	-	-	+	0.7
3	-	+	-	0.1
4	-	+	+	0.5
5	+	-	-	1.7
6	+	-	+	2.9
7	+	+	-	1.1
8	+	+	+	2.3

Using the spreadsheets provided the collected data shows that the length had the most influence on the deflection of the blade, the load had the second most influence on the deflection of the blade, and the material choice for the blade had the lowest effect on the deflection. While the yielded data is unable to be put into practice with this year's competition design, learning that the material choice didn't really affect the amount the blade deflected will allow future designs to note that the use of the more expensive carbon fiber toe is not required to limit deflection.

6.4 – Budget

The current amount budgeted for the CWC 2016 Team is $1500, of which Team A has $500 allocated for use due to the budget being split across the three teams. This includes funds provided by the DOE and contributions from private donors. The majority of the budget is being set aside for travel to the competition in May 2016. The anticipated costs will change as parts are purchased for the construction process. The budgeted amount does not include other donations that are possible from other private parties or the donation of time and materials to the competition team from Novakinetics. The anticipated budget can be seen in Table 12.

Table 12: Anticipated budget for CWC 2016 Tunnel Team ME

Parts	Materials	Quantity	Cost per unit	Total Cost
Generator	Aluminum	3	$55	$165
Hub Assembly	Aluminum Alloy	2	Donated	$0
Tower	4130 Chromoly	2	$50	$100
Blades	Carbon fiber	8	Donated	$0
Nose Cone	Aluminum Alloy	2	$20	$40
Base	1018 Steel	1	Donated	$0
Blade Mold	Aluminum	1	Donated	$0
Fasteners	12.9 Hardened Steel	10	$0.20	$2
Power Coating	Paint	1	$20	$20
		Total		327

6.5 – Schedule for Spring 2016

The schedule for the spring semester can be viewed in Appendix A, Table A1. The schedule contains the milestones set by the team to ensure that the project will be completed and remain on schedule throughout the semester. The milestones are currently listed on a weekly basis, as set meeting times are once a week when the entire team will be available. The major milestones include finalizing the budget and the course requirement due dates for ME486C. Completion of testing procedures is necessary to identify alterations that may need to be made. Purchase order submissions will need to be completed by the end of the day on March 4th 2016 to allow for time to receive the necessary parts. Once everything has been received, manufacturing will begin, as the engineering drawings have been approved by the faculty sponsor. Once the complete assembly has been tested, time will be allotted for additional adjustments that may be necessary for optimization.

6.6 – Resources Required

The resources required for the construction of the project build include a workspace for the construction of the turbine, assistance with the fabrication of the blades, and the necessary tools to assemble the tower. A workspace for the project was provided by the faculty sponsor. The alternative energy testing building on campus was provided as a workspace for assembly of the turbine. The machine shop/senior projects building will be utilized for machining the required components and welding the tower pieces together. The amount of space needed will be minimal, as the size restrictions imposed by the DOE require small components. Novakinetics has offered workspace to the team for the purpose of manufacturing the turbine blades. They have also provided assistance and training in working with carbon fiber to allow the team the greatest chance to build uniform blades that will be successful within the competition. Assembling the structural components requires access to metal fabrication and welding equipment, which the machine shop will have readily available.

6.7 – Sourcing and Bill of Materials

Two different generators have been selected, and the purchase order process for them has been completed. The design and materials have been selected for the tower and the purchase order process has been completed. Table 13 shows the final bill of materials and sourcing locations for the components that were ordered. Due to the budget total being shared, line items have been added for the total expenditures from the other teams to keep the budget balanced. For simplicity, the other Teams' expenditures have been listed as total amounts spent; leaving $702.08 of the $1500 allotted remaining as funds available for future purchases.

Table 13: Bill of materials

Component	Source	Unit cost	Number	Tax & shipping	total
SunnySky X4130S	Amazon.com	$49.50	1	$0.00	$49.50
Turnigy 4114	HobbyKing	$37.94	1	$18.56	$56.50
Tower/Nacelle	Aircraft Spruce	$41.50	2	$18.54	$101.54
Blades	Novakinetics	Donated	9	0	$0.00
Blade Mold	IMS	Donated	2	0	$0.00
Hub Assembly	Donated	Donated	2	0	$0.00
Base Plate	Norfab Steel	Donated	1	0	$0.00
Nose Cone	NAU	Donated	1	0	$0.00
Powder Coating	Flag Powder Coating	$20.00	1	0	$20.00
3 phase Rectifier	Digikey	$6.60	2	$7.79	$20.99
Team B expenses	-	-	-	-	$549.39
Deployment Expenses	-	-	-	-	$0
				Total	$797.92

7 – Testing

Two types of testing are being utilized for the components designed for the project, theoretical testing using FEA and physically testing the component where applicable. The FEA testing is a requirement of the faculty sponsor before drawings can be signed off to move forward with the manufacturing process. The physical testing will take place post-manufacturing if necessary. In the case of the generator, there was no FEA performed because the generator is an off-the-shelf item and the RPM range it will see during testing is within the manufacturer's specifications.

7.1 – Blade Testing

The FEA has been completed on the final blade design. With the assistance of SOLIDWORKS, the calculated loads were applied to the blade and a failure analysis was ran based on the material specifications that were provided by Novakinetics for the carbon fiber used for their construction. The overall deflection of the blade under a maximum load of a 24 m/s wind speed is 34.8 mm, and the overall factor of safety for the blade is 1.930. The factor of safety was calculated based off the stress/strain loads compared to the strength of the carbon fiber. Figures 24 - 25 show the results of the analyses.

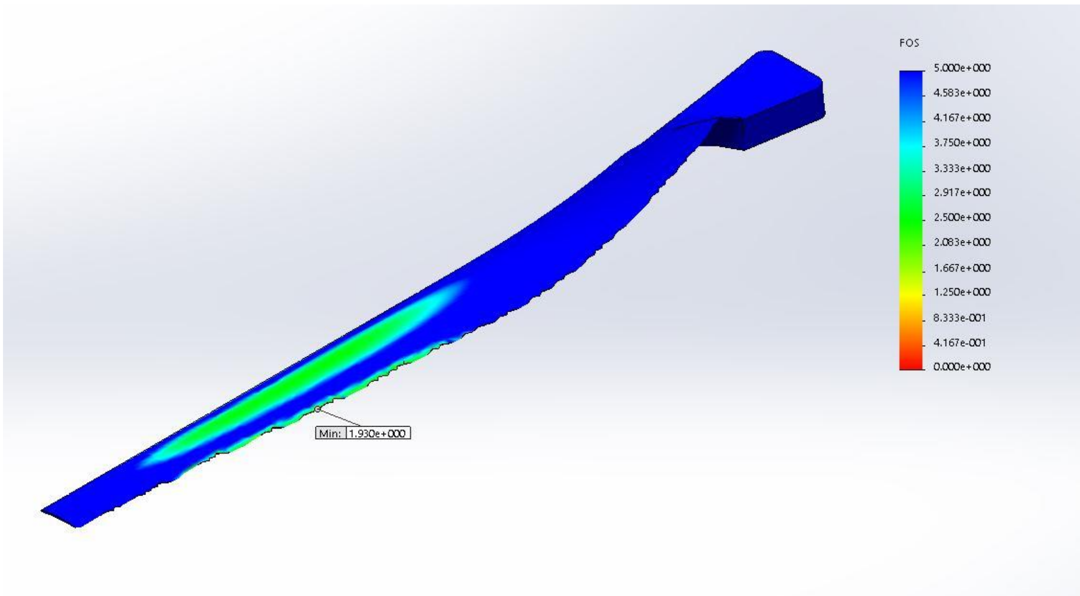


Figure 24: Factor of safety results

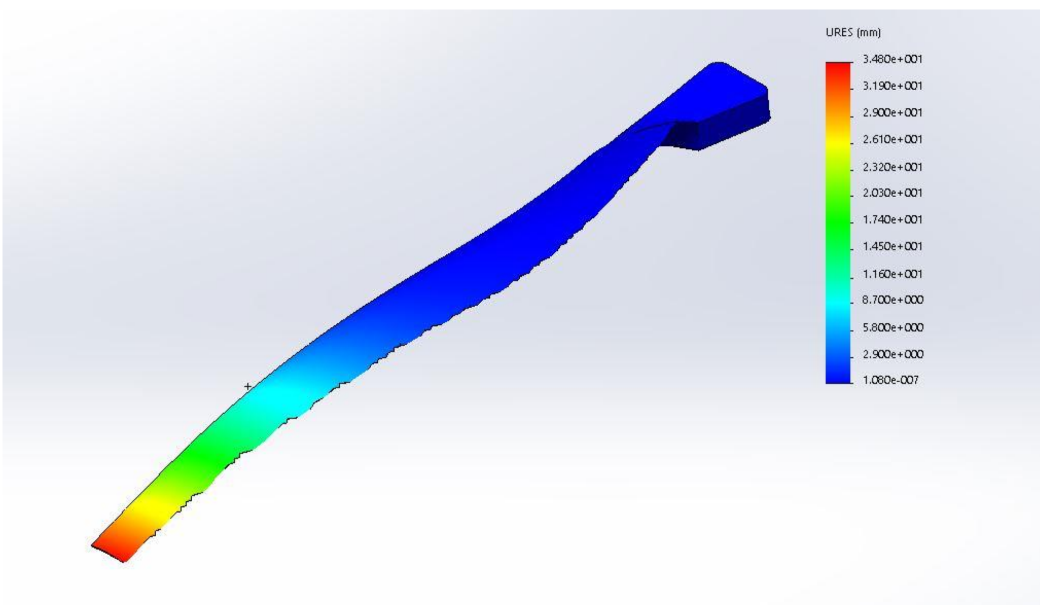


Figure 25: Deflection analysis results

7.2 – Structural Testing

The FEA for the tower and baseplate have been completed. The calculated loading from the wind on the blade and rotor was used to determine deflection and the overall stresses that the tower would undergo during the competition. Figures 26 and 27 show the deflection analysis and the Von Mises stress calculations for the tower. Using the maximum experienced stress with the yield strength of the Chromoly steel, the factor of safety on the tower was calculated to be 18.2, with the likely failure point being the weld between the baseplate and the tower. The overall deflection expected is less than one mm.

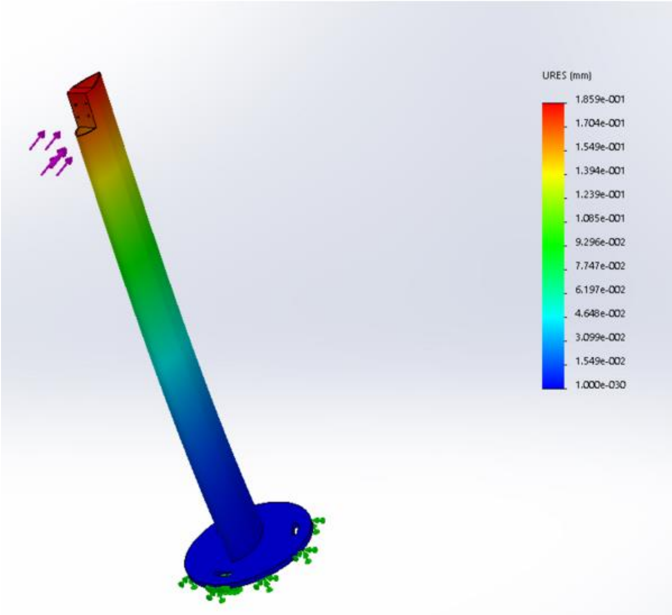


Figure 26: Deflection Analysis

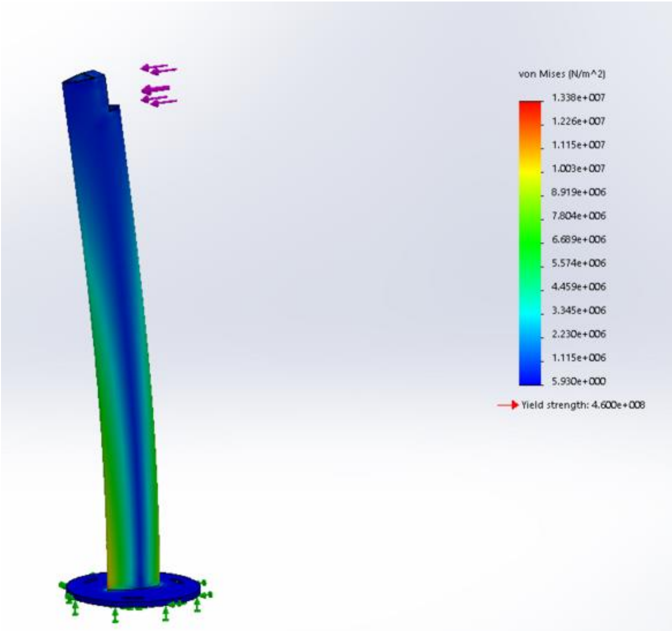


Figure 27: Von Mises stress analysis

7.3 – Generator Testing

The generator testing is comprised of two parts. The first was determining the cogging torque experimentally; the second was to use a dynamometer to run the generator to measure output under varying conditions.

7.3.1 – Cogging Torque Analysis

To measure the amount of force that was required to overcome the cogging torque on the generator, an experiment was designed to allow for weight to be placed on a lever arm. Once the generator rotated from its cogged position, the amount of weight was recorded and the amount of torque required was calculated. This procedure was performed 20 times for each generator tested; the repetition was to reduce random errors and to normalize the data for analysis if needed. Figure 28 shows the testing setup.

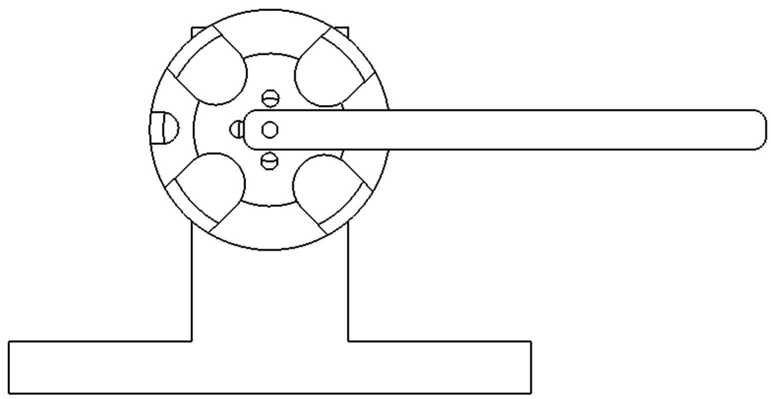


Figure 28: Cogging torque testing setup

The weights selected for testing were 4 grain steel ball bearings. These were selected due to having a consistent weight and allowing for a testing resolution of .25 grams. The same container for the weights was used for all of the tests. It consisted of a cup and a string that was placed into a notch on the lever arm that was 80 mm from the center of the generator. Weights were added until the motor rotated. To simplify the calculations, the cup and ball bearings were treated as a point load, and the lever arm was treated as a distributed load. The weight of the generator case was ignored due to its symmetry. A total of 5 different generators were tested for cogging torque: the SunnySky, Turnigy, both of the Mystery generators used in 2015, and the original testing motor that was used when the dynamometer was constructed. Table 14 shows the results of the cogging torque analyses performed on each motor.

Table 13: Cogging torque results

Generator	Cogging torque at 95% confidence
SunnySky X4108s	0.019 N-m ± 0.002 N-m
Turnigy 4114	0.040 N-m ± 0.005 N-m
Mystery (new)	0.035 N-m ± 0.003 N-m
Mystery (old)	0.105 N-m ± 0.010 N-m
Big Blue (original test motor)	0.250 N-m ± 0.015 N-m

Based on the results, the SunnySky X4108s requires the least amount of force to overcome the cogging torque. This factor was used in selecting this generator for use in the competition.

7.3.2 – Generator Power Curve Testing

In order to gain the proper information for selecting electrical components for the wind turbine, the team was required to test the voltage and current characteristics of the generator. These tests were necessary because the generator selected was originally designed as a quadcopter motor. The data needed for using the motor as a generator for the competition was not available from the manufacturer.

The first test that was performed was the open circuit voltage test (V_{OC}). This test was performed with no load attached to the generator's three-phase leads. The team measured V_{OC} between 1000 and 8000 RPM. The voltages that were measured ranged from 1.94V to 16.31V for the speeds that were tested. For the purpose of electrical component selection, the team used a V_{OC} of 13.0V which was 125% of the 10.41V that was measured at 5000 RPM or 23.25m/s. The results of the open circuit test can be seen in Figure 29.

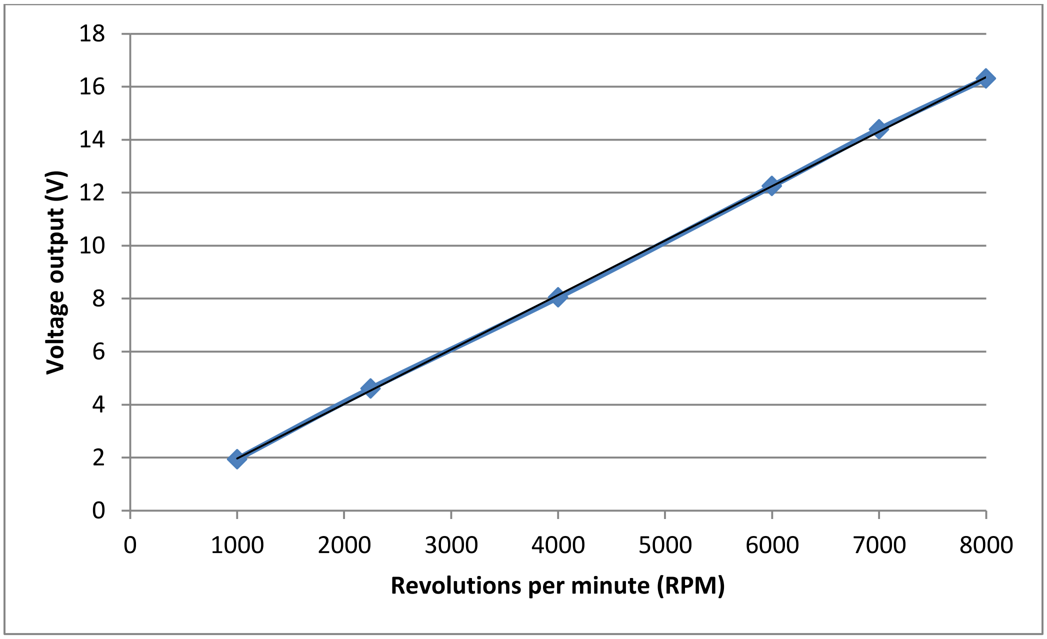


Figure 29: V_{oc} versus RPM results

The second test was to measure the voltage and current when a load was applied. The team applied five different load resistances in the range of 0.59 Ω to 1.64 Ω. The different loads were applied to the generator to analyze voltage and current production characteristics. Analyzing the results of the current and voltage tests, it was determined that maximum current production occurred when the circuit resistance was 0.9 Ω. This value was used because the resistance in the system will be above 1.0 Ω at any given time during power generation. The team used a maximum wind speed of 24 m/s and a maximum current value of 21ADC which was 125% of the 16.8ADC measured at 5000 RPM or 23.25 m/s. The results of these tests can be seen in Figure 30. The resulting data can be found in Appendix B Tables B1 – B6.

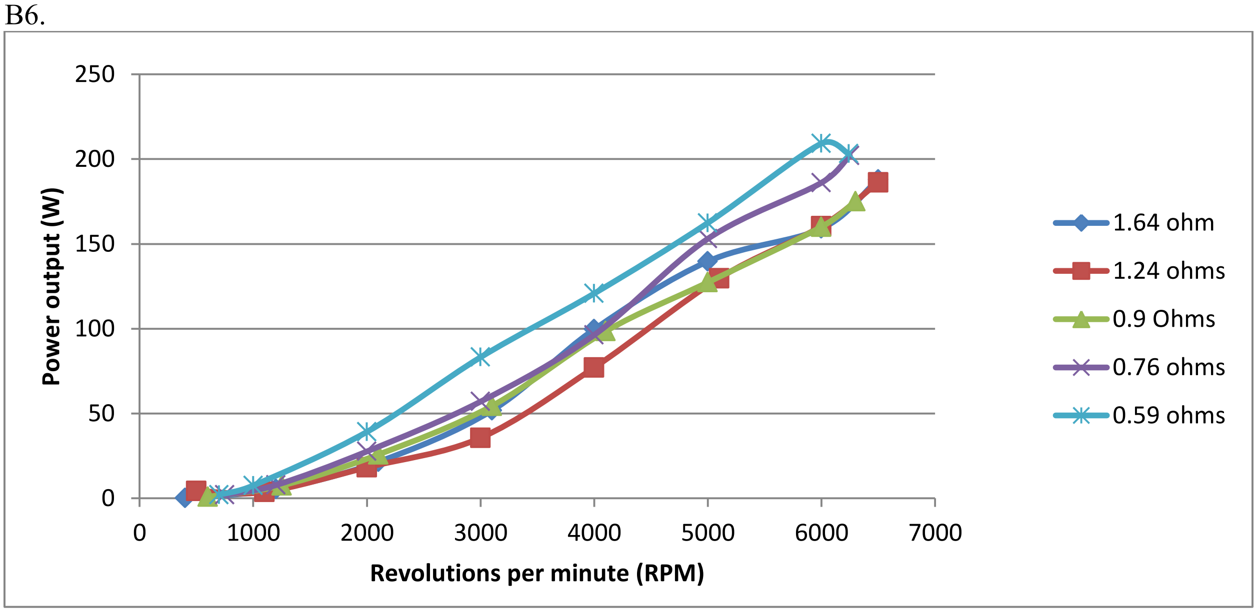


Figure 30: Power output versus RPM

8 – Conclusion

The overview of the competition requirements derived from the DOE's rules and regulations have been explained in detail and have assisted with the preliminary design of the small scale build. These requirements will allow the Tunnel Team to produce a competitive turbine for the competition in Spring of 2016. By utilizing the different aspects of the build, researching on state of the art technology and looking at the previous builds, the final product will meet the requirements outlined for the competition.

By using the House of Quality to ensure our engineering requirements meet our customer needs, the process for further design and research will be more efficient. Using the research already compiled and the ability to break down and analyze the previous competition builds will prevent costly errors during the design and prototype process. These steps will prepare the team for a successful test during the competition.

Due to making the needed revisions to the design in order to compensate for issues that arose in the theoretical testing process the project fell behind schedule. The redesigned components offer higher factors of safety when compared to the original submitted designs. With the drawings being approved, the project can move towards manufacturing. Once these steps are completed the project will be back on schedule.

9 – Post Mortem Analysis

1) Did the team complete the mission?

The mechanical tunnel team was able to complete the mission of the project, but at a whole the wind turbine was not able to be tested without issues before the end of the semester with regards to electrical component.

2) Which aspects of project performance were positive?

The development time and cost was a positive aspect of the project. Although many hours were spent in completing the design, the results of the efforts were rewarded with a successful product in the second semester. With this in mind, many of the team members were required to forfeit personal time to contribute to the success of the design.

A second aspect of the project performance was the support from outside individuals. The team was assisted by individuals for blade construction, generator testing, and wind tunnel testing, all of which required a considerable amount of time. The team was fortunate to receive these aspects of support in order to make the design a success.

3) Which aspects of project performance were most negative?

One major aspect of project performance that was not positive was team structuring. In the beginning of the project the electrical and mechanical teams were both combined. The combination of 12 individuals attempting to coordinate schedules and create fluid documents was difficult. For this reason the two teams were separated and thus helped smooth out team logistics for the remainder of the school year.

Another aspect of project performance that was negative was the amount of time that needed to be spent by team members in blade molding and trimming as well as redesigning aspects of the structure. Each blade required about 5 hours of work to be prepared for testing. One components that needed redesigned were the mounting plate for the tower. It was determined that the generator needed to be fastened with 4 bolts instead of 2 and therefore the mounting plate was widened to allow for this alteration. This was done to ensure that the generator would not shear from the tower during testing as it did during one of the tunnel tests.

4) Which tools, methodologies and practices contributed to positive (or negative) aspects of performance?

Throughout the project the team used several tools in order to successfully design and build turbine. For design of the tower, base, mounting plate, and blades the team started by using the method of sketching to create a design. The team was then able to use Solid Works in to successfully integrate the components into a single structure. After the design was complete, the team completed a finite element analysis (FEA) on the components of the turbine to ensure that failure would not occur.
In order to construct the blades, a three axis mill, sand paper, dremel, and clamps were used. For purposes of generator analysis, a dynamometer, multimeter, and power supply was used. The tower construction was completed with the use of a band saw, welder, and grinder.
Once the turbine was successfully completed, the team tested it in a local wind tunnel for electrical characteristics, structural integrity, and competition readiness.

5) What problems did the team encounter?
Throughout the project the team encountered some issues. One issue that the team had was properly working together with twelve members. The solution to this was dividing the team in half and working somewhat independently on deliverables for the class and on wind turbine components.

Another problem that was encountered was the issue of properly delegating responsibilities to team members. At times some team members carried a heavier load than others. This was especially evident with regard to the design and construction of the blades and the tower.
Another aspect that the team found as a challenge was the design of the website. It was a difficult process to design a website that would represent the mechanical and electrical aspects of the project. This was a challenging due to each team having different priorities regarding the website. In the end the mechanical team determined that the mechanical aspect of the website would be designed to fit its needs and the electrical team could implement its information when ready and in a way that fit its needs.
Lastly, the team experienced a generator and blade failure while in tunnel testing. The failure required the team to rapidly produce new blades and order a new generator. In order to reduce the risk of further issues the team purchased higher grade mounting hardware and increase the number of mounting bolts from 2 to 4.

6) What specific organizational actions could have been taken to improve performance?

One aspect that could have been considered to improve the team's performance would be increasing the number of team meetings from 1 to 2 per week for the entire second semester. This would have been a useful tool especially if the team meetings would have been scheduled in locations where component construction could have been done as a team and all members would have assisted with portions of every responsibility.

7) What specific technical lessons were learned?

Throughout the project the team members learned valuable technical lessons. One of these lessons was that of carbon fiber blade design. Some of the team members gained extensive experience in this aspect by dedicating many hours to successfully build the blades for the turbine.
Another technical lesson that was learned was in testing a generator for power characteristics. With the use of the dynamometer the team was able to gain technical knowledge of testing open circuit voltage,

operating current and operating voltage.

The team members were able to implement technical knowledge regarding finite element analysis of the wind turbine components. Many hours were dedicated to ensuring that the designs would stand up to the forces placed upon them.

10 – References

[1] BBlearn, 'DOE CWC 2016', 2015. [Online]. Available: https://bblearn.nau.edu/bbcswebdav/pid-3754870-dt-content-rid-30184537_1/courses/1157-NAU00-ME-476C-SEC001-2247.NAU-PSSIS/Wind%20Turbine%20Challenge%20description.pdf. [Accessed: 04- Nov- 2015].

[2]A. Hoffman, C. Tarango, I. Mason, J. Parks, J. Pepper, M. Caronan, N. Croswell, D. Martindale, G. O'Reilly, N. Khoo, C. Feyen, K. Saxer, C. Bozorth, M. Head, K. Yates, A. Manning, C. Burge and A. Jerome, 'Wind Turbine Technical Design Report', 2014.

[3]A. Sandigo, J. Vielma, H. Mohammad, H. Dai and A. Hunter, 'Micro Wind Turbine Design NAU/KSU Design Project', 2015.

[4] Alternative Energy Tutorials "Should wind turbine blades be flat, bent or curved" [Online] Available. http://www.alternative-energy-tutorials.com/energy-articles/wind-turbine-blade-design.html

[5] M. S. Selig and B. D. McGranahan, "Wind Tunnel Aerodynamic Tests of Six Airfoils for Use on Small Wind Turbines," Journal of Solar Energy Engineering, pp. 986-1001, 2004.

[6] (2015, September 4). U. S. Department of Energy Collegiate Wind Competition 2016 rules and requirements (2nd ed.) [Online]. Available: http://energy.gov/sites/prod/files/2015/09/f26/CWC%20Rules%20and%20Regulations%20Manual_Rev2_150904.pdf

[7] R.T Prabhakaran, "Are Reactive Thermoplastic Polymers Suitable for Future Wind Turbine Composite Materials Blades?", Mech of Adv materials and Structures, vol 23, no 2, 213-221, May 2013

[8] S. Vennam, J, Watson, C, Richards. Composite Materials for Wind Blades: Current Performance and Future Directions. (PDF). Available: http://windpower.sandia.gov/2010BladeWorkshop/PDFs/2-1-A-3-SERRANO.pdf

[9] E. Dimopoulos, I. Trintis, S. Munk-Nielsen. Comparison of the dielectric electroactive polymer generator energy harvesting cycles. International Society for Optics and Photonics.

[10] J.D. Glover, M.S. Sarma, T.J. Overbye. Power System Analysis and Design. Fifth ed, Chicago, IL 2014

[11] Helipal, 'Hengli 4830 Brushless Motor (370kv)', 2015. [Online]. Available: http://Hengli 4830 Brushless Motor (370kv). [Accessed: 01- Nov- 2015].

[12] Amazon.fr, 'Foxnovo SunnySky X4108S 480KV KV480 Kit moteur Brushless pour RC mulÂTIÂ-ROÂTor Quadcopter (noir): Amazon.fr: High-tech', 2015. [Online]. Available: http://www.amazon.fr/Foxnovo-SunnySky-Brushless-mul%C2%ADTI%C2%ADRO%C2%ADTor-Quadcopter/dp/B00OXOR2YQ. [Accessed: 01- Nov- 2015].

Appendix A – Schedule

Table A1: Schedule for Spring 2016

Week of	Tasks to be completed by
Jan 17-23	Team planning and budget meeting
Jan 24-30	3D CAD complete
Jan 31- Feb 6	Design analysis/integration complete
Feb 7-13	Purchase orders submitted
Feb 14- 20	Manufacturing planning/begins/Experiment design
Feb 21-27	Hardware review 1
Feb 28 – Mar 6	Purchasing completed
Mar 7-12	Midpoint presentation
Mar 13 - 19	Spring Break/Testing/construction
Mar 20-26	Manufacturing process complete/ Hardware review 2
Mar 27- April 2	Wind turbine testing/UGRADS preparation
April 3-9	Wind turbine Modifications complete
April 10-16	Operations Manual complete
April 17-23	Presentation walkthroughs
April 24-30	UGRADS
May 1-7	DOE and ME486 Final paper due

Appendix B – Generator Testing Data

Table B1: 1.61 ohm test results

RPM	VAC	VDC	Shunt mV	IDC	Power supply	Power VDC*IDC
400	0.2	0.4	0.04	0.4	14V/0.25A	0.16
1200	2.36	1.9	0.28	2.8	14V / 0.5A	5.32
2100	3.88	3.7	0.58	5.8	14V/1.5A	21.46
3100	5.64	5.95	0.87	8.7	14V /3A	51.765
4000	7.22	7.78	1.28	12.8	14V/5A	99.584
5000	8.88	9.7	1.44	14.4	14V/7.5A	139.68
6000	10.46	11.61	1.37	13.7	14V/10A	159.057
6500	11	12.12	1.55	15.5	14V/11.5A	187.86

Table B2: 1.24 ohm test results

RPM	VAC	VDC	Shunt mV	IDC	Power supply	Power VDC*IDC
500	0.94	0.71	0.6	6	14V/0A	4.26
1100	2.14	1.96	0.19	1.9	14V/0/5A	3.724
2000	3.67	3.72	0.49	4.9	14V/1.5A	18.228
3000	5.38	5.66	0.63	6.3	14V/3.5A	35.658
4000	7.15	7.41	1.04	10.4	14V/6A	77.064
5100	8.44	9.01	1.44	14.4	14V/9A	129.744
6000	9.55	10.22	1.57	15.7	14V/11A	160.454
6500	10.1	10.89	1.71	17.1	14V/13.5A	186.219

Table B3: 0.9 ohm test results

RPM	VAC	VDC	Shunt mV	IDC	Power supply	Power VDC*IDC
600	1.09	0.79	0.11	1.1	14V/0A	0.869
1250	2.25	1.88	0.4	4	14V/0.5A	7.52
2100	3.59	3.44	0.75	7.5	14V/2.5A	25.8
3100	5.1	5.04	1.08	10.8	14V/5A	54.432
4100	6.49	6.52	1.51	15.1	14V/8A	98.452
5000	7.47	7.58	1.68	16.8	14V/10.5A	127.344
6000	8.53	8.7	1.84	18.4	14V/14A	160.08
6300	8.76	9.03	1.94	19.4	14V/14A	175.182

Table B4: 0.76 ohm test results

RPM	VAC	VDC	Shunt mV	IDC	Power supply	Power VDC*IDC
750	1.24	0.82	0.25	2.5	14V/0A	2.05
1200	2.08	1.77	0.44	4.4	14V/1A	7.788
2000	3.35	3.07	0.9	9	14V/2.5A	27.63
3000	4.81	4.56	1.25	12.5	14V/5.5A	57
4000	6.12	6.02	1.6	16	14V/9A	96.32
5000	7.17	7.15	2.14	21.4	14V/12A	153.01
6000	8.06	8.09	2.3	23	14V/15A	186.07
6250	8.11	8.18	2.47	24.7	14V/16A	202.046

Table B5: 0.59 ohm test results

RPM	VAC	VDC	Shunt mV	IDC	Power supply	Power VDC*IDC
700	1.21	0.7	0.3	3	14V/0A	2.1
1000	1.73	1.3	0.58	5.8	14V/0.5A	7.54
2000	3.15	2.7	1.45	14.5	14V/3A	39.15
3000	4.43	4.18	1.99	19.9	14V/6A	83.182
4000	5.56	5.32	2.27	22.7	14V/9.5A	120.764
5000	6.4	6.15	2.64	26.4	14V/12.5A	162.36
6000	7.26	6.19	3.38	33.8	14V/16A	209.222
6240	6.63	6.29	3.23	32.3	14V/16A	203.167

Table B6: Open circuit voltage test results

RPM	Voltage	RPM/Voltage
1000	1.94	515.4639175
2250	4.61	488.0694143
4000	8.05	496.8944099
6000	12.25	489.7959184
7000	14.39	486.4489229
8000	16.31	490.4966278

Appendix C – Airfoil Profiles

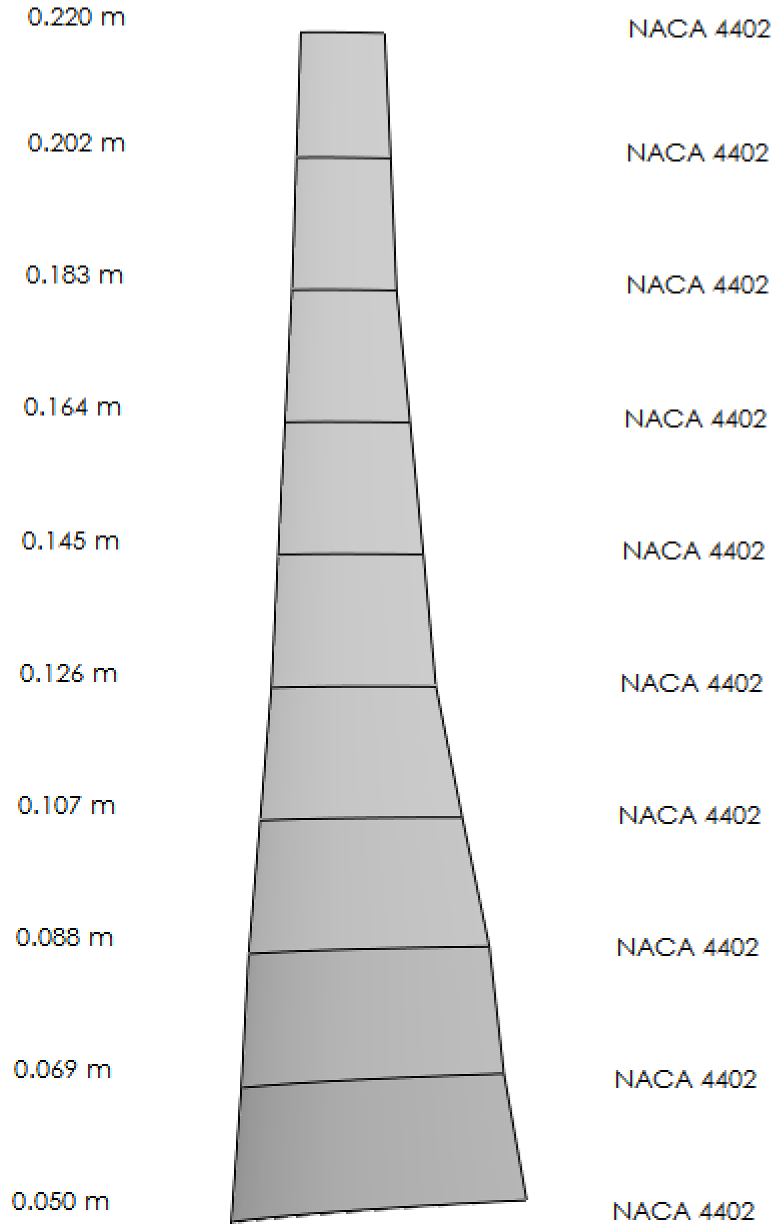


Figure C1: Final blade profile

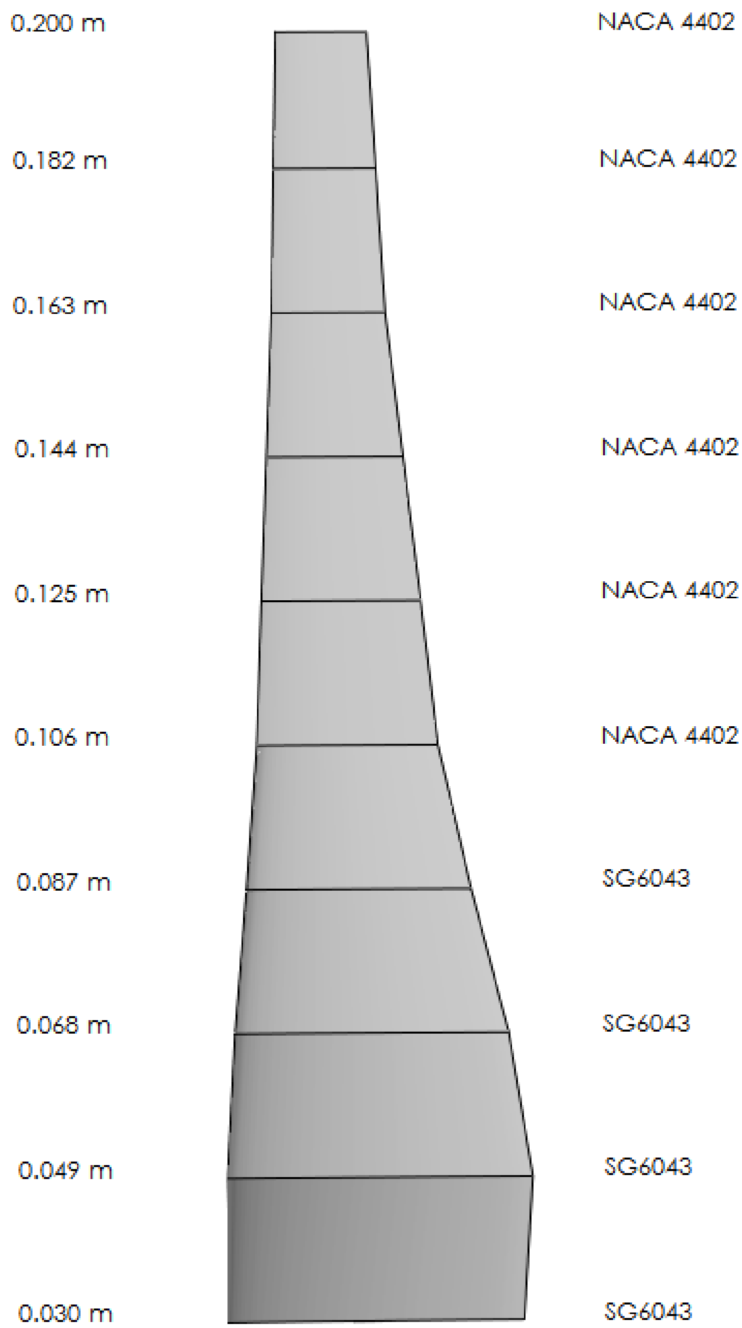


Figure C2: Iteration 1 profile

Appendix D – Engineering Drawings

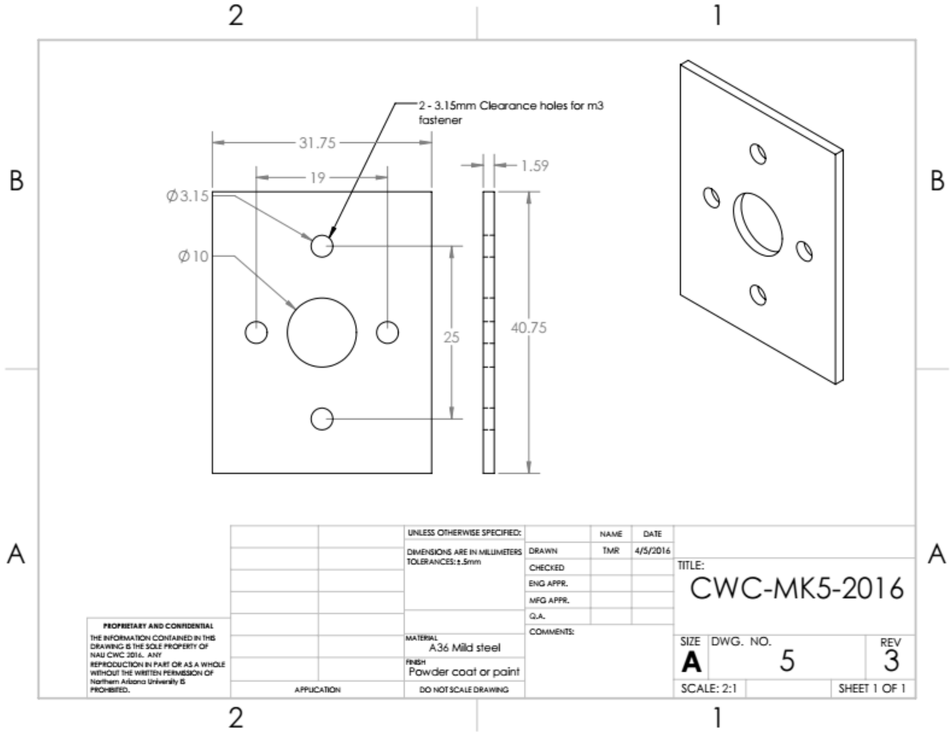


Figure D1: Mainframe front

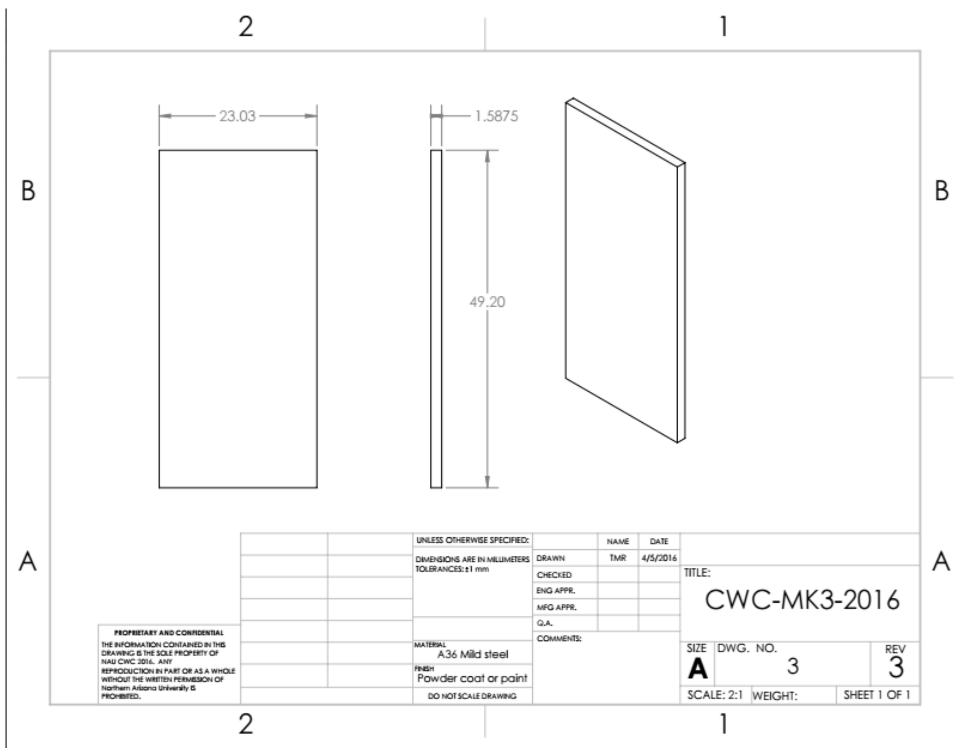


Figure D2: Mainframe bottom

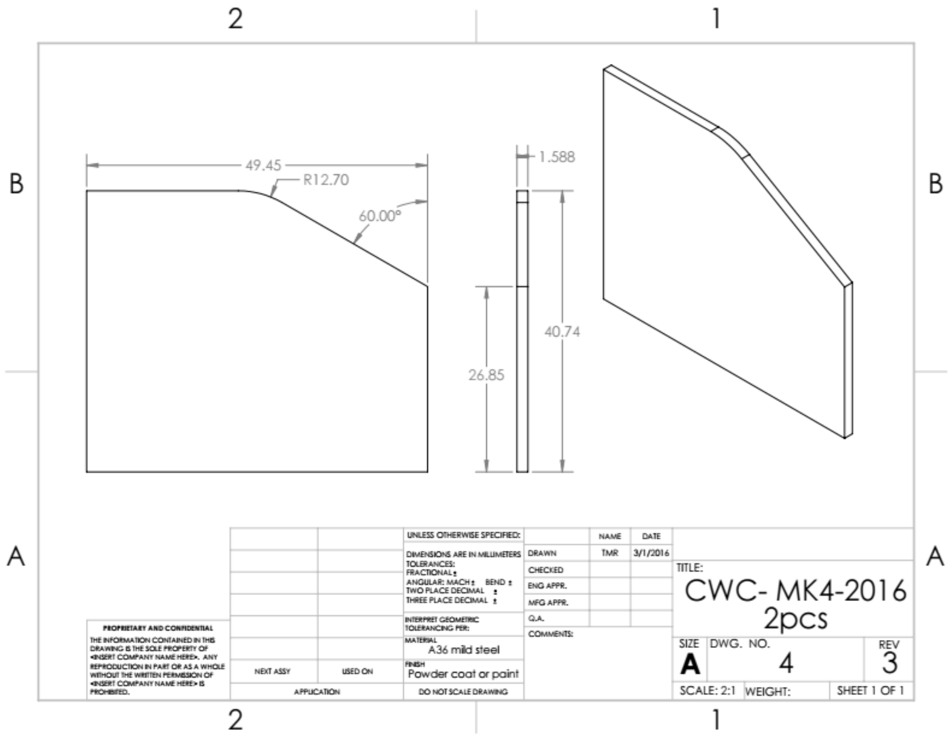


Figure D3: Mainframe side

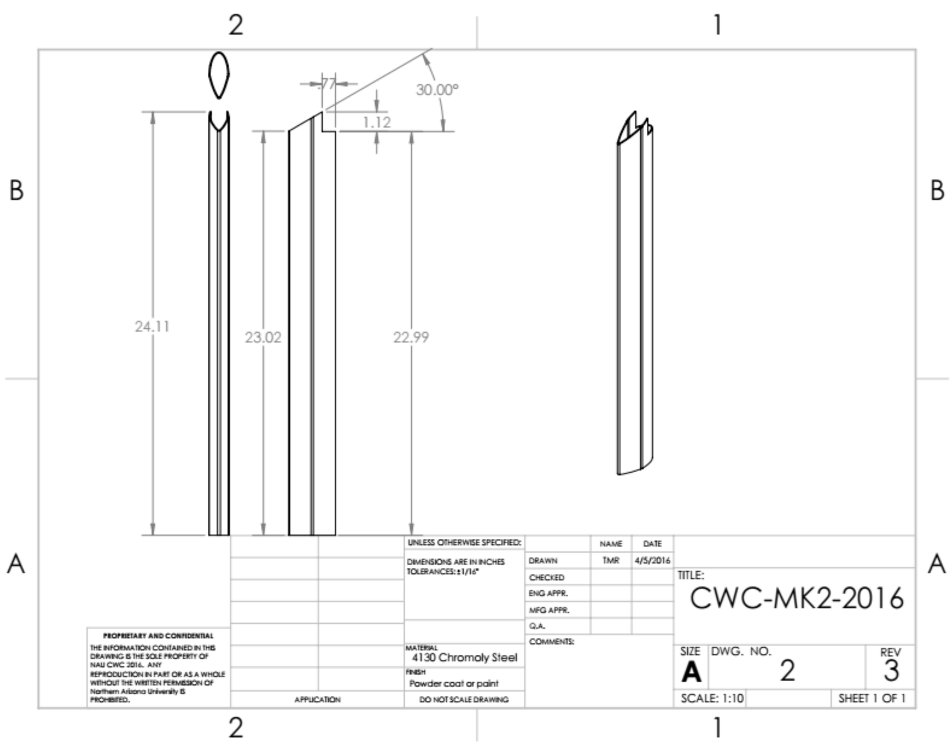


Figure D4: Tower

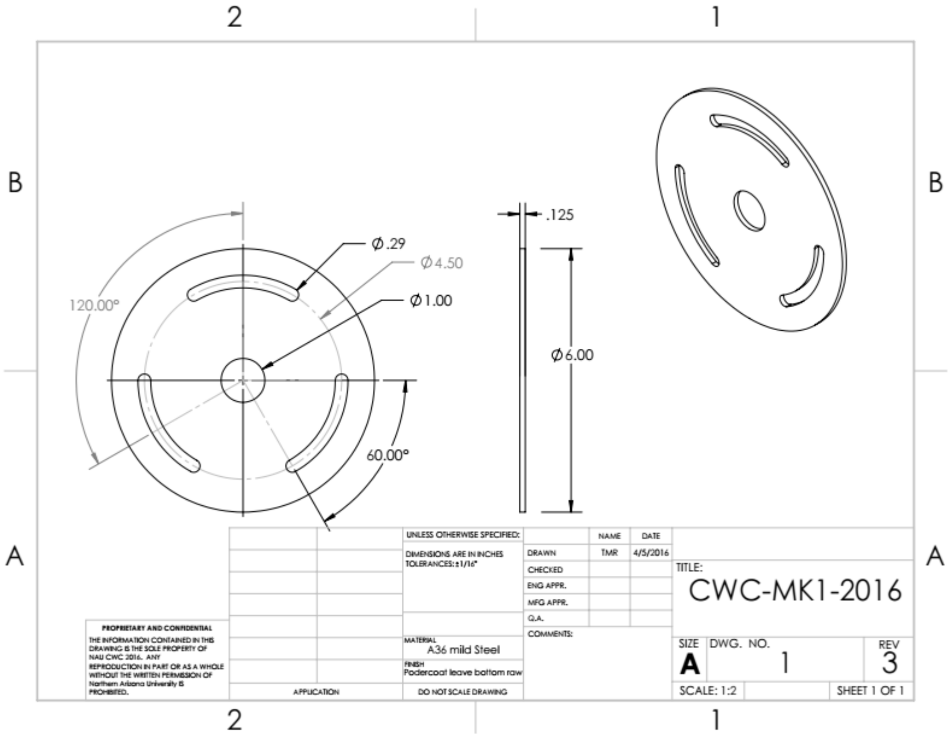
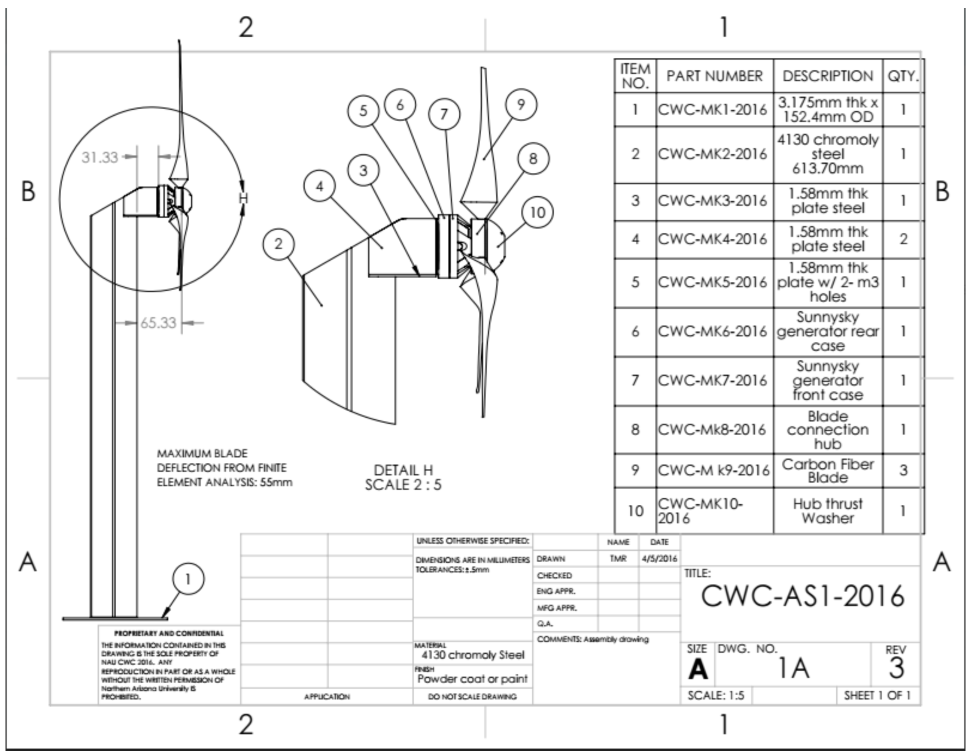


Figure D5: Base Plate



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	CWC-MK1-2016	3.175mm thk x 152.4mm OD	1
2	CWC-MK2-2016	4130 chromoly steel 613.70mm	1
3	CWC-MK3-2016	1.58mm thk plate steel	1
4	CWC-MK4-2016	1.58mm thk plate steel	2
5	CWC-MK5-2016	1.58mm thk plate w/ 2- m3 holes	1
6	CWC-MK6-2016	Sunnysky generator rear case	1
7	CWC-MK7-2016	Sunnysky generator front case	1
8	CWC-Mk8-2016	Blade connection hub	1
9	CWC-M k9-2016	Carbon Fiber Blade	3
10	CWC-MK10-2016	Hub thrust Washer	1

Figure D6: Tower Assembly

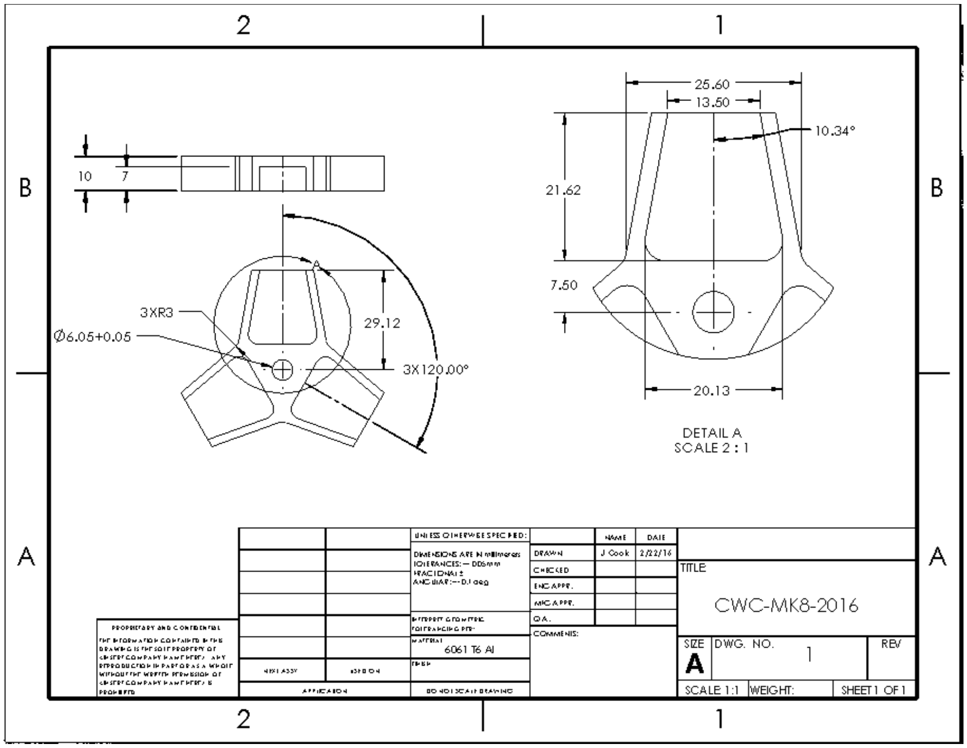


Figure D7: Hub