Final Project Report

Team 25

Taller Wind Turbine for Low Wind Speed Regions

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ABSTRACT

Wind energy is one of the cleanest ways of harnessing electricity in today's society. However, current 80 meters wind turbines are not cost effective in Florida due to lower average wind speeds. Since wind speeds increase with altitude, the project goal was to build a taller economical wind turbine. This concept would allow wind power to be harnessed more universally. The team focused on designing a blade and a tower. The most important factors when designing the blades were increasing the length while decreasing the weight. The blade was 61.5 meters long and was composed of high performance materials to improve the efficiency. Additionally, an innovative three I-beam spar was used to improve current models. A 157.5 meters lattice structure was designed for the tower. The tower takes a heptagonal shape and was designed to ease assembly. After designing the wind turbine, wind data was taken from the target location of Belle Glade, FL to determine the profitability. The levelized cost of energy was calculated to be $65 per MW*h. Compared with the current standard for levelized cost of energy being approximately $72 MW*h, this shows there is great potential in this new development.

ACKNOWLEDGMENTS

There were several individuals that have helped us throughout this semester. Without help from these people the project would not have made as much progress as it has. We are very thankful for the time they took out of their busy schedules in order to instruct us and make sure we understood how to fix our problem before they let us go. Dr. Sungmoon Jung allowed the group to work on this very exciting project and always made time to attend biweekly meetings and answer any questions we had. Dr. Jung has always been extremely positive even when the team has been confused or stuck on a topic related to the project. Dr. Kunihiko Taira has been an excellent mentor and helped us with approaching the design of the wind turbine blades and always provided great ideas that we had not considered. Dr. Powell at the Center for Ocean and Atmospheric Studies helped us understand how to find the wind speed at different heights and good sites to build the turbine. Dr. Hollis has been very helpful in the modeling of the wind turbine blades in Pro Engineer. Dr. Atul introduced the team to the FAST software that is essential to determining the power output from our designed turbine. The senior design instructors, Dr. Shih and Dr. Gupta have provided guidance on deliverables and helpful feedback to make sure the team stays on track.

1. Introduction

In order to reduce global carbon emissions and continue to generate electricity, renewable energy is a dependable alternative to current power generation methods. There are many renewable sources to access including wind, solar, and hydro energy. In the United States, wind energy accounts for 30% of all renewable energy generated. To generate power a certain wind speed must be present. Unfortunately, the Southeastern United States does not have sufficient average wind speed to make current turbines viable. The goal of this project is to develop a wind turbine that would be effective in low wind speed regions like the Southeastern United States. By designing a wind turbine that is taller than current turbines we will be able to harness larger wind speeds at higher altitudes. The mechanical engineering students worked with students from the civil engineering department to develop and design the tower and blades of a new wind turbine. This report details all of the work done on the development of the taller wind turbine from background information to final design and model.

1.1 Problem Statement

Currently there are no major wind farms in the Southeastern United States due to low wind speeds at 80 meters, which is the standard height of current land based wind turbines used in the United States. Developing an effective wind turbine that could be used in the Southeast would open a new market for renewable wind energy. There is a desire to develop a taller wind turbine that can use the faster winds at higher elevations to generate wind power in areas like Florida.

“Current 80 meter wind turbines are not cost-effective for use in the Southeastern U.S.”

1.2 Design Requirements

The goal of the project had several important design requirements that the team needed to meet to be successful. The team had to utilize new technologies and ideas in their design of the wind turbine. The new structural/mechanical designs had to be structurally sound at the height of 120 to 160 meters. In order for the turbine to be a realistic option for the southeast the design had to be cost competitive with current wind turbines in the market. Along with being financially competitive, the turbine had to be able to generate at least the same electrical power as current turbines. The team was given $2,000 dollars for building a scaled model of the wind turbine design. The performance specifications for the project are listed below.

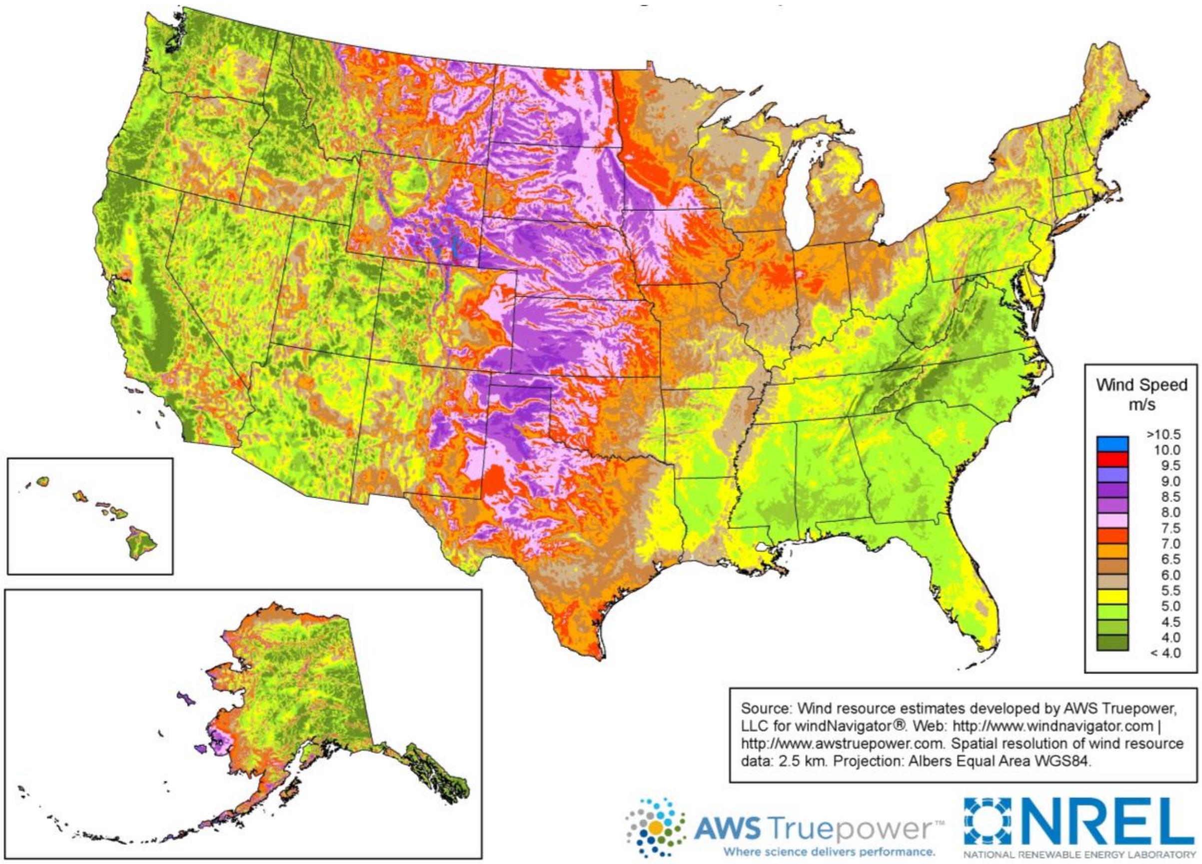
- Operating in all weather conditions with exception of winds >25 m/s
- There will be no energy used or fuel consumed
- The efficiency will be within a range of 30-40%

1.3 Objective

The main objective of this project was to design a wind turbine viable for use in the southeastern United States. In order to obtain this goal the wind turbine designed had to be taller than current wind turbines. Additionally, the blades had to be lighter allowing for the blades to spin and thus generate electricity at lower wind speeds.

2. Background and Literature Review

Wind energy is one of the leading sources of renewable energy in many countries. The United States is increasing its investment into renewable clean energy opposed to dirty energy like coal and gas power plants. In 2013, 13% of the country's electricity generated was from renewable sources. Wind power constituted 30% of the total renewable energy generated[1]. The growing use of wind energy in the country has not traveled to the Southeastern United States due to low wind speeds. Most of Florida's renewable energy comes from solar plants. Light winds make commercial wind farms not currently viable[2]. This project seeks to explore new ideas that would make wind power a feasible method to generate power in Florida and the Southeastern United States. Figure 1 below shows average annual wind speeds throughout the United States, higher wind speeds are shown in purple/red.



Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.

Figure 1. United States: Annual average wind speed at 80m[3]

If there was a wind turbine that could operate effectively at lower wind speeds a huge market, roughly two-thirds of the country, would develop for wind turbine producers. The question then becomes how to make wind turbines work in areas where the wind speed is too low for current turbines to operate effectively. The solution proposed by the sponsor is to make the wind turbine taller so it can utilize faster wind speeds at higher altitudes. The higher wind speed at higher altitudes can be explained by looking at wind flow like water flowing through a pipe with a boundary layer being developed. The velocity vectors will increase with distance from the ground. An example of this wind gradient is shown below in Figure 2.

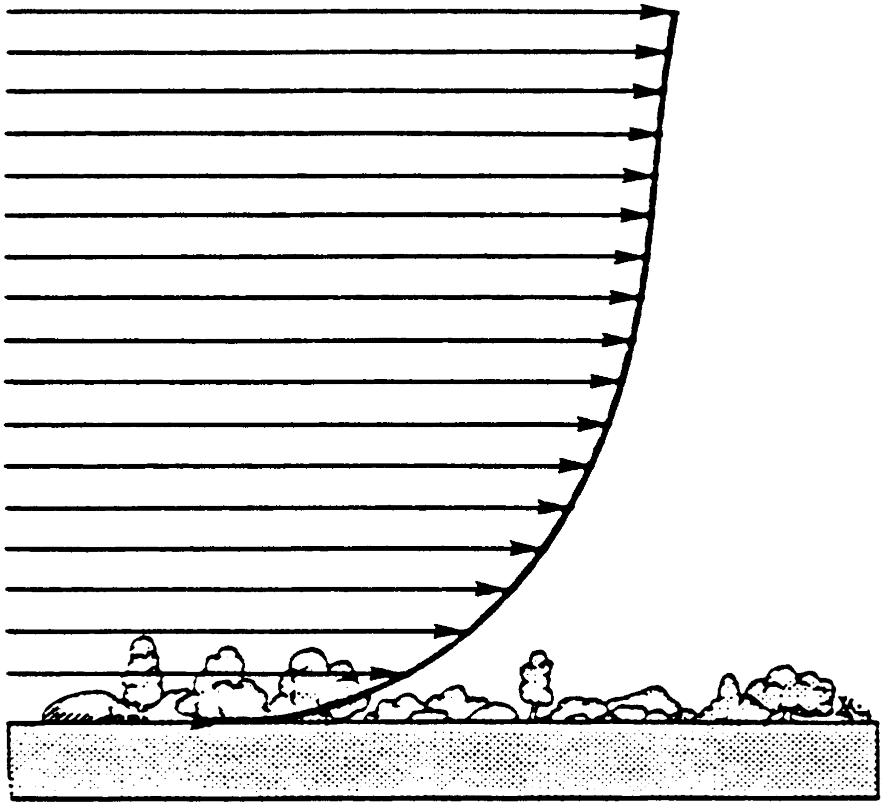


Figure 2. Development of wind gradient with increasing altitude[4]

In order to generate electricity, there must be some sort of input energy. In the case of wind turbines, the input kinetic energy is the wind. This wind causes the blades on a turbine to rotate. These blades are attached to a rotor that spins the generator producing electricity. Currently there are two types of wind turbines used to generate electricity. These include horizontal axis turbines and vertical axis turbines[5]. The senior design team is faced with is the lack of input kinetic energy in low wind speed regions such as Florida. As a result of these low wind speeds, current wind turbines cannot generate sufficient energy. This leaves the senior design group with the task of overcoming the uncontrollable obstacle of low wind speeds and designing a turbine that can generate sufficient energy in low wind speed regions.

The speed of the wind on the wind turbine is critical to generating enough power to be cost-effective. Wind turbines have a “Cut-in Speed” which is the minimum wind speed needed to generate useable power[6]. For most wind turbines this speed is typically 3 to 4.5 m/s. From Figure 1 it can been seen that Florida wind speeds barely make this cut at 80 meters. Since the most common wind turbine used in the United States is 80 meters tall, this project is focused on designing a wind turbine 150 to 200% taller to utilize the higher wind speeds at higher altitudes.

In September 2014, the Energy Department announced that they would be putting $2 million in funding towards two companies in Iowa and Boston focused on producing taller wind turbines in a cost-effective manner[7]. This commitment to taller wind turbines by the government shows that there is a strong incentive to develop this technology for the private and public sector.

3. Concept Generation

3.1 Concept Generation of the Blades

The team originally came up with three designs for the wind turbine blade bracing beam that were aimed at reducing weight while still supporting the forces on the turbine blade. After the three designs were compared a fourth design for the bracing beam was developed and the new design was compared to the best of the original designs. The three original designs and the fourth final design along with descriptions of each are shown below.

The internal cylinder design, shown in Figure 3, consists of a standard airfoil turbine blade, internally supported by a hollow cylinder. The idea behind this design is that the hollow support will reduce the amount of material in the blade, thus reducing the overall blade weight, while still maintaining strength. It was found that this design would be great at supporting the load, but would result in a very heavy bracing beam so it was removed as an option. The cylinder bracing beam also did not function very well in bending, which is the main load that the bracing beam faces.

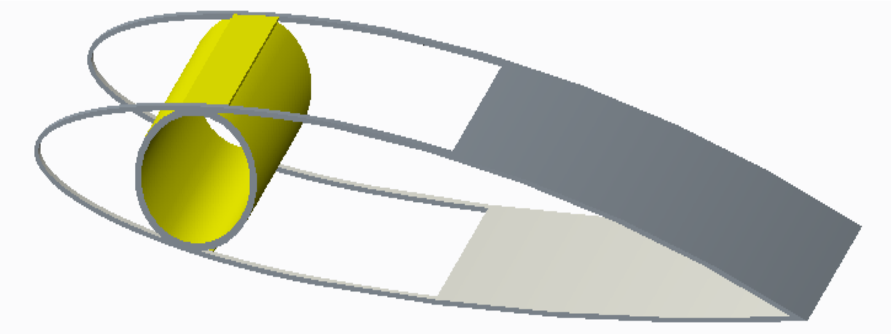


Figure 3. Blade design concept 1 (internal cylinder)

The internal truss blade turbine blade design shown in Figure 4 uses triangular trusses for the shear web. This design eliminates much of the material used. Triangles were chosen in this design because they distribute the compressive load uniformly. This design hopes to significantly reduce the mass while providing enough support so the blades do not bend. This design was very good at reducing the total material used as the bracing beam for the turbine blade, but the truss structure means that during construction the beam would have many points of bonding between the shear web and bracing truss. It was decided that the connections contain too many points of failure for the bracing beam. Because the blade cannot be opened and fixed after construction it was decided to go for a design that was more reliable even if more material was required.

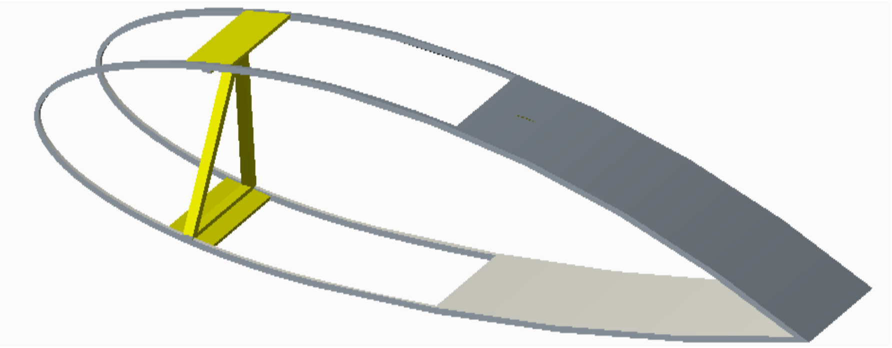


Figure 4. Blade design concept 2 (internal truss)

Figure 5 shows a design that uses a central I-beam placed in between two curved domes. To prevent the load from being too great on a single point in the blade, the top and bottom of the beam will sit on two curved surfaces which will attach to the top and bottom inner surface of the blade. The curved surface will take the point load from the central I-beam and distribute it over a larger area to prevent damage to the blade. As the dome size increases, the load decreases on the contact points and the shape of the dome will resist flattening out even if the load becomes too large. This design was very innovative which was requested by the project sponsor, but the central I-beam posed a problem because it has to support the entire load along a single line on the domes. This means that if the connection between the beam and curved domes is severed, the entire bracing beam will fail. Also, the curved surfaces are difficult to fabricate which means that the beam will increase costs and production time for new turbine blades.

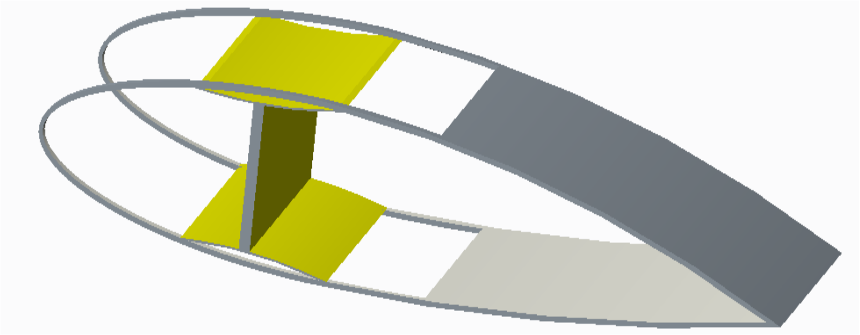


Figure 5. Blade design concept 3 (single post)

After analyzing the three original internal blade designs, none of the designs were deemed sufficient. Therefore, a fourth design was created. This design features a shear web that is supported by three posts that are evenly distributed across the shear web. The triple I-beam design means that the bracing beam will be able to handle large bending loads due to the wind force on the beam. By distributing the three posts over the surface the load is not placed upon a single line like the single post or truss design and this bracing beam can be easily produced because there are no complicated shapes to the design and the three posts means that if one post was to fail, the other two could still support the bending load. These mean that the bracing beam can use less material to support the same load which means less material can be used. This design can be seen below in Figure 6 and is described in more depth in Section 4 of this report.

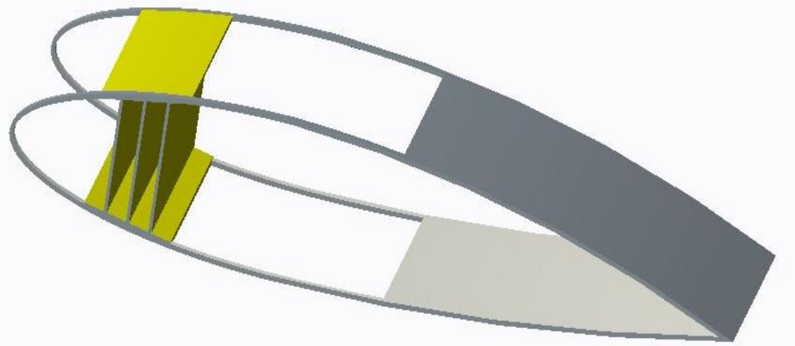


Figure 6. Blade design concept 4 (triple post)

3.1.1 Analysis of Blade Concepts

There was a multi-step process used in selecting the best shape and material to be used for the bracing beam in the 61.5m turbine blade. The bracing beam analysis was based upon the two bracing beams of the internal cylinder and triple post since the truss and single post beams were rejected earlier.

Shape Factor Analysis of Bracing Beam

The first step was to determine how the two beam designs reacted in bending and torsion, with bending being the most important since bending due to a wind load is the largest stress applied to the bracing beam. In order to determine how the beams reacted in bending and torsion, shape factor analysis was done. The shape factor shows how well a shape will withstand a bending or a torsional load. The higher a shape factor of a shape is the better it functions in that method of loading. For the two bracing beams the shape factors were compared in elastic bending and elastic torsion. The equations for the internal cylinder are

$$\varphi_{B:Cylinder} = \frac{3}{\pi} \cdot \frac{r}{t} \tag{1}$$

$$\varphi_{T:Cylinder} = 1.14\frac{r}{t} \tag{2}$$

where, Equation 1 is for the bending cylinder and Equation 2 is for the cylinder in torsion, r is the outer radius of the cylinder, and t is equal to the wall thickness of the cylinder. The equations for the triple post beam are

$$\varphi_{B:Triple\ Post} = \frac{1}{2} \cdot \frac{h}{t} \cdot \frac{\left(1+\frac{3b}{h}\right)}{\left(1+\frac{b}{h}\right)^{1/2}} \tag{3}$$

$$\varphi_{T:Triple\ Post} = 1.19 \cdot \frac{t}{b} \cdot \frac{\left(1+\frac{4h}{b}\right)}{\left(1+\frac{h}{b}\right)^{2}} \tag{4}$$

where, h is the height of the bracing beam, b is the width of the top and bottom base, and t is the thickness of the top and bottom base and one-third the thickness of the three inner posts. To solve for the shape factor of both shapes accurately they have to have the same cross sectional area. The height, base, and thickness of the triple post beam were set and using Mathcad the thickness and radius of a cylinder were solved for. This can be seen in Appendix A. The results for the shape factor analysis of the two beams are shown below in Table 1.

Table 1. Shape factor analysis of bracing beams

Bracing Beam	Elastic Bending	Elastic Torsion
Internal Cylinder	8.531	0.104
Triple Post	22.553	10.185

As can be seen above in Table 1, the triple post bracing beam performs almost four times as well in bending but about 100 times worse in torsion. Bending is by far the dominant load placed upon the bracing beam and torsion is mostly at the root of the wind turbine blade.

Material Selection of Bracing Beam

The second step to the bracing beam analysis was to calculate the forces on the bracing beam and then solve for the proper amount of material needed to withstand the load without fracturing. Once the minimum thickness for each bracing beam was found, the mass could be calculated. The wind load is based upon the wind speed blowing on the turbine. Data for wind speeds was only available at 80m so the team had to extrapolate the wind speed to a height of 160m. The average wind speed was found to be 8.3m/s at 160m in Florida. A factor of safety of two was introduced to account for any stronger gusts. The force on the wind turbine blade was found by multiplying the wind pressure by the surface area on one half of the blade. The wind pressure equation is

$$P = 0.5\, \rho_{air} {v_{air}}^{2} c_{d} \tag{5}$$

where, ρ is the density of air, v is the air velocity, and c_d is the coefficient of drag. The worst case scenario was solved for which was when the maximum amount of area is exposed to wind load. In this case the wind turbine was treated like a flat plank, giving it a coefficient of drag of 1.2. The found pressure on the wind turbine blade was 206 Pa. The force on the blade was found by multiplying the pressure by the surface area and was found to be 44.8kN.

With the force on the bracing beam calculated it became possible to solve for the thickness of the triple post beam and the internal cylinder. The thickness of the triple post beam is

$$t_{Triple\ Post} = \frac{F_{wind} L}{\sigma_y C\left(\frac{1}{3}h^2 + hb\right)} \tag{6}$$

where, F is the wind load of 44.8kN, L is the length along the wind turbine blade where the force was applied with a value of 30m, σ_y is the yield strength of the material, C is a constant of 1, h is the height of the beam of 0.375m, and b is the base width of the beam of 0.375m. The yield strength was dependent on the on the material chosen. The thickness for the internal cylinder is a function of the inner and outer radii and is

$$r_i = \left({r_o}^4 - \left(\frac{4F_{wind} L r_o}{\pi \sigma_y C}\right)\right) \tag{7}$$

where, F is the wind load, L is the 30m length of the centroid, r_o and r_i are the outer and inner radius, σ_y is the yield strength of the material, and C is a constant of 1.

Both the radius and thickness of the cylinder were a function of the yield strength of the material chosen so the next step was to choose the best materials for the situation. To do this the best materials were chosen using a material index for a beam in elastic deformation since all deflection on the bracing beam needs to be only elastic. The goal is to select a material that can withstand the deflection of a wind turbine blade while minimizing the mass of the beam. The material index for both of the bracing beams is

$$M = \frac{E}{\rho} \tag{8}$$

where, E is the Young's Modulus of the material and ρ is the density of the material. The material index can be graphed as a line on a material properties graph shown below in Figure 7. Maximizing the material index shows that the best materials for this situation are at the top left of the chart.

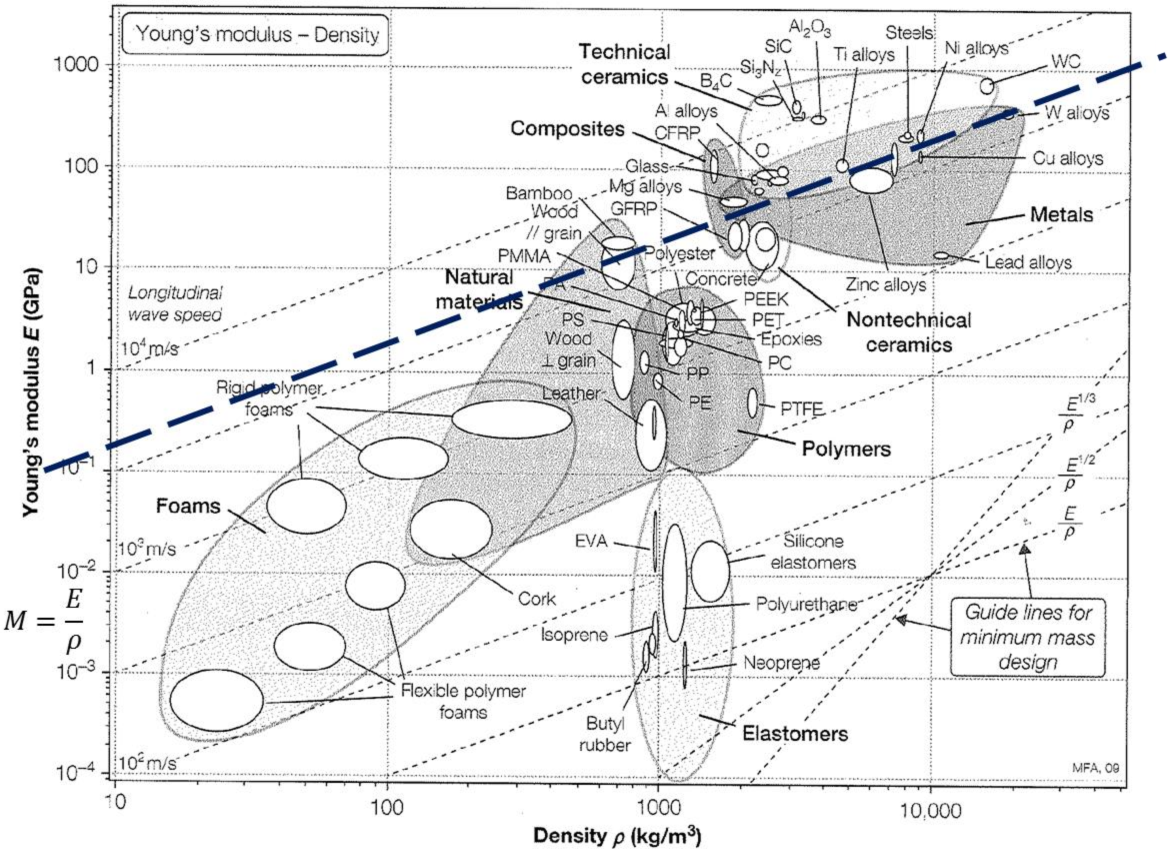


Figure 7. Young's modulus versus density graph

Materials above the line are the best materials for the bracing beam. From Figure 7 it can be seen that the best materials for the bracing beams are steel, aluminum alloys, bamboo, and CFRP (carbon fiber reinforced polymer). These will be the materials chosen to calculate the thickness and radius of the cylinders. The materials, densities, yield strength, calculated thickness, and radius values are shown below in Table 2.

Table 2. Materials for triple post bracing beam

Material	Density(kg/m^3)	Yield Strength (MPa)	Triple Post Thickness (mm)	Internal Cylinder Inner Radius (mm)
Carbon Steel	7,800	322.5	22	125
Aluminum	2,700	265	27	71
Bamboo	700	39.5	181	>375
CFRP	1,550	800	0.9	170

From Table 2 it can be seen that for the bamboo the inner radius for the cylinder is larger than the space available in the blade so it is removed as an option. CFRP has the smallest thickness and the smallest wall thickness for the internal cylinder, but with CFRP costing 30 times that of aluminum and 70 times the cost of steel it is also rejected. This leaves carbon steel and aluminum as possible options for the internal bracing beam. With these two materials the mass can be calculated using

$$m = \rho A_c L \tag{9}$$

where, ρ is the density of the material, L is the length of the bracing beam with a value of 61.5m and A_c is the cross sectional area of the bracing beam based upon the thickness and cylinder radius. The mass of the cylinder and triple post for both materials is shown in Table 3.

Table 3. Mass for bracing beams

Shape	Mass (Carbon Steel) (kg)	Mass (Aluminum) (kg)
Internal Cylinder	45,430	15,730
Triple Post	19,640	6,738

Table 3 above clearly shows that the internal cylinder has a much higher required mass to support the bending load than the mass of the triple post beam and then using aluminum as the material results in a mass of roughly one-third that of carbon steel. Since the triple post is also the best shape for use in bending the bracing beam will be a triple post beam made out of aluminum alloy with a thickness of 22mm and a mass of 6,738kg.

Material Selection of Blade Shell

The material selection for the shell of the wind turbine blades were designed with considerations of strength, stiffness, weight, and cost. To optimize these properties the shell will be constructed as a layered structure which will include the selected fabric(s), a resin, and a structural core. The layered structure will resemble Figure 8 below.

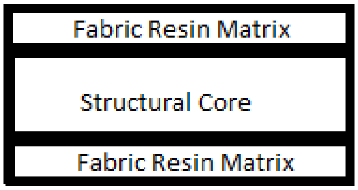


Figure 8. The layered structure of the external fabric design

Most of the blade shells in use today are made from E-glass fabrics, vinyl ester resin, and a PVC or balsa core. With technology continually improving, new materials have been created which will optimize the performance of the blade.

For fabrics, the shell will use mostly E-glass and carbon fiber reinforcements in high stress areas. The much lower cost of E-glass led to the decision for its use. Fabric orientations of mat, double bias, and unidirectional E-glass will be layered to improve the strength of the blade. Also, a unidirectional carbon fiber fabric will be applied in to reduce the weight while increasing the strength and stiffness. Since carbon fiber costs approximately 20 times more than E-glass it will be used sparingly.

Epoxy was selected as the resin for the shell of the blade. Compared to vinyl ester, epoxy has greater strength, stiffness, and fatigue strength while having the same density. Epoxy costs more, but has a greater strength than vinyl ester. This will leads to less fabric which will reduce the blade weight and along with the cost. Additionally, the epoxy will be pre-impregnated into a reinforcement fabric to further enhance the shell properties.

The core of the shell is used to help distribute the load and stresses on the outer fabric. For the core, styrene acrylonitrile foam (SAN) was selected. Key components that led to this decision was the good strength-to-weight ratio, stiffness-to-weight ratio, along with the high fatigue strength. Another feature of the material is the chemical stability which makes the core compatible with epoxy pre-impregnated materials. On the other hand, Poly Vinyl Chloride Foam (PVC) tends to have compatibility issues with resins and balsa has a much greater resin uptake which would increase the weight of the shell.

With growing industrial needs, it is expected for higher quality materials to be more cost effective in future projects. For fabrics, chemically modified glass fibers such as S-glass may become prevalent in the industry with a decrease in price. Also, the use of carbon fiber seems to be becoming more prevalent with the increasing demand. As for structural cores, there has recently been much development. One foam that may stand out in the future is Polyethylene Terephalate foam (PET). This foam is abundant, recyclable, and chemically stable. Since it has recently been introduced as a structural foam, the mechanical properties are lower than other options.

3.2 Concept Generation of the Tower

The most common wind turbines are supported by a steel tubular structure, shown in Figure 9. This tower is effective for use at 80 meters and below but it becomes less cost effective if built to taller heights. If this design is made for the project constraint of 120-160 meters, the base will become much larger and this could affect the transportability of the cylindrical sections. This tower is useful as a good baseline to measure the team’s designs against.

Figure 9. Standard tower design (steel tube)

In order to create a more cost effective wind turbine, innovative alternatives were considered. The main concerns for the design of the tower included transportation of the materials, assembly of the structure, the overall weight of the structure, and above all, the ability to withstand the forces caused by the rotation of the blades. Initially, the construction materials considered included concrete and steel because they are both high-strength materials that are readily available. However, steel was decided to be the most efficient construction material due to its high strength-to-weight ratio. The use of steel would also increase the ease of transportation. Furthermore, a lattice structure was considered to make the best use of the material to keep the weight of the tower at a minimum while also maintaining the strength of the structure. Despite the increased construction time due to the assembly of the lattice structure, the tower is expected to be more cost efficient due to the reduced amount of material and ease of transportation. Lastly, the tower will be wrapped in an architectural fabric in order to insulate the internal system protecting it from weather, corrosion, and wildlife. The two initial structure designs consist of a three-sided and a seven-sided steel lattice tower. The concept behind these two designs are described in depth in the following section.

3.2.1 Structure

The seven-sided space frame tower, shown in Figure 10, was originally conceptualized based on a current innovation by GE. As previously stated, the use of a steel lattice structure has the benefits of minimizing the amount of material while maintaining the strength of the tower. Moreover, the use of seven sides allows the tower to be transported in standard semi-trailers, as opposed to the specialized transportation used for the tubular towers. This will greatly reduce the costs associated with transportation. Furthermore, the sections could be pre-assembled, pre-wrapped and then stacked on site similar to the tubular towers.

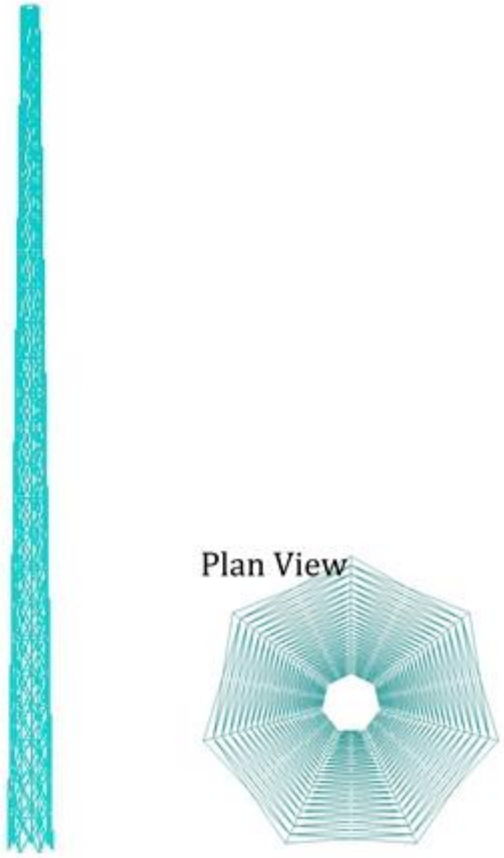


Figure 10. Tower design concept 1 (heptagonal space frame)

The three-sided space frame tower, shown in Figure 11, was initially considered because it was thought to have reduced the overall amount of material used in the tower. Additionally, with four less sides than the heptagonal tower, the number of connections throughout the tower would be reduced resulting in more rapid construction. Another feature that would increase the construction time is the ring connection between each section. The tower could be assembled in sections and then stacked into place with the ring connections easing the sections into one another. The cylindrical shape made by the fabric wrapped around the ring would also allow the wind load on the tower to flow around the tower to prevent excessive force from being applied on one single side. However, this would significantly increase the amount of fabric required.

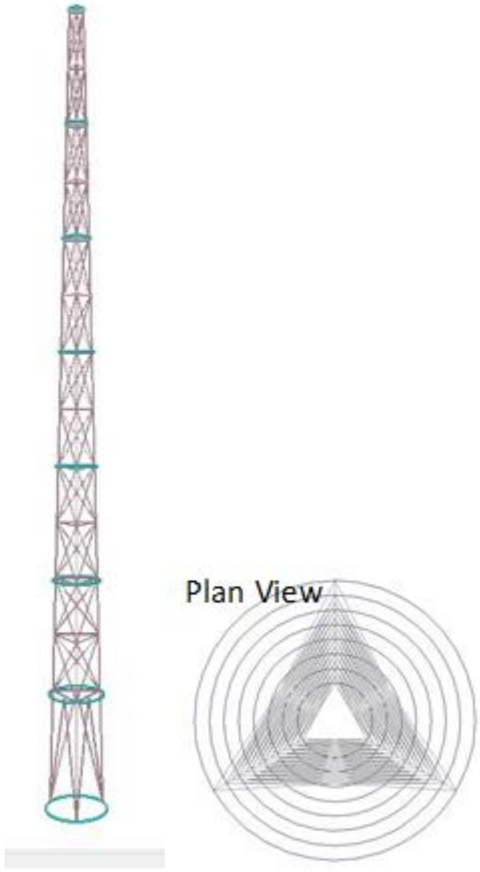


Figure 11. Tower design concept 2 (triangular space frame)

Of the two designs, the seven-sided tower was considered to be more adequate. Even though the three-sided tower was thought to have reduced the amount of material, the weight of the two towers were actually very similar due to the difference in geometry. Furthermore, after running force analysis on the towers, the seven-sided space frame appeared to have a higher strength. Therefore, analyses and improvements continued to be made to the seven-sided tower design.

Several changes were made to the heptagonal space frame in order to make the design more effective and economically efficient. These changes include widening the base to increase the strength of the tower. Previously, the structure was failing due to bending about a third of the way up the tower caused by the force of the blades. Increasing the size of the tower's base, made the structure more stable and eliminated this potential failure. Another addition to the design included internal bracing, which strengthened the tower and allowed the weight of the tower to be dramatically reduced. The reinforcement within the tower allowed smaller sections to be used throughout the tower. The connections between the sections of the heptagonal tower were based on the concept of the connection idea for the triangular tower. This design is explained in the next section.

3.2.2 Connections

In order to decrease the construction time of the tower, a modular construction method was considered. Due to limitations on transportation, the bottom three spans are required to be assembled on site. However, the upper spans will be pre-assembled into cylindrical-like sections and then connected to one another using heptagonal rings. These heptagonal ring connections contain plugs located at each corner to receive the incoming column. This design allows the sections to be placed on top of one another with ease and security once the section is in place. Additionally, the assembly of the upper sections is very similar to that of a tubular tower. Therefore, the only additional time and costs associated with the tower are a result of the assembly of the lower spans. This increase in cost is factored into the initial cost of the tower in the Economics section.

The connections between the bracing will resist axial forces but will allow for twisting. There is one highly stressed area that need to be welded on site to ensure a strong connection. This area is located between the wider base and the more narrow upper section. This section experiences high stresses due to the tapering of the area and welding the connection would provide the strength necessary to prevent localized stresses.

4. Final Design

4.1 Blade Design

The turbine is made up of blades, nacelle/generator, and the tower. The team did not design the nacelle or 5MW generator, but used predefined weight and dimensions provided by NREL to account for the size and weight. The final design of the blade is a NACA-64 airfoil with a triple I-beam spar. The triple I-beam spar is made of Aluminum 6061, and can be seen below in Figure 12.

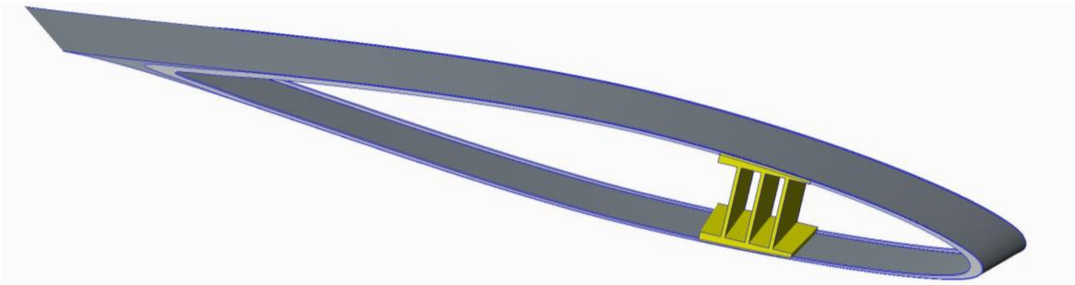


Figure 12. Cross section of blade

One cross-section of the spar is dimensioned below in Figure 13, the dimensions of the spar are based on the chord length. The ratio of spar dimensions remain constant throughout the blade.

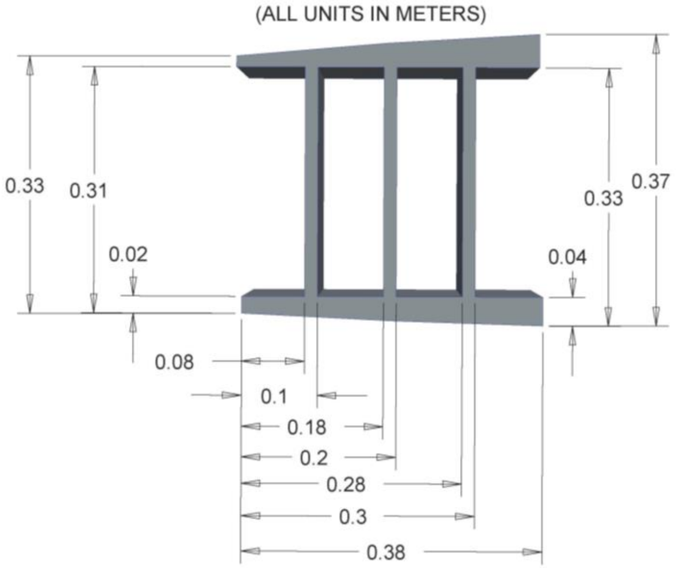


Figure 13. Dimensioned internal spar

In order to maximize lift of the blade the team implanted a varying angle of twist throughout the length of the blade. The angle of twist varies from approximately 0-13 degrees, a table of cross-sections and the blades' angle of twist can be seen in Appendix B. Looking down the fully wrapped blade, the angle of twist is difficult to visualize; however, it can be seen easily by looking down the blade from the root without the blade wrapping which can be seen in Figure 14.

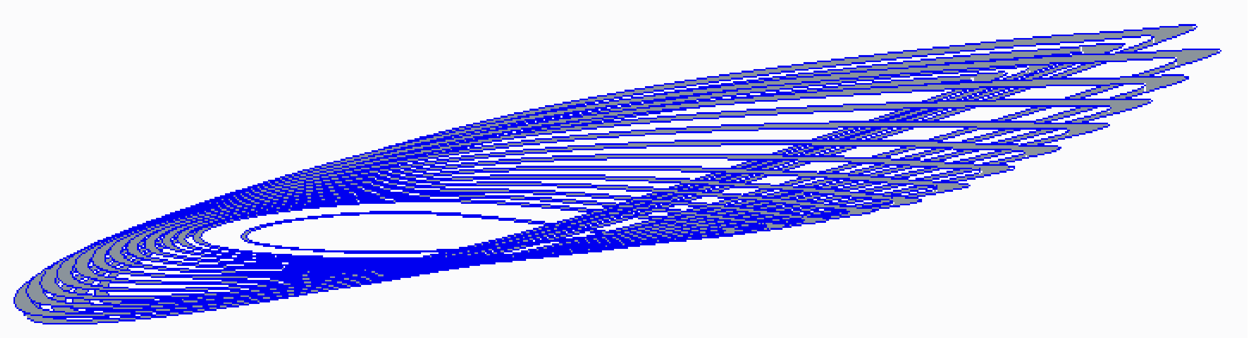


Figure 14. Blade angle of twist shown without blade wrapping

The team used a predefined airfoil shape to create the blade cross-sections. The team obtained the NACA-64 airfoil shape non-dimensionalized by the chord lengths. The table of X & Y coordinates obtained to create the airfoil can be seen in Appendix B. From NREL, the team also obtained the number of cross-sections, the cross-section lengths, and chord lengths for multiple high output blades. Once the team had multiple blades the team further researched each one and picked the best suited blade for the project. The table of dimensions for the blade can be seen in Appendix B. Once each of these dimensions were found the team used both tables to create the outer layer of the blade. The team chose to remain with the typical 61.5 meter turbine blade length due to the fact of tip deflection caused by the wind. If the blade deflects too much, they can hit the tower and cause failure. Along with blade deflection, blades that are longer than 62 meters are much more difficult to transport to the construction site because the trucks needed to transport a single blade cannot be longer and still drive safely. The team also worked to reduce the weight of the blades as much as possible and still maintain the shape and strength that was required for safe operation of the wind turbine. Typical 61.5 meter blades weigh 21,132 kg and the designed blades have an individual weight of 20,381 kg[2]. The specifications for the blades are shown below in Table 3 and dimensions of the blade are shown below in Figure 15.

Table 3. Wind turbine blades for use in full-scale design

Blade Weight	20,381 kg
Blade Length	61.5 m
Airfoil Shape	NACA64
Material (Internal Spar)	Al6061
Material (Blade Shell)	E-glass, epoxy, SAN foam, carbon fiber

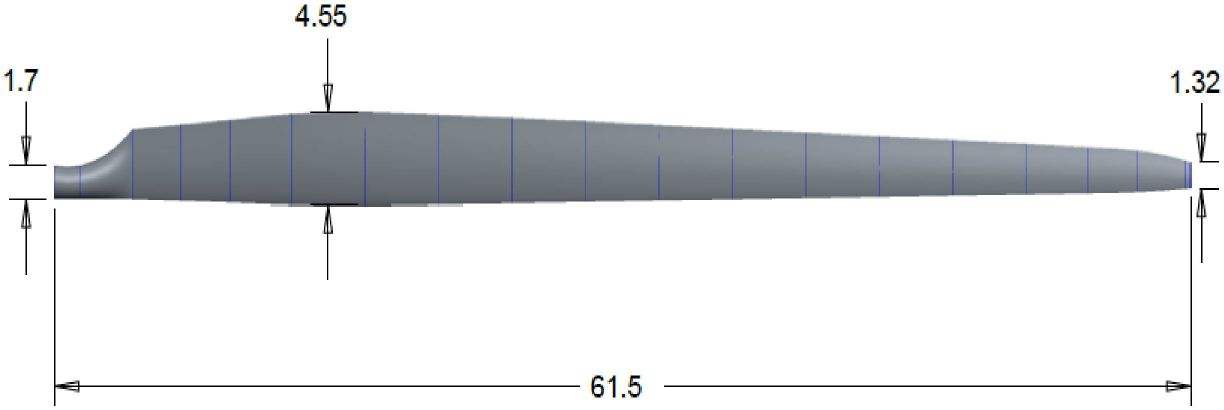


Figure 15. Full-Scale turbine blade dimensioned in meters.

4.1.1 Blade Analysis

After the final design was complete, the blade was tested in Creo with an applied load twice of what would be expected in Florida. On average a 60 meter turbine blade deflects 2.5 meters. Upon finite element analysis the designed spar deflected only 1.15 meters, which is well below the average deflection. The spar is only a portion of the blades strength, consequently it is proved that our design will be much stronger than typical turbines. This can be seen below in Figure 16.

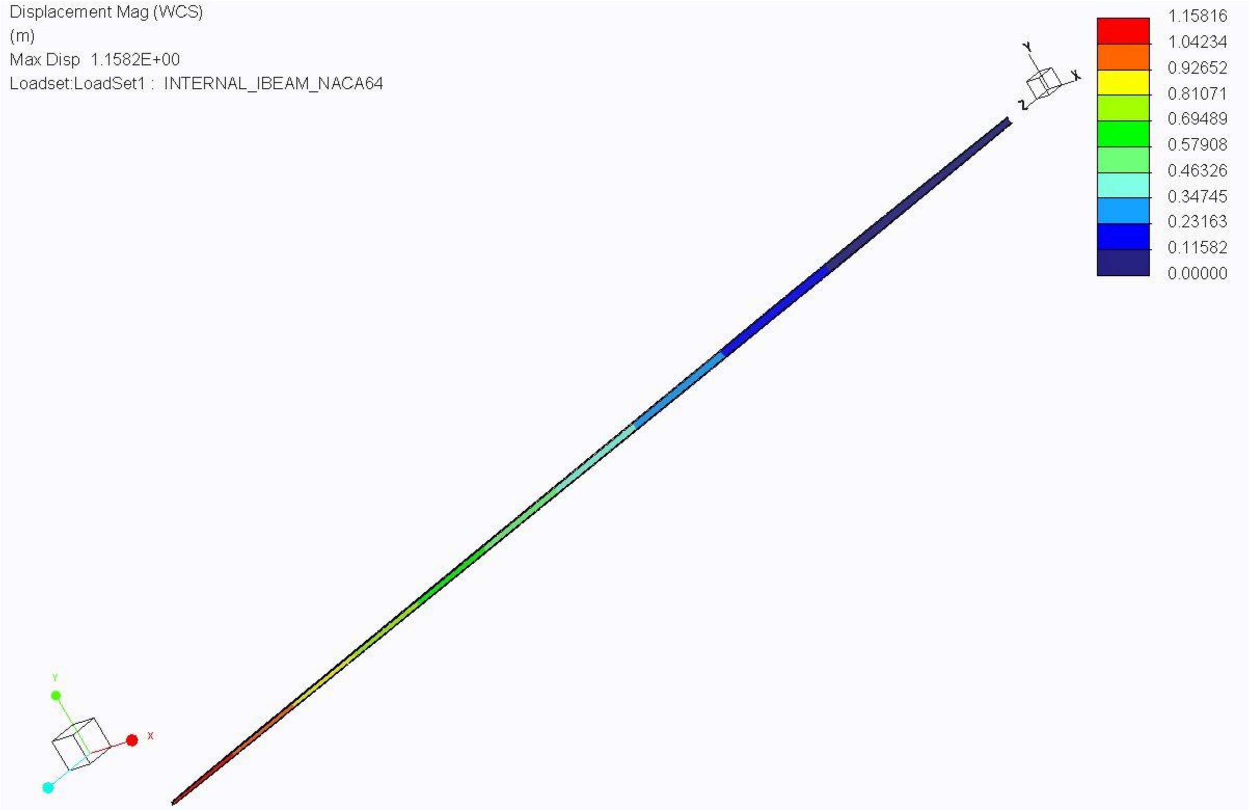


Figure 16. Blade deflection under load

From Figure 16 it can be seen that the root of the blade, on the right, is shaded purple and has no deflection while the blade tip, in red, has deflected the maximum amount of 1.15 meters. Along with deflection, the von Mises stress was calculated through the entirety of the blade. The blade was loaded as a cantilevered beam and the high stress areas were located the connection of the beam as expected. With the higher stress levels, these areas were focused on and this is shown in Figure 17.

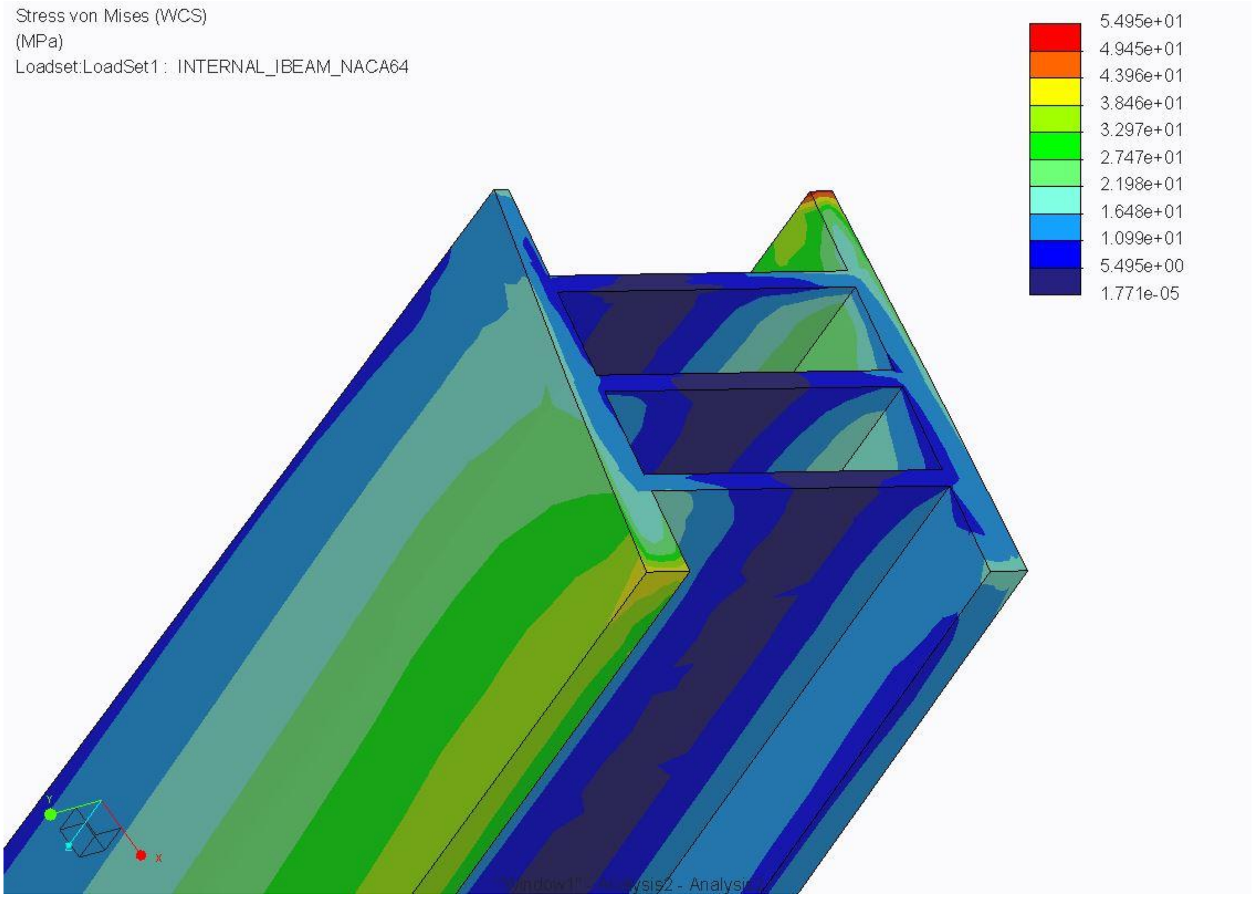


Figure 17. Stress analysis of spar

From Figure 17, it can be seen that the highest loads are located at the corners with a maximum values of approximately 55MPa, but the majority of the spar had stresses below 15MPa. The Aluminum 6061 spar has a yield strength of 276MPa, therefore yielding will not be a factor with this design.

4.2 Tower Design

The final design of the tower is a seven-sided steel lattice structure wrapped in an architectural fabric. The tower has a hub height of 157.5 meters. The final design is shown in Figure 18. The tower consists of 20 vertical spans, with the bottom three spans making up the widened base. The base was designed to be much wider than the rest of the tower in order to account for the large moment at the base. With each side of the base being about 9.6 meters wide, the sections will be transported to the construction site prior to assembly to allow for the use of standard semi-trailers.

The construction time of the tower will be increased due to the onsite assembly of the lower three sections. However, the construction of the upper spans closely reflects the current method of construction for tubular towers.

The tower design also features internal bracing, which increases the strength of the tower in all directions. The internal bracing was added after the tower was passing the analyses but was still too heavy to be comparable to current wind turbines. The addition of the internal bracing allowed the required sections throughout most of the tower to be reduced to smaller sizes, which decreased the weight to about 272Mg. This weight is comparable to the weight of current 80 meter wind turbine towers.

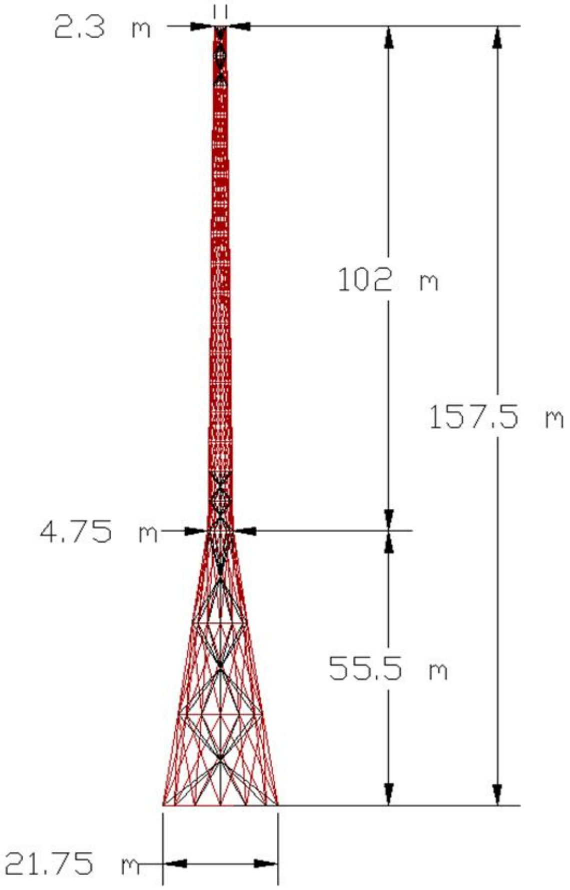


Figure 18. Final tower design (tapered heptagonal lattice)

4.2.1 Tower Analysis

Analyses were performed with Bentley System’s software STAAD Pro V8i. The design file used to perform analyses and optimizations was created using AutoCAD Civil 3D. After the analyses, the tower could be altered in AutoCAD and inputted back into STAAD to re-run analysis in an iterative process.

The material selected for the design was standard A500, grade C steel which has a yield strength of 317MPa. The material sizes ranged from HSS6x6 to HSS 20x12.

The 2010 ASD design code along with optimization parameters were used to analyze the tower and achieve the lightest passing structure possible. However, the optimization only considers the load applied in one direction. Therefore, individual spans were “regularized” based on the largest section sizes selected. After applying these changes, the weight increased from 245 to 363Mg, but the deflection at the top of the tower also reduced from approximately 2 to 0.9 meters. The weight of the design was comparable to typical 80 meter wind turbines which weight approximately 345Mg.

Load was applied by inserting a vertical member in the center of the tower and loading this member, as shown in Figure 19. This member was then braced to all surrounding joints. This allowed for a much more even distribution of wind loading forces than simply applying load to exterior of the structure, as was originally done.

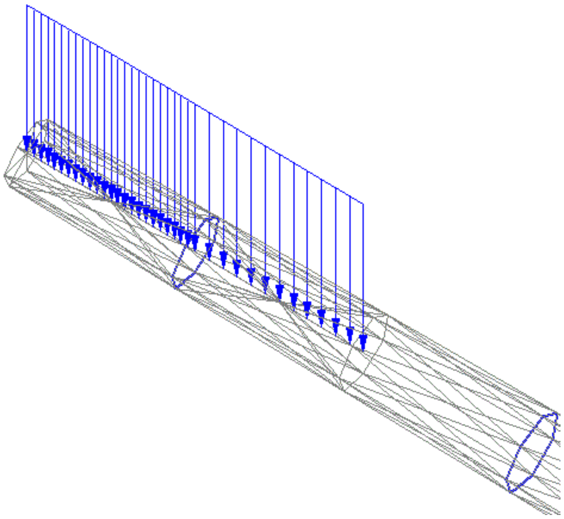


Figure 19. Simulation of wind load on tower

After seeing the success of this loading application, internal bracing was added in a simlar fashion near the base and middle of the tower, which were the highest stressed parts of the tower. This bracing distributed the built-up moment within the critical members. After re-optimizing, the tower's weight was reduced by approximately 50% from 680Mg.

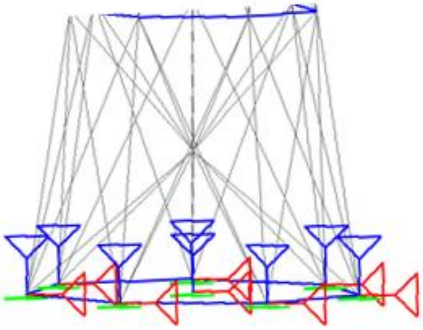


Figure 20. Bottom span of tower showing internal bracing

Loading was altered until the horizontal reactions at the base of the tower was over 534kN, our maximum expected loading. Additional loading definitions were created to simulate a 50% strength earthquake per Canadian seismic design specifications. Additionally, modal analysis commands were inputted to produce 3 modes for comparison with the blades' modes. . Selfweight had to be applied in all three directions to allow for free translation and vibration in any direction, including the vertical (Z) direction due to the shaking of the earth itself. Although the team does not expect seismic loading in Florida, hurricanes and other natural events were not able to be tested in this program. The final structure successfully passed analysis with zero failed members and no instabilities at any joints. The deflection at the top of the tower was 0.94 meters.

4.2.2 Connection Design

The connections for the final design of the tower includes bolted connections and one area of field welding. The connection designs are based on specifications found in the American Institute of Steel Construction (AISC) Manual [8]. In the analysis of the connections, the allowable strength design factors are used to include a factor of safety in the calculations.

To determine the bolts required for the connections, it was first determined whether the connection was in tension or compression. Equation 10 was used to find the nominal strength for bolts in tension, while Equation 11 was used for bolts in compression or under combine loading. In these equations, R_n is the nominal strength, F_n is the nominal tensile stress, A_b is the nominal unthreaded body area of the bolt, and F'_{nt} is the shear stress

$$R_n = F_n * A_b \quad . \tag{10}$$

$$R_n = F'_{nt} * A_b \ . \tag{11}$$

In order to take the bearing of the bolts into account, Equation 12 was applied, where l_c is the clear distance, in the direction of the force, between the edge of the hole and the edge of the adjacent hole or edge of the material, t is the thickness of the connected material, F_u is the specified minimum tensile strength of the connected material, and d is the nominal bolt diameter

$$R_n = 1.2 l_c * t * F_u \leq 3.0 * d * t * F_u \ . \tag{12}$$

Taking the yielding of connecting elements into account, Equations 13-14 were then used to find the nominal strength. Equation 13 was used to find the tensile yielding of the element and Equation 14 was used to find the tensile rupture. F_y is the yield strength of the material, A_g is the gross area subject to shear, and A_e is the effective net area

$$R_n = F_y * A_g \quad . \tag{13}$$

$$R_n = F_u * A_e \quad . \tag{14}$$

The shear of connecting elements was analyzed using Equation 15 for shear yielding and Equation 16 for shear rupture. In these equations, A_{gv} is the gross area of the element subject to shear and A_{nv} is the net area subject to shear.

$$R_n = 0.6 * F_y * A_{gv} \ . \tag{15}$$

$$R_n = 0.6 * F_u * A_{nv} \ . \tag{16}$$

Finally, the available strength to prevent block shear rupture along a shear failure path was found using Equation 17. In this equation, U_{bs} is a uniformity factor of stress distribution and A_{nt} is the net areas subject to tension

$$R_n = 0.6 * F_u * A_{nv} + U_{bs} * F_u * A_{nt} \leq 0.6 * F_y * A_{gv} + U_{bs} * F_u * A_{nt} \ . \tag{17}$$

As mentioned earlier, the connection between the spans consists of a custom designed heptagonal ring. Each of the rings contain plugs to connect into the columns. The plugs will be welded to the ring, and the columns will be bolted into the plugs. The minimum weld fillet sizes are ¼-inch for ½ - ¾-inch gauge steel. This fillet size will be used throughout the tower where welds are necessary. Furthermore, using the equations listed above in this section, the minimum size bolts for the connections between the columns and the plugs are ¾ inch Group B, A490 bolts[8]. The bolts have a nominal tensile strength of 780MPa and a nominal shear strength of 580MPa. Based on the bolt sizes and connection area, the minimum distance from the edge of the connecting element to the center of the bolt is .0254 meters. To increase the ease of construction the same bolt size will be used throughout the tower; however, the number of bolts at each connection will vary. The connection between the bracing and the columns will also be bolted connections. The tower is to be constructed by welding steel angle sections to the outside of the columns. The bracing, which are made up of channel sections specifically C7x12.25, will connect to the angles. The intersection where the bracings cross will also be a bolted connection to prevent bending but allow for rotational translation in the tower, these connections are shown in Figure 21.

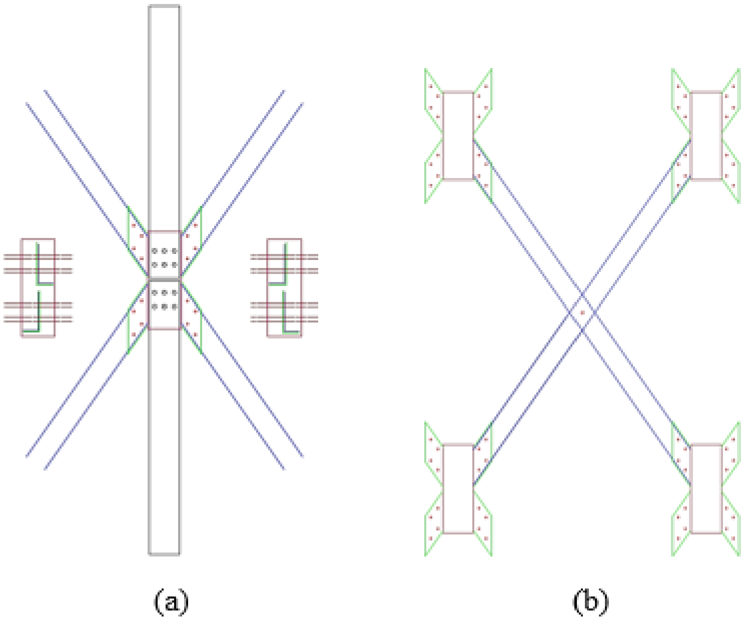


Figure 21. (a) Bracing-to-column connection and (b) Bracing-to-bracing connection

4.2.3 Architectural Fabric

The type of architectural fabric to be used to wrap the tower was chosen based on the strength, durability, and cost. The materials considered include PVC-coated polyester and High Density Polyethylene (HDPE). While the PVC-coated polyester would theoretically last the lifetime of the wind turbine, it was much too expensive to make the wind turbine economically efficient. Therefore, a less expensive Low Density Polyethylene (LDPE) coated HDPE woven membrane was chosen. The high-strength, light-weight, and fire retardant properties of this fabric make it a suitable option. Even though the fabric may need to be replaced after 10-15 years, the overall cost is still less than the PVC-coated polyester.

4.3 Nacelle Design

The design of a full-scale nacelle was not requested for the project so the team was provided with a nacelle to use in the design of the full-scale turbine. A representation of the nacelle is shown below in Figure 22.

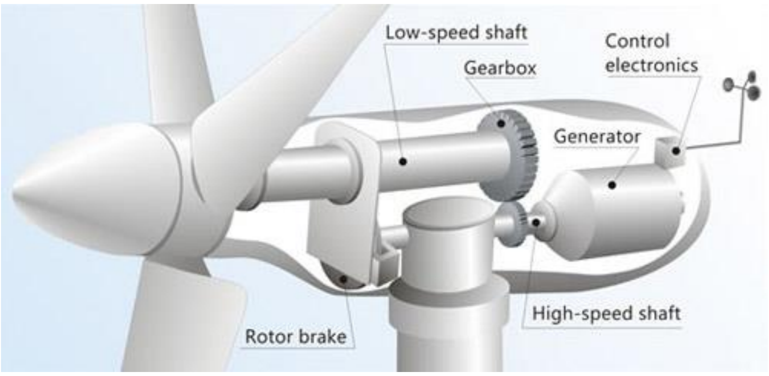


Figure 22. Interior of nacelle for wind turbine[9]

High wind speeds generate lift on the wind turbine blades and cause them to spin which spins the rotor. The rotor shaft enters the nacelle and is connected to a gearbox which takes the low speed rotation and uses a high gear ratio to spin a generator shaft at high speeds. The spinning of the generator shaft creates electricity. Inside the nacelle is also the electronics to control the rotation of the nacelle and a rotor brake that stops the blades from spinning too fast for safety.

4.4 Turbine Assembly

The blades will be manufactured offsite and transported to the construction site by flatbed truck. Once the blades arrive at the site they will be lifted by crane to the nacelle where they will be connected to the rotor with bolts. Workers will climb the center of the tower and tighten the bolts. All workers will be harnessed and safely connected while the blades are being connected. The connection will be checked before the tower is cleared to operate.

In the assembly of the tower, the material is transported to the construction site by standard semi-trailers. The upper seventeen sections are preassembled and prewrapped while the lower three sections will be assembled and wrapped in the architectural fabric onsite. Using a crane, the sections will be lifted into place on the tower. Using the male-to-female connections, the upper sections may rest on the section beneath until the connections are made.

Upon arrival at the site, segments will be inspected, wrapped in architectural fabric, and hoisted into place by a crane operator. The widened base requires the first three spans (one third of the height) to be completely assembled and wrapped on site before placement can begin with the use of a crane. This will require more workers to be present and longer hours to be worked. But such a process is necessary to meet primary design goals and this method of erection will only need to continue for however long it takes to assemble three spans, after which rapid assembly may begin with the remaining smaller 17 spans.

The nacelle will be built offsite and shipped to the construction site. The nacelle will be lifted by crane to the top of the tower where the nacelle will be attached with bolts. The electrical wires will be fed through the center of the tower to protect them from the outside environment. The low speed rotor shaft will be inserted into the front of the nacelle and connected to the gear box. The hub that connects the nacelle to the blades will be attached last to the rotor shaft with bolts. All connection points will be inspected before moving on to the next step in construction.

4.5 Modal Analysis

With resonance frequencies being a major factor to the well-being of the tower and things around it, the team simulated both the tower and the blade set to determine the modes of each. By comparing each mode of the tower to the blades, the team was able to determine that the chance of harmonic resonance within the turbine is low. The modes of each are shown below in Table 4.

Table 4. Modal analysis comparison

Mode	Blade Modes (Hz)	Tower Modes (Hz)
1	0.1308	0.0500
2	0.1809	0.2700
3	0.7423	0.5690

4.6 Design for Reliability

4.6.1 Reliability of Full-Scale Wind Turbine

Reliability Concerns for Tower

One initial drawback to our lattice frame design was the lack of insulation within the tower. The team liked the design because it could increase the hub height, decrease material usage, and even reduce undesirable wind loading on the structure's walls. It was concluded that the tower would need to be insulated with an architectural fabric. This insulation would keep unwanted moisture away from the structural steel of the tower and the mechanical and electrical components of the nacelle and rotor. Due to our widened base design sufficient insulated room was available to store the generator within the tower itself. As an additional precaution all structural steel will be painted to resist corrosion. Maintenance of the tower itself would then be limited to visual inspections to ensure no unexpected corrosion is taking place, along with inspections on all bolts and connections.

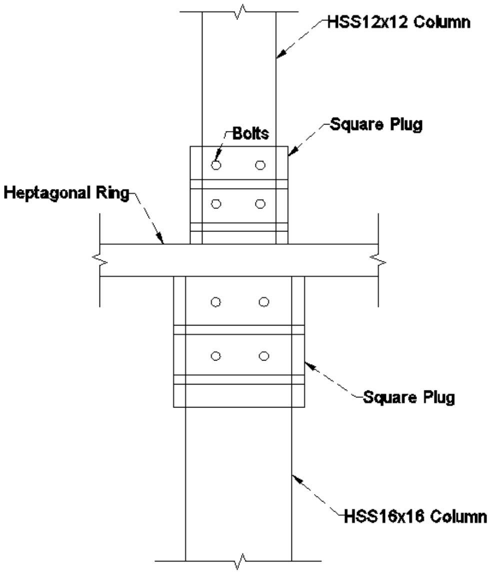


Figure 23. Full scale tower connection design

The connections, shown in Figure 7, were made simplified through use of HSS shapes. Thorough connection design and plug welds were utilized to allow for “male-to-female” slip fits. Not only will this allow for a faster assembly process, but it will also ensure that all vertical load bearing members will be supported by directly bearing upon one another. In theory, every bolt will not carry any load. Therefore they will serve as additional safety factors to the design, unless yielding were to occur.

Reliability Concerns for Blades

The main reliability concerns for the blades are cracks or fracture that occur during transportation and operation. Because of the size of the blades a small force at one end of the blade will generate a large moment at the other end. This moment can cause large loads on the E-glass and internal structure of the blades. During transportation it is possible that the jostling of the trucks or carelessness while driving would place a large load on the blade which could cause fracture of the fiberglass or fracture of the bracing spar. In order to prevent this, drivers must be well qualified and experienced with transporting large pieces of equipment like wind turbine blades to ensure they arrive safely to the construction site. The other concern for the blades is failure during the operation of the wind turbine. As explained in Section 4.1.1 the blade is expected to deflect less than half of the average deflection of typical turbine blades.

4.6.2 Reliability of Small-Scale Wind Turbine

The reliability concerns of the small-scale representation of the final design can be split into two parts, the tower and the blades.

Reliability Concerns for Tower

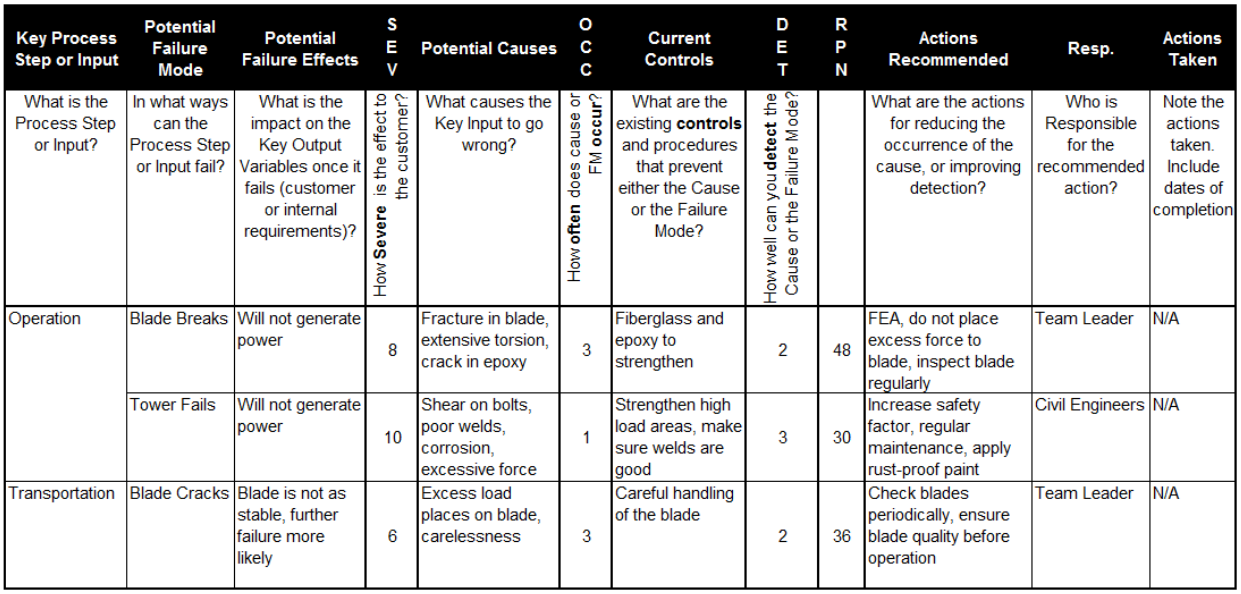
There are two main causes for a structure to experience failure which are defects in the material or insufficient design. In terms of the design, the tower prototype should be able to withstand multiple uses as long as the members are placed properly and the connections are secure. Since the tower is made of structural steel and the blades are relatively light, the tower is not expected to fail due to excessive loading. Considering material failure there is a slight possibility that the steel may include weak points as a result of poor manufacturing. However, there is no preventative solutions to material defects unless they are visually apparent. Nonetheless, there are several reliability concerns for the tower over time. There is the possibility of corrosion within the steel. This can be prevented by applying protective coatings on the steel surfaces at least once a year. Another concern may be local failure at the connections. If there are unexpected high stresses in areas where connections are placed, then the connection may break weakening the entire tower as a result. In order to prevent local failures at the connections, the bolts will be given plenty of tear-out distance and high-grade bolts will be used. Also, the welds will be examined as much as possible to ensure that they are strong enough to carry the anticipated loads. Apart from the steel, the fabric wrapped around the tower has the possibility of tearing or unraveling if it comes in contact with a sharp object or experiences excessive stretching. However, unless it comes into contact with the moving blades, a tear in the fabric is only a visual defect and has no effect on the functionality of the prototype.

Reliability Concerns for Blades

One of the main reliability concerns for the blades is that they will fail during operation of the system. There are several points of possible failure for the blades. As discussed in Section 2.2.2 the multiple sections of the blades had to be connected using epoxy putty. This connection was strengthened by wrapping the blades in two layers of fiberglass. The full-scale blades lack these failure points. It is possible that high stress applications on the small-scale blades will cause the epoxy putty to deform, resulting in the blades failing at the connection between the sections. This will be accounted for by handling the blades with caution and making sure there is never a large point load placed on the blades. The other main failure point of the blades is the connection between the blades and the rotor of the nacelle. The blades will be connected to the rotor with a piece of all-thread that is tapped into both the rotor and root of the blade. It is highly unlikely that this connection will fail, although if the blade is pulled away from the rotor or excess torsion is applied to the blade the thread inside the root of the blades could strip causing the blades to fall off the all-thread. The blades are printed out of ABS plastic which means the threads will not be as strong as those in the Al6061 rotor and all-thread. This failure mode will be prevented by not applying excess loads to the blades at the connection point and ensuring that the all-thread is fully screwed into the connection before operation of the small-scale representation.

The failure mode effect analysis can be seen below in Table 5. This table displays multiple ways that the design could possibly fail throughout its lifetime, as well as recommended actions that should be taken to prevent these failures from occurring.

Table 5. Failure Mode Effect Analysis



Key Process Step or Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN	Actions Recommended	Resp.	Actions Taken
What is the Process Step or Input?	In what ways can the Process Step or Input fail?	What is the impact on the Key Output Variables once it fails (customer or internal requirements)?	How **Severe** is the effect to the customer?	What causes the Key Input to go wrong?	How **often** does cause or FM **occur?**	What are the existing **controls** and procedures that prevent either the Cause or the Failure Mode?	How well can you **detect** the Cause or the Failure Mode?		What are the actions for reducing the occurrence of the cause, or improving detection?	Who is Responsible for the recommended action?	Note the actions taken. Include dates of completion
Operation	Blade Breaks	Will not generate power	8	Fracture in blade, extensive torsion, crack in epoxy	3	Fiberglass and epoxy to strengthen	2	48	FEA, do not place excess force to blade, inspect blade regularly	Team Leader	N/A
	Tower Fails	Will not generate power	10	Shear on bolts, poor welds, corrosion, excessive force	1	Strengthen high load areas, make sure welds are good	3	30	Increase safety factor, regular maintenance, apply rust-proof paint	Civil Engineers	N/A
Transportation	Blade Cracks	Blade is not as stable, further failure more likely	6	Excess load places on blade, carelessness	3	Careful handling of the blade	2	36	Check blades periodically, ensure blade quality before operation	Team Leader	N/A

5. Proof of Design

The most important information when designing a wind turbine is determining how much power it will generate. Due to the scale of the design, a physical experiment was not plausible. Instead the power generation was estimated using equations for 61.5m blades and 157.5m tower at the target location. The next sections will cover how much power the wind turbine will generate at different wind speeds and the yearly power generation at the target location.

5.1 Power

The power generated was calculated using the swept area method shown by Equation 18, where ρ is air density, v is the wind speed, A_{swept} is the area swept by the blades, and ε is the efficiency

$$P = 0.5 * \rho * v^3 * A_{swept} * \varepsilon. \tag{18}$$

The two assumptions made in this equation were the density of the air and efficiency. The density of the air depends on multiple factors such altitude and humidity. For simplicity it was assumed to be $1.225\frac{kg}{m^3}$. The maximum power that can be extracted from the wind is 59.3% which is known at Betz' Limit. Due to drag and other forces this is not feasible in real application. Currently an average efficiency of 40% is common for large wind which will be used in the calculations. Additionally, a cut-in wind speed of 3 m/s and a cut-out wind speed of 25 m/s were used for the wind turbine. A power generation curve was plotted in Figure 24 using this information.

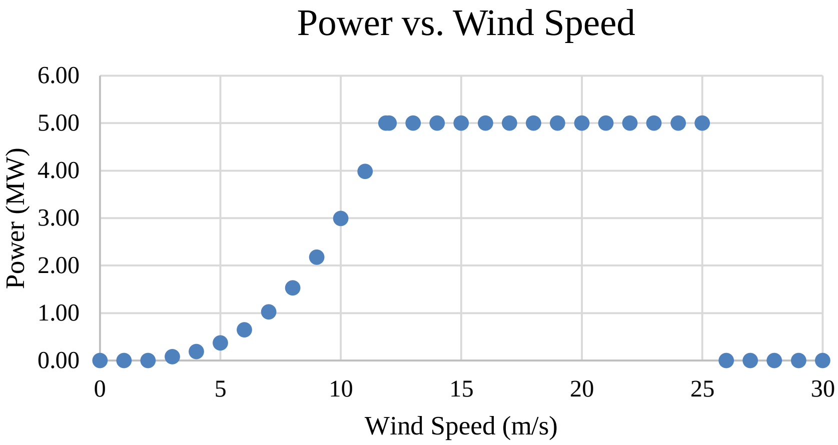


Figure 24. Power generation curve

The figure shows how much power is generated with wind speeds from 0 to $30\frac{m}{s}$. Taking a closer look, no power is generated with wind speeds less than $3\frac{m}{s}$. After this wind speed, the power exponentially increases until a wind speed $11.9\frac{m}{s}$. This wind speed is where the turbine reaches its rated power of $5MW$. The wind turbine will produce 5 MW of power up to speeds of $25\frac{m}{s}$. If wind speeds become greater than $25\frac{m}{s}$, the turbine will cut off to prevent damage resulting in no power generation.

5.2 Wind

The next step taken to determine the predicted power generation is to determine the wind speeds at the target location of Belle Glade, FL. This site was selected because it has the highest average wind speeds in Florida. Due to unavailability of wind data at this location, wind data was taken at the nearby West Palm Beach Airport to represent our target site. [9] The average hourly wind speeds for 2014 were obtained at a height of 10m. Due to changing wind speeds throughout the day, the team felt using hourly wind data would give the best representation. The wind data then had to be interpolated to the hub height of the designed wind turbine which was 157.5m. Equation 19 shows the equation estimating wind speeds at higher altitudes where v the wind speed is, h is the height, and α is the wind constant

$$v(h) = v_{10} * (\frac{h}{h_{10}})^{\frac{1}{\alpha}} . \tag{19}$$

An assumption made for this equation was the wind constant α. This constant varies for different types of terrain. The location site selected most resembles "rough" land. This entails cultivated area with high crops. Since the target site would most likely be surrounded by sugar cane fields, this terrain gave the most accurate description. The wind constant α of the target site was projected to be 11.4. Figure 25 shows a histogram of the yearly distribution of wind speeds at the interpolated height.

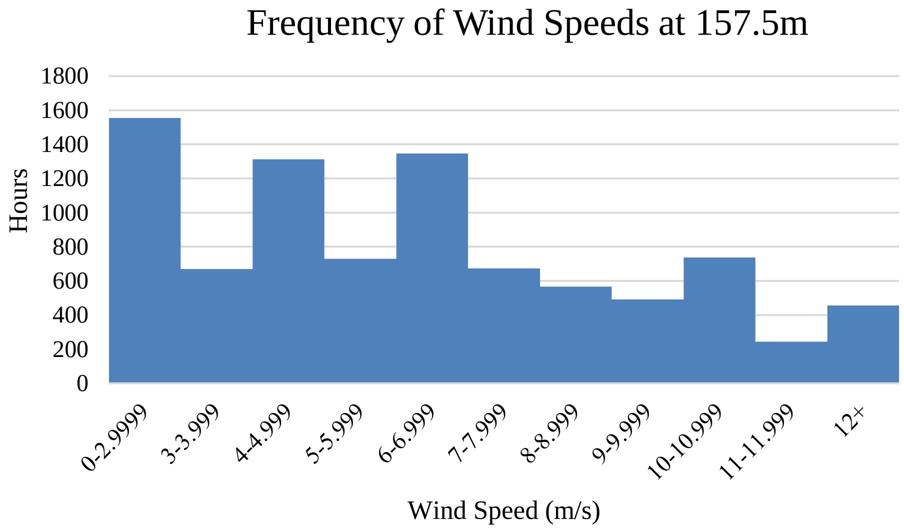


Figure 25. Frequency of winds speeds in Belle Glade, FL at 157.5 m

The plot shows in 2014 the average hourly wind speed was greater than 3 $\frac{m}{s}$ 82.3% of the time. This is significant because winds speeds greater than 3 $\frac{m}{s}$ will be generating power. Additional statistics show the mean and median of this set of data are 6.02 and 6.03$\frac{m}{s}$, respectively. According to U.S Department of Energy, sites with average wind speeds of 6.5 $\frac{m}{s}$ or greater are typically considered for wind development[10]. However, as technology grows, a new standard for low wind regions is increasing opportunity.

5.3 Power Generation

Using the wind speeds at the target site, the power generation was calculated. Figure 26 displays a histogram with the amount power generated using the yearly wind data.

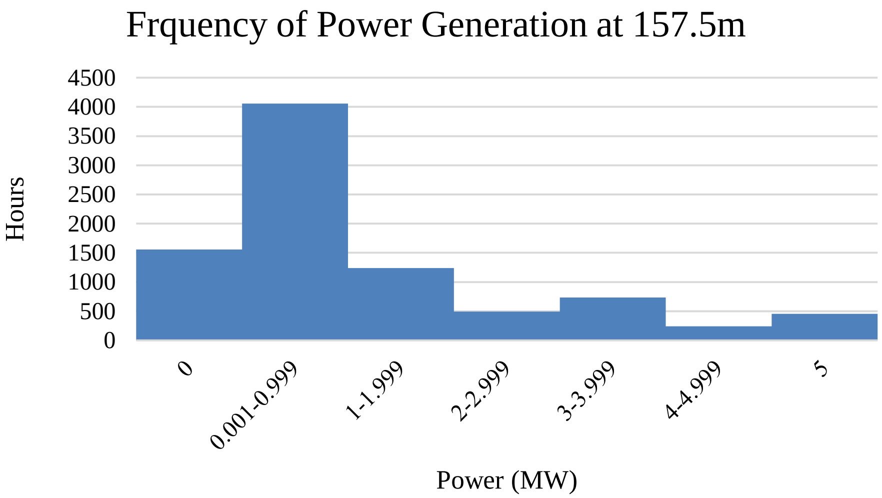


Figure 26. Power generation of the turbine in target site over a 1 year period

The plot shows 63.9% of the time, the wind turbine would have been generating less than 1 MW of power. Additionally, the plot shows the wind turbine would have been running at its rated power 5.2% of the time. After these finding, it may be worth looking into reducing the rated power of the wind turbine to a 2, 3, or 4MW wind turbine. Furthermore, the energy was calculated for the year to be 10,786$MW * h$.

6. Economics

The economics of the full scale wind turbine was made through a series of equations and estimations. This section consists of the building and running costs of the wind turbine as well as the lifetime power generation. From this the levelized cost of energy was calculated which can be compared to the current standard for wind turbines in the United States.

6.1 Blade Cost

The cost of the blades were estimated based on *GLWN's* study *U.S. Wind Energy Manufacturing and Supply Chain: A Competitive Analysis*[11]. The total cost of a 61.5m blades is approximately $363,710. This was based off materials, labor, burden, SGA (sales, general, administrative), engineering, logistics, and profit which is in Table 6.

Table 6. Cost of blades

Item	Cost ($)
Materials	147,825
Labor	31,300
Burden	64,165
S.G.A	36,494
Engineering	14,597
Logistics	45,000
Profit	24,329
Total	363,710

The blades used for the design are similar to the "standard" blades used in this study. The main difference between blades is the spar. The estimation in Table 6 was based off a fiberglass sandwich structure spar with two beams. The spar used in the design is composed of three aluminum beams. It was estimated the labor cost would increase while the material cost would decrease using this design. Therefore, the cost difference would be negligible and the total standard cost would be used for the design in the cost analysis.

6.2 Tower Cost

The cost of the tower is a function of the steel material, architectural fabric, and the assembly costs related to each. The steel material, at 272Mg, was estimated to cost about $707/Mg for a total of $234,000. The construction method of the tower varies from that of a typical tubular wind turbine. Therefore, alternative methods were used along with NREL data in estimating the anticipated construction costs.

The upper sections of the lattice tower are designed to be fabricated before arrival on site to allow for a rapid assembly method similar to that of a typical steel tubular tower. Equations from *NREL Turbine Design Cost and Scaling Model* were employed to scale the cost of the assembly and installation of the upper portion of the tower[12]. The cost is scaled based on the total height of the upper sections and the rotor diameter including the blades. The final estimate without material costs is $110,000.

The lower portion of the tower is the widened base which must be assembled on site. This assembly method can be compared to that of a steel truss bridge. Since the geometry and assembly method would be very similar, the only scaling necessary would account for the varying dimensions between the bridge and the tower. Cost estimates on the construction of a pedestrian steel truss bridge are obtained from *RSMeans Heavy Construction Cost Data 2012*[13]. The final estimate for the cost of assembly is $211,000.

The costs of a PVC-coated polyester fabric were found from the *Architectural Record* and includes the cost of installation[14]. This fabric is ideal to last the lifetime of the wind turbine, but at $40 per square foot it is much too costly to be considered. It would cost over $1 million just for the fabric. Therefore, after considering other fabric alternatives, the most efficient option would be to use LDPE (Low Density Polyethylene) coated HDPE (High Density Polyethylene) woven membrane, which is high-strength, light-weight, and fire retardant but needs to be replaced after 10-15 years. The cost of this fabric is closer to $12 per square foot which comes to a total of $442,800.

Similar to the lower portion of the tower, the foundation costs were estimated using the *RSMeans Heavy Construction Cost Data 2012*[13]. The reinforced concrete foundation is considered to be a circular spread footing with a 23-meter diameter. The foundation cost is estimated to be about $240,000 which includes excavation, material, and equipment. The total cost of the foundation and the tower, including material, equipment, and labor, comes to $1,178,000.

6.3 Additional Components Costs

There are many components involved in building a wind turbine. The cost of these additional components are in Table 7. These values come from *NREL Turbine Design Cost and Scaling Model*[15]. Since these estimations are about a decade old, a market adjustment cost of $362 $per\ kW$ was added to the costs[15].

Table 7. Additional component cost of wind turbine

Item	**Cost ($)**
Hub Cost	95,706
Total Pitch System Cost	183,552
Nose Cone Cost	10,084
Low Speed Shaft Cost	115,753
Total Bearing Cost	95,050
Brake/Coupling Cost	9,947
Generator Cost	1,096,650
Variable Speed Electronics Cost	395,000
Yaw Drive and Bearing Cost	113,954
Main Frame Cost	66,010
Electrical Connections Cost	200,000
Hydraulic and Cooling Systems Cost	60,000
Nacelle Cover	61,535
Control, Safety System, Condition Monitoring Cost	35,001
Road, Civil Work Cost	256,450
Electrical Interface/Connections Cost	432,250
Engineering Permits Cost	125,050
Additional	1,750,000
Market Adjustment	1,810,000
Total	**6,911,990**

6.4 Soft Costs

The soft costs includes things such as contingency, insurance, and construction finance. For land based turbines this costs is approximately $163 $per\ kW$[15]. The soft costs were calculated to be $815,000.

6.5 Leasing Land

When building wind farms, it is most common to lease sections of agricultural land. Since, wind turbines only require approximately 3-5 acres per site much of the land remains usable for farming. After looking at multiple recent wind farm contracts, the cost ranged from \$1500 to \$5000 per MW per year[15]. The site locations included states from all around the country except for the south east. Taking into account the wind speeds in Belle Glade would be considered a low speed region nationally, it was estimated the leasing cost would be around \$2500 per MW per year.

6.6 Operational and Maintenance Costs

Operations and maintenance involves keeping the wind turbine running effectively after construction. Some of the tasks include turbine and blade failure, monitoring and control systems, safety, repowering, wind monitoring, and site security. Based off an NREL study, it is estimated the fixed and variable operational and maintenance costs are approximately \$34 per MW per year[15].

6.7 Cost Summary

The best way to see the profitability of the wind turbine is to calculate the levelized cost of energy (LCOE) which is the present value of the total cost divided by the energy produced of the project lifetime. For this value it was estimated the project would have a lifetime of 20 years. Table 8 shows the estimated cost over 20 years based on the capital, leasing, operation, and maintenance costs.

Table 8. Total cost over 20 years

Item	Cost ($)
Blades	1,091,130
Tower/Foundation	1,178,000
Additional Components	5,101,990
Soft Costs	815,000
Lease	250,000
O & M	3,400,000
Total	**13,646,119**

The estimation of the power generation was done by multiplying one year of power generation by 20 years. Then to account for scheduled maintenances, that number was multiplied by 98%. The total power generated with this design and location site would be approximately 211,401 $MW * h$. Combining the total cost with the total power generation yields a levelized cost of energy of \$65 per $MW * h$. The target number for levelized cost of energy in the wind industry ranges between \$58 per $MW * h$ to \$108 per $MW * h$. According to this number, the turbine would be very profitable. However in real application the efficiency would decrease with wear which would lead to a small increase in the levelized cost of energy.

7. Turbine Model

The wind turbine designed for this project is 157.5 meters tall with blades approximately 61.5 meters long. As it would be highly unrealistic to construct a full-scale prototype for this design, a small-scale representation of the design was constructed.

7.1 Tower Model

The tower model is approximately 2.6 meters tall, consisting of three sections. Although, the full-scale tower contains twenty sections, it was decided that three typical sections would suffice to represent the general geometry of the tower. The upper two sections are 0.79 meter tall while the bottom section is 0.91 meters tall. At either end of each section, a custom connection is used. This connection consists of a heptagonal ring with plugs on the top and/or bottom where the columns slide in to be connected. A total of four rings were fabricated to be used in this design. The entire heptagonal ring connection is made up of 1-inch square hollow structural steel (HSS) tubes. The columns are made of ¾-inch square HSS tubes, while the bracing is made of ½-inch steel angle. The columns and bracing are connected to the plugs with steel bolts.

In order to fabricate the model, the steel was prepared, measured and cut to the correct dimensions. To create the connections, each of the sides of the heptagonal ring were cut so that when placed next to each other, they formed a heptagon. Each location between two consecutive members of the ring was welded to create one continuous shape.

Each of the heptagonal rings varies in diameter due to the widening of the tower from top to bottom. The outside diameter of the uppermost ring measures 0.2 meters while the outside diameter of the ring located at the base measures over 0.61 meters. After the heptagonal rings were prepared, the plugs to be attached to the rings were cut and grinded down to the correct angle so that when placed flat against the surface, the plug would line up with the incoming column. Each of these plugs were then welded to the corresponding vertex of the heptagonal ring to create one whole connection. The plugs were cut to be 0.06 meters long to provide sufficient area for bolted connections to both the columns and the bracing at those locations. The complete heptagonal ring is shown in Figure 27 connecting the lower and upper columns.

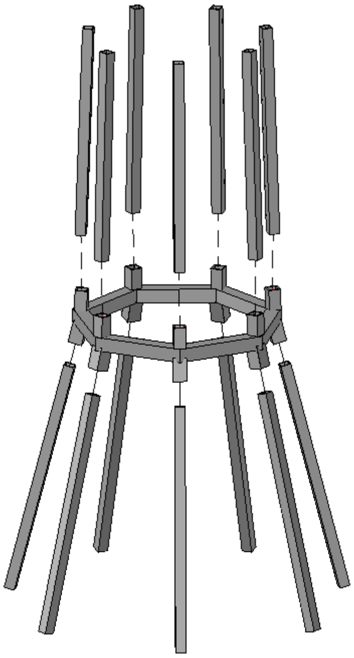


Figure 27. Exploded view of tower connection

In order to fabricate the columns of the tower, they were cut to the desired dimensions. The columns located in the upper two sections are 0.79 meters in length, while the columns in the bottom section are 0.9 meters in length.

The bracing is connected to the plugs, where the columns are also connected. The tower will be braced at every section. After the entire tower is assembled, fabric will be wrapped around the entire tower. In order to attach the fabric to the tower, Velcro will be used. The majority of the fabric will be opaque white, while a portion will be transparent to allow the inside structure of the tower to be seen.

The actual time it took to prepare, measure, and cut the steel for the tower was close to the expected time. Overall, this process took a total of 15 hours spanning over five days. However, there was a delay in obtaining welding services to complete the heptagonal ring connections. Once the welding is done, the assembly of the tower should take no more than twenty minutes. The fabric wrap has yet to be made due to a delay in ordering the material. However, once the material arrives, it should only take a day to sew the fabric together and attach the Velcro so that the fabric fits taut around the tower.

Overall, the tower model is a simplified version of the full-scale tower design. Given the time and monetary constraints, it was unrealistic to create an exact replica of the full-scale design. Although it would have been possible to add the internal bracing component to the model, it was added to the design after the material for the model had already been ordered. Therefore, there was an insufficient amount of steel to include the internal bracing in the model. Otherwise, the tower model effectively represents the full-scale design. If any of the components had been removed, the tower would not be stable or comparable to the full-scale design.

7.2 Blades and Nacelle Model

The three foot blades were 3D printed in four sections, each section nine inches long. The scaling of the turbine blades from 61.5 meters to 3 feet meant that a lot of the complexity of the full-scale design could not be incorporated into the model blades. A lot of the design in the Fall semester was focused on developing an innovative interior spar that would strengthen the blades from bending under load. But scaling the design down meant that they could not be included in the model because the 3D printer did not have the resolution to print the interior of the blade. So the team decided to fill the interior of the blades when printing to ensure they were strong enough. With the lower printing resolution, the 3D printer still had difficulties printing the trailing edge of the airfoil which can be seen below in Figure 28. This was corrected by sanding the blades down before fiberglass was applied.

Figure 28. Chipping of 3D printed blades

Epoxy putty was used to connect each section of the blade. The blade was then wrapped in e-glass, a type of fiberglass, which was applied by means of an epoxy and hardener mixture. Standard wind turbines have over a hundred layers of fabric; however, this amount of fabric was unnecessary for the small-scale model. The model blades were wrapped with fiberglass until appropriate blade strength and stiffness was achieved. These characteristics were achieved once the blades had been wrapped in two layers of fiberglass. The excess fiberglass along the edges of the blades was trimmed off and the blades were sanded to provide a smooth finish, as seen below in Figure 29.

Figure 29. Fully fiber-glassed blades before paint

Once the blades were smooth, a coat of primer followed by several layers of white paint was applied. This made the blades aesthetically pleasing as well as a closer representation of the full-scale wind turbine.

In order to ensure the epoxy was fully cured the team waited a minimum of 24 hours between each application. Fiberglass was applied on three blades at a time so it took a total of four days to apply two layers on each side of the three blades. The blades were finished in the same time that the team felt it would take.

Creating a nacelle for the full-scale design was not included in the project description. But for the model a nacelle is required in order attach the blades to the tower and generate electricity so the team developed a simple nacelle early in the Spring semester. The nacelle design can be seen below in Figure 30.

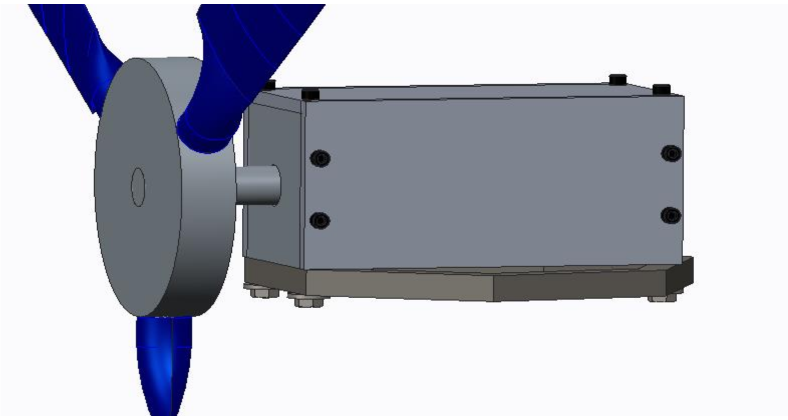


Figure 30. Creo model of nacelle

The nacelle is made out of Aluminum 6061 and is used to attach the blades to the tower. The blades are interconnected to the motor by a rotor and shaft that run through a series of bearings which allow the system to be rotated easily. The shaft is connected to a motor with a roll pin to secure no losses between the motor and shaft. The motor, which is back driven by the spinning shaft, will generate electricity. The nacelle is assembled with 10-24 bolts and ¼-20 bolts to secure it to the top of the tower. To show how the parts of the nacelle and blades connect an exploded view of the design along with a major bill of materials can be seen in Appendix C. The nacelle was machined in the machine shop in the FAMU-FSU College of Engineering and the team assembled the pieces together. The machine shop was behind schedule which caused a long waiting period for the parts to be machined, but the actual assembly of the nacelle was finished in one day and can be seen in Figure 31.

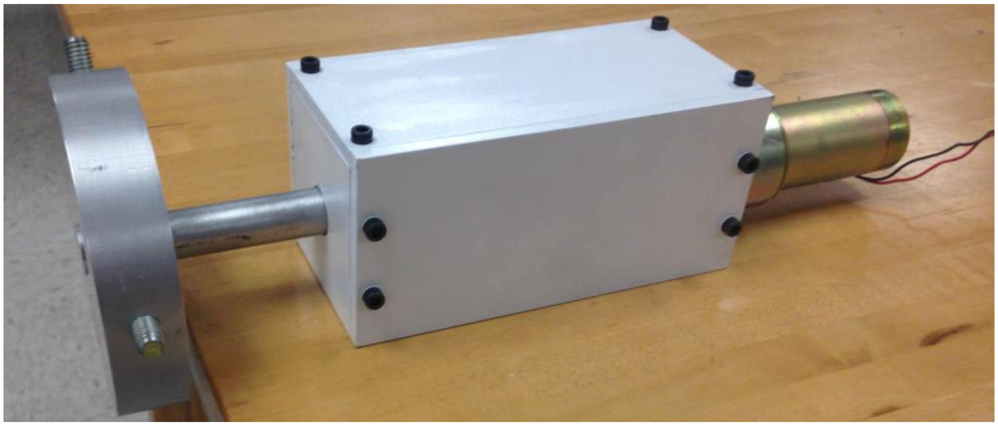


Figure 31. Assembled model nacelle

The design of the nacelle was very simplistic because it was not a part of the original project requirements. The design could have been more complex by including a system to sense wind direction and rotate the blades to be perpendicular to the wind direction. This would have added extensive work that the sponsor did not want the team to focus on due to time and money constraints.

Once the blades, nacelle, and tower were individually complete the team assembled each together for the final model. The blades were attached to the nacelle using 3/8-16 all thread. The nacelle and blades were then attached to the tower by bolting the nacelle to the tower using pre-tapped ¼-20 holes. The final touch to the wind turbine model was attaching fabric. The final model assembly can be seen below in Figure 32.

Figure 32. Completed model turbine assembly

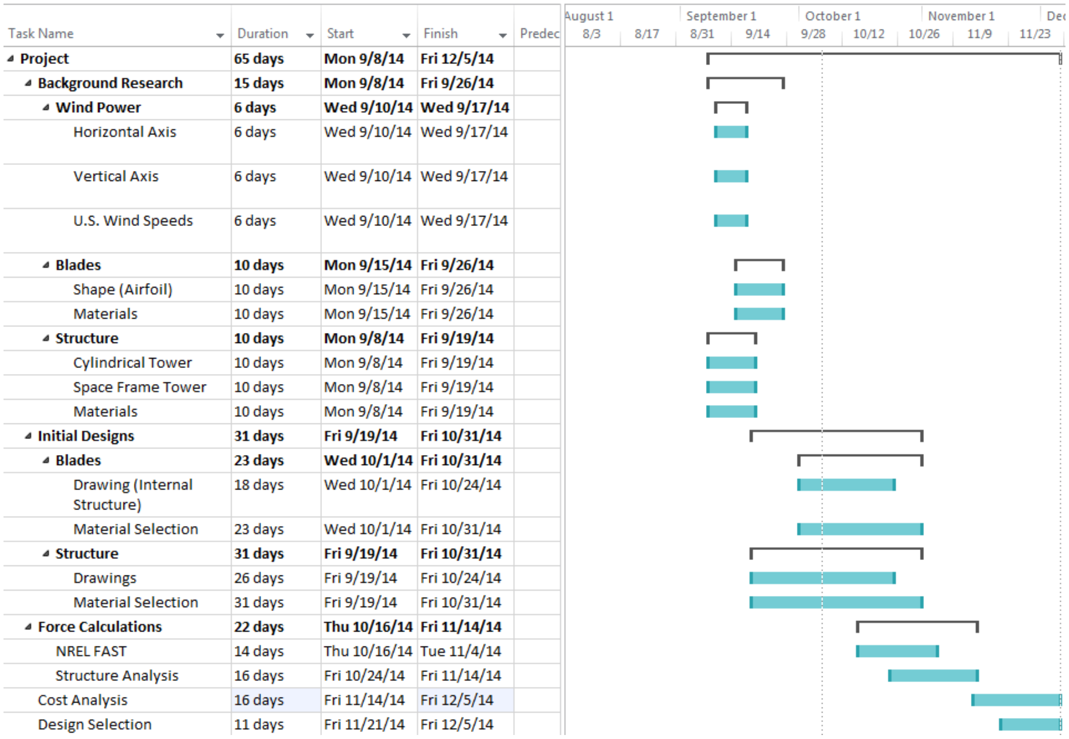
8. Considerations for Environment, Safety, and Ethics

There are few environmental and safety concerns involved with this tower design. The main environmental concern is the tower disrupting the flight paths of birds in the area. Therefore, the wind turbines will be placed outside of common flight paths of birds. The tower and blades have been designed so that the can be transported to the work site without extra modification to current methods. The blades have been designed to withstand two times the average wind load in Florida. This increases the factor of safety, decreasing the necessity of repairs. Maintenance on the wind turbine can be performed through a central ladder that uses a harness line and multiple attachment points for extra safety. Materials will be obtained from trusted sources to ensure all ethical standards are kept. The project plans to have as minimal an impact on the environment as possible since the wind turbine is focused on generating clean electricity.

9. Project Management

9.1 Schedule

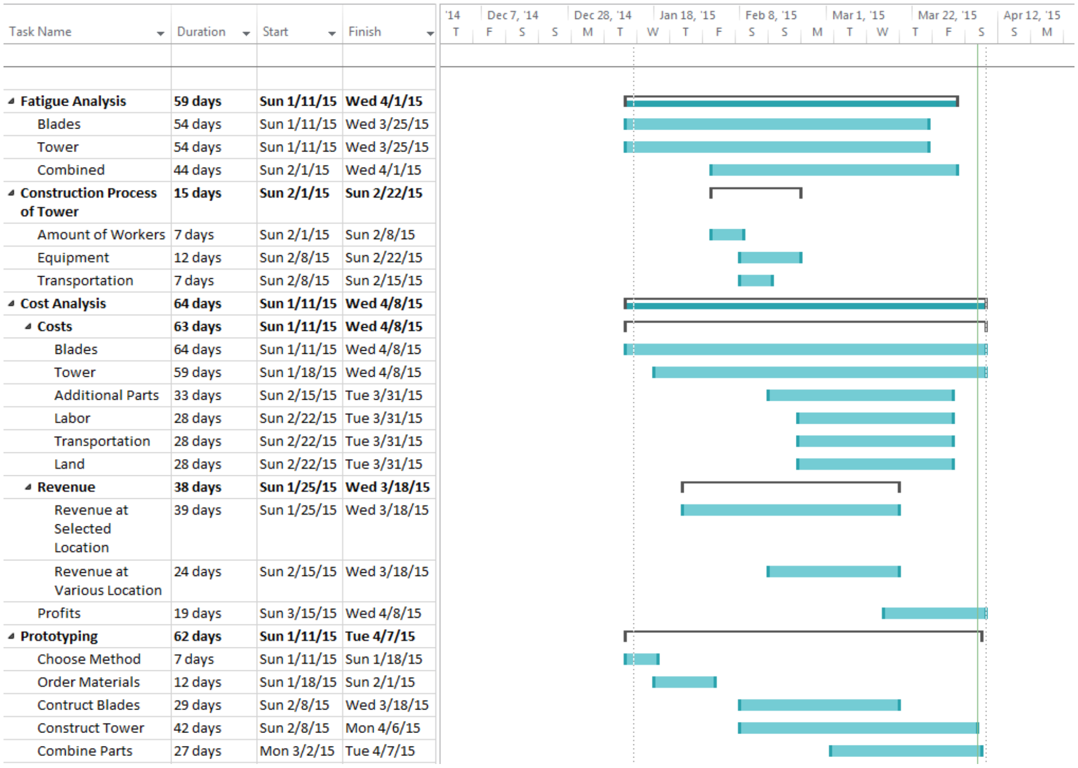
Throughout the year a gantt chart was used to manage the teams time to accomplish the project. The gantt chart of the Fall semester is shown is below in Figure 33. During the Fall semester the team remained on schedule for the majority of tasks. The team unknowingly received FAST (NREL's primary CAE tool) with invalid input parameters, which lead to delays in the time line along with cost anaylsis.



Task Name	Duration	Start	Finish	Predec
Project	**65 days**	**Mon 9/8/14**	**Fri 12/5/14**	
Background Research	**15 days**	**Mon 9/8/14**	**Fri 9/26/14**	
Wind Power	**6 days**	**Wed 9/10/14**	**Wed 9/17/14**	
Horizontal Axis	6 days	Wed 9/10/14	Wed 9/17/14	
Vertical Axis	6 days	Wed 9/10/14	Wed 9/17/14	
U.S. Wind Speeds	6 days	Wed 9/10/14	Wed 9/17/14	
Blades	**10 days**	**Mon 9/15/14**	**Fri 9/26/14**	
Shape (Airfoil)	10 days	Mon 9/15/14	Fri 9/26/14	
Materials	10 days	Mon 9/15/14	Fri 9/26/14	
Structure	**10 days**	**Mon 9/8/14**	**Fri 9/19/14**	
Cylindrical Tower	10 days	Mon 9/8/14	Fri 9/19/14	
Space Frame Tower	10 days	Mon 9/8/14	Fri 9/19/14	
Materials	10 days	Mon 9/8/14	Fri 9/19/14	
Initial Designs	**31 days**	**Fri 9/19/14**	**Fri 10/31/14**	
Blades	**23 days**	**Wed 10/1/14**	**Fri 10/31/14**	
Drawing (Internal Structure)	18 days	Wed 10/1/14	Fri 10/24/14	
Material Selection	23 days	Wed 10/1/14	Fri 10/31/14	
Structure	**31 days**	**Fri 9/19/14**	**Fri 10/31/14**	
Drawings	26 days	Fri 9/19/14	Fri 10/24/14	
Material Selection	31 days	Fri 9/19/14	Fri 10/31/14	
Force Calculations	**22 days**	**Thu 10/16/14**	**Fri 11/14/14**	
NREL FAST	14 days	Thu 10/16/14	Tue 11/4/14	
Structure Analysis	16 days	Fri 10/24/14	Fri 11/14/14	
Cost Analysis	16 days	Fri 11/14/14	Fri 12/5/14	
Design Selection	11 days	Fri 11/21/14	Fri 12/5/14	

Figure 33. Fall 2015 Gantt chart

The Spring semester gantt chart is shown in Figure 34. Initially the team planned on completing the entire project roughly a month before the due date. However, as problems arose many of the task completion dates were moved back. Most of the project scope will be completed on time. One task that was unable to be completed was using FAST. Alternatively, the force and power generation that were going to be caluated with FAST were calculated by hand. Other than that the fatigue anaylsis, cost analysis, and prtotyping to several weeks longer than anticipated.



Task Name	Duration	Start	Finish
Fatigue Analysis	**59 days**	**Sun 1/11/15**	**Wed 4/1/15**
Blades	54 days	Sun 1/11/15	Wed 3/25/15
Tower	54 days	Sun 1/11/15	Wed 3/25/15
Combined	44 days	Sun 2/1/15	Wed 4/1/15
Construction Process of Tower	**15 days**	**Sun 2/1/15**	**Sun 2/22/15**
Amount of Workers	7 days	Sun 2/1/15	Sun 2/8/15
Equipment	12 days	Sun 2/8/15	Sun 2/22/15
Transportation	7 days	Sun 2/8/15	Sun 2/15/15
Cost Analysis	**64 days**	**Sun 1/11/15**	**Wed 4/8/15**
Costs	**63 days**	**Sun 1/11/15**	**Wed 4/8/15**
Blades	64 days	Sun 1/11/15	Wed 4/8/15
Tower	59 days	Sun 1/18/15	Wed 4/8/15
Additional Parts	33 days	Sun 2/15/15	Tue 3/31/15
Labor	28 days	Sun 2/22/15	Tue 3/31/15
Transportation	28 days	Sun 2/22/15	Tue 3/31/15
Land	28 days	Sun 2/22/15	Tue 3/31/15
Revenue	**38 days**	**Sun 1/25/15**	**Wed 3/18/15**
Revenue at Selected Location	39 days	Sun 1/25/15	Wed 3/18/15
Revenue at Various Location	24 days	Sun 2/15/15	Wed 3/18/15
Profits	19 days	Sun 3/15/15	Wed 4/8/15
Prototyping	**62 days**	**Sun 1/11/15**	**Tue 4/7/15**
Choose Method	7 days	Sun 1/11/15	Sun 1/18/15
Order Materials	12 days	Sun 1/18/15	Sun 2/1/15
Contruct Blades	29 days	Sun 2/8/15	Wed 3/18/15
Construct Tower	42 days	Sun 2/8/15	Mon 4/6/15
Combine Parts	27 days	Mon 3/2/15	Tue 4/7/15

Figure 34. Spring 2015 Gantt chart

9.2 Resources

The team had many resources throughout the course of their project. During the construction of the small scale representation of the wind turbine the civil engineering students utilized the FAMU-FSU College of Engineering machine shop for the machining of the steel parts necessary for the tower. After all of the parts had been machined (i.e. cut to correct size and welded in proper locations), the FAMU-FSU College of Engineering structures lab was utilized to construct the tower. The mechanical engineering students also utilized the FAMU-FSU College of Engineering machine shop for the fabrication and construction of the nacelle. Due to cost considerations, the mechanical engineering students purchased the 3D printed blades from the UPS Store out of Panama City, Florida. The 3D printing capabilities available at the FAMU-FSU College of Engineering were not employed for this task because of budget constraints.

9.3 Procurement

The team was given $2,000 to build a small-scale representation of the wind turbine designed. After purchasing all of the materials the team spent $1,420.75 leaving $579.25 in the budget. Of the money spent, approximately $850 were spent by the mechanical engineering students on materials used for the wind turbine blade construction while approximately $595 were spent by the civil engineering students on materials used for the wind turbine tower construction.

Below, Figure 35 displays a pie chart of the project expenditures. It can be seen that 71% of the budget has been spent, while 29% remains. The excess money shows that the allotted budget was more than enough for the production of the small scale representation created for this project. An in depth description of all purchases can be seen in Appendix D.

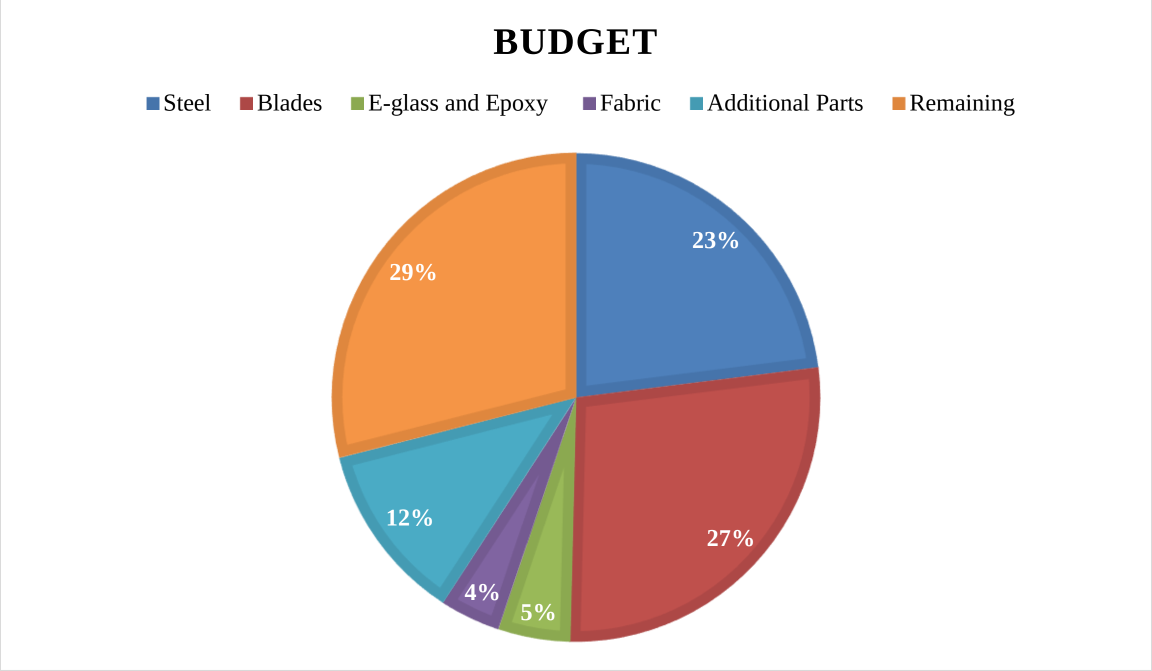


Figure 35. Model budget

9.4 Communications

The main form of communication was through phone calls and text-messaging among the group. Email was a secondary form of communication for issues that were not time sensitive.

For the passing of information, i.e. files and presentations, email and Dropbox were the main form of file transfer and proliferation.

Members checked their emails at least twice a day to check for important information and updates from the group. Members were told of meeting times and location through email with reminders sent through text messaging. If a meeting was canceled, an email was sent to the group at least 24 hours in advance. All group members responded to team emails within 24 hours of receiving them.

Any team member that could not attend a meeting provided advance notice of 24 hours informing the group of his/her absence. Reason for absence was appreciated but was not required if personal.

Email was the main form of communication between the team members and the sponsor as well as with the team members and the advisor. Meetings were held every other Monday at 5:00PM for all team members to attend as well as the project sponsor and project advisor. This ensured that all members were on schedule while also keeping the sponsor and advisor in the loop.

10. Conclusion

This project was conducted due to the location limitations on wind turbines, specifically in Florida. Since Florida has relatively low wind speeds, building wind turbines there is not cost effective. One concept to change this, is by building a taller tower. This is based off the fact that wind speeds increase at higher altitudes. The initial project scope was to design a tower 50-100% taller than the standard 80m blade. Additionally, the team designed wind turbine blades to increase the efficiency of the wind turbine.

When designing the blades the biggest factors were the length, weight, and cost. The length was selected to be 61.5m. The longer the blades, the more power could be generated. This length was the longest the blades could be and still be transported. The shape of the blade is a NACA-64 airfoil. The shell of the blade was composed of epoxy, SAN foam, E-glass, and carbon fiber. The internals of the blade is composed of a three I-beam spar. The spar will be composed of Al6061.

A 157.5m tower was designed by the team. The tower is a 7 sided lattice structure composed of 30 sections made out of HSS that are assembled offsite and then brought to the site. The sections are connected with male-female connections so little on site welding is required. The lattice structure will allow the tower to be lighter but just as strong as a typical concrete turbine tower.

The target location for this project was Belle Glade, FL located just south of Lake Okeechobee. This location was selected for having the highest average wind speeds in Florida. Using this location a power estimation was made based off the average hourly wind data in 2014. The yearly power generated was calculated to be 10,786 MW*h. That is enough to power approximately 970 U.S. homes a year.

The costs of the wind turbine was based off the building, soft, lease, operational, and maintenance costs over a 20 year period and was computed to be $13,646,119. By including the power produced over 20 years the levelized cost of energy was determined to be $65 per MW*h. This number was slightly lower than what is considered to standard in the wind industry market. Through this project it was determined it was very feasible to produce a cost effective wind turbine in Florida.

A model was made to demonstrate the teams design. The blades demonstrate a scaled down version of the shape of the actual design. It is 3ft long and was made by being 3D printed then wrapped with E-glass and epoxy. The tower model is 8.5ft tall and composed of 3 sections versus 30 sections used in the actual design. The tower model displays the overall shape and the connections in the design.

The team realized there were some things that could have been improved in the project. Since the team focused on the blades and tower, other components were overlooked until the end of the semester. The team was advised to start by using NREL’s 5MW design for the nacelle. After calculating winds speeds at the target location, it was determined a smaller capacity nacelle would be a better option. Another way to improve the project would to have used NREL’s program fast. Many of the calculations would have been more accurate.

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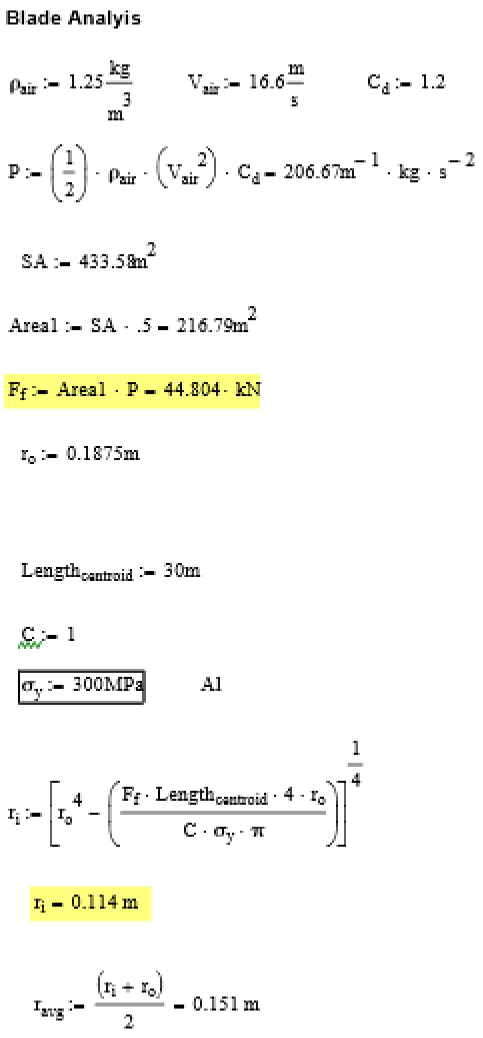
Appendix A: MathCad Analysis



Blade Analyis

$\rho_{air} := 1.25\frac{kg}{m^3}$ $\quad V_{air} := 16.6\frac{m}{s}$ $\quad C_d := 1.2$

$$P := \left(\frac{1}{2}\right)\cdot\rho_{air}\cdot\left(V_{air}^{2}\right)\cdot C_d = 206.67m^{-1}\cdot kg\cdot s^{-2}$$

$SA := 433.58m^2$

$Area1 := SA\cdot .5 = 216.79m^2$

$F_f := Area1\cdot P = 44.804\cdot kN$

$r_o := 0.1875m$

$Length_{centroid} := 30m$

$C := 1$

$\boxed{\sigma_y := 300MPa}$ A1

$$r_i := \left[r_o^{\,4} - \left(\frac{F_f\cdot Length_{centroid}\cdot 4\cdot r_o}{C\cdot\sigma_y\cdot\pi}\right)\right]^{\frac{1}{4}}$$

$r_i = 0.114\ m$

$$r_{avg} := \frac{(r_i + r_o)}{2} = 0.151\ m$$

For Aluminum

$\rho := 2700 \frac{kg}{m^3}$ $\quad$ $E := 75GPa$

$Length_{blade} := 61.5m$

$C_2 := 3$ $\quad$ constant dependent on how the blade is loaded

$\delta := 2.91m$ $\quad$ δ is deflection of the centroid solved based on tip deflection

$$mass := \rho \cdot Length_{centroid} \cdot \left(\frac{2F_f \cdot Length_{centroid}{}^3}{C_2 \cdot E \cdot \delta \cdot r_{avg}{}^2} \right)$$

$mass = 1.321 \times 10^4 kg$

Blade I-Beam Analyis

$\rho_{air} := 1.25 \frac{kg}{m^3}$ $\quad$ $V_{air} := 16.6 \frac{m}{s}$ $\quad$ $C_d := 1.2$

$P := \left(\frac{1}{2}\right) \cdot \rho_{air} \cdot \left(V_{air}{}^2\right) \cdot C_d = 206.67m^{-1} \cdot kg \cdot s^{-2}$

$SA := 433.58m^2$

$Area1 := SA \cdot .5 = 216.79m^2$

$F_f := Area1 \cdot P = 44.804 \cdot kN$

$h := .375m$

$b := 0.375m$

$Length_{centroid} := 30m$

$C := 1$

$\boxed{\sigma_y := 300MPa}$ $\quad$ Al

$$t := \frac{F_f \cdot Length_{centroid}}{\sigma_y \cdot C \cdot \left(\frac{1}{3}h^2 + h \cdot b\right)}$$

$t = 0.024\, m$

$t = 0.941 \cdot in$

$\text{Length}_{blade} := 61.5\text{m}$ $\rho := 2700\,\frac{\text{kg}}{\text{m}^3}$

$\text{volume} := \left[2t \cdot (h + b) \cdot \text{Length}_{blade}\right] = 2.204\,\text{m}^3$

$\text{mass}_{brace} := \text{volume} \cdot \rho$

$\text{mass}_{brace} = 5.952 \times 10^3\,\text{kg}$

$\text{weight}_{brace} := \text{mass}_{brace} \cdot 2.2\,\frac{\text{lb}}{\text{kg}}$

$\text{weight}_{brace} = 1.309 \times 10^4 \cdot \text{lb}$

$\text{Volume}_{shell} := 1.1043186\text{m}^3$

$\rho_{fiberglass} := 2580\,\frac{\text{kg}}{\text{m}^3}$

$\text{mass}_{shell} := \text{Volume}_{shell} \cdot \rho_{fiberglass}$

$\text{mass}_{shell} = 2.849 \times 10^3 \cdot \text{kg}$

$\text{weight}_{shell} := \text{mass}_{shell} \cdot 2.2\,\frac{\text{lb}}{\text{kg}}$

$\text{weight}_{shell} = 6.268 \times 10^3 \cdot \text{lb}$

$\text{weight}_{blade} := \text{weight}_{shell} + \text{weight}_{brace}$

$\text{weight}_{blade} = 1.936 \times 10^4 \cdot \text{lb}$

Clyinder Blade Analysis

$\rho_{air} := 1.25 \frac{kg}{m^3}$ $\quad V_{air} := 16.6 \frac{m}{s}$ $\quad C_d := 1.2$

$$P := \left(\frac{1}{2}\right) \cdot \rho_{air} \cdot \left(V_{air}^{2}\right) \cdot C_d = 206.67 m^{-1} \cdot kg \cdot s^{-2}$$

$SA := 433.58 m^2$

$Area1 := SA \cdot .5 = 216.79 m^2$

$F_f := Area1 \cdot P = 44.804 \cdot kN$

$r_o := 0.1875 m$

$Length_{centroid} := 30m$

$C := 1$

$\boxed{\sigma_y := 300MPa}$ $\quad$ Al

$$r_i := \left[r_o^{4} - \left(\frac{F_f \cdot Length_{centroid} \cdot 4 \cdot r_o}{C \cdot \sigma_y \cdot \pi}\right)\right]^{\frac{1}{4}}$$

$r_i = 0.114 m$

$$r_{avg} := \frac{(r_i + r_o)}{2} = 0.151 m$$

$Length_{blade} := 61.5m$ $\quad \rho := 2700 \frac{kg}{m^3}$

$$volume := \left[\pi \cdot \left(r_o^{2} - r_i^{2}\right) \cdot Length_{blade}\right] = 4.301 m^3$$

$mass_{brace} := volume \cdot \rho$

$mass_{brace} = 1.161 \times 10^4 kg$

$$weight_{brace} := mass_{brace} \cdot 2.2 \frac{lb}{kg}$$

$weight_{brace} = 2.555 \times 10^4 \cdot lb$

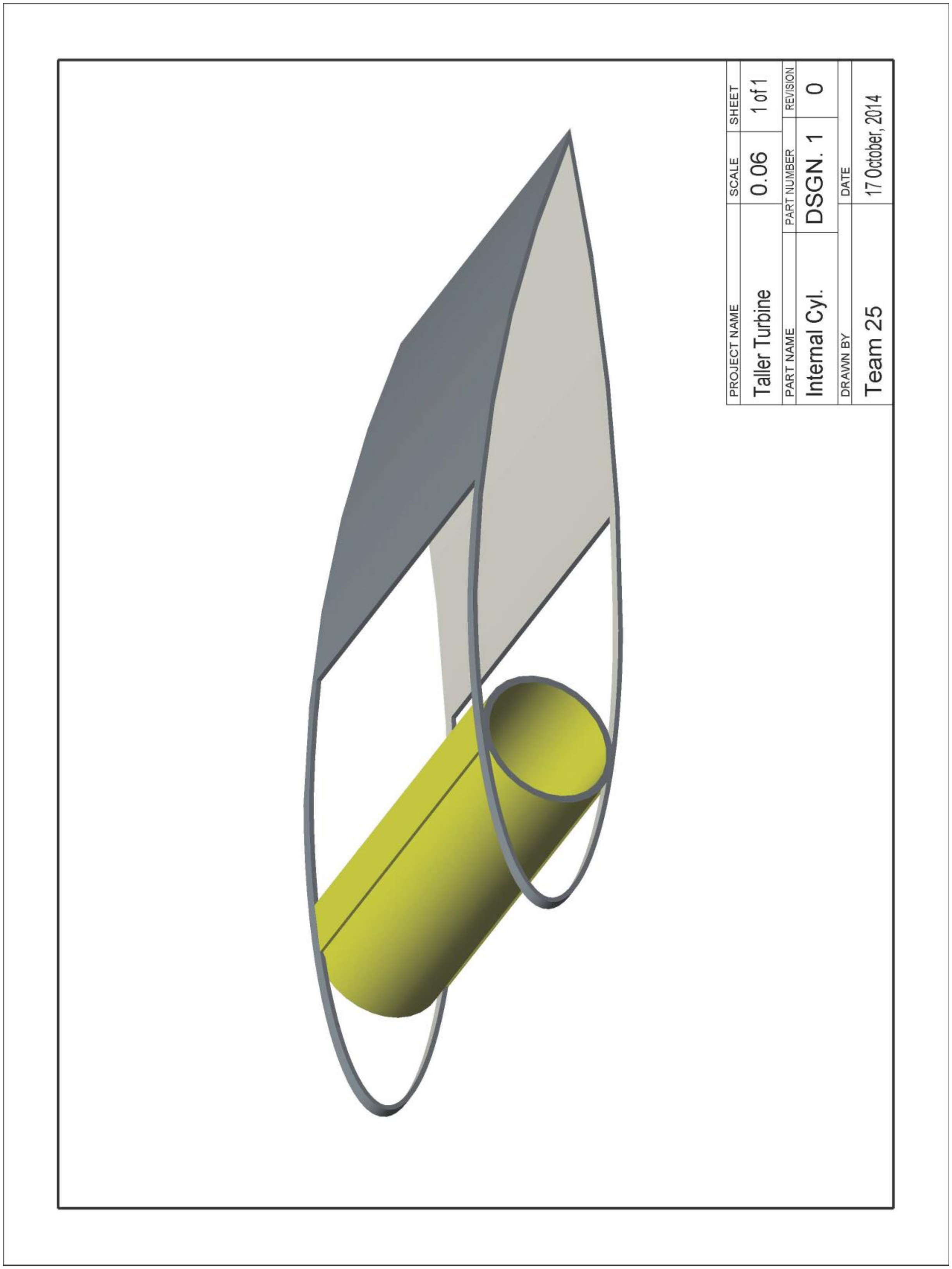
Appendix B: Blade Properties

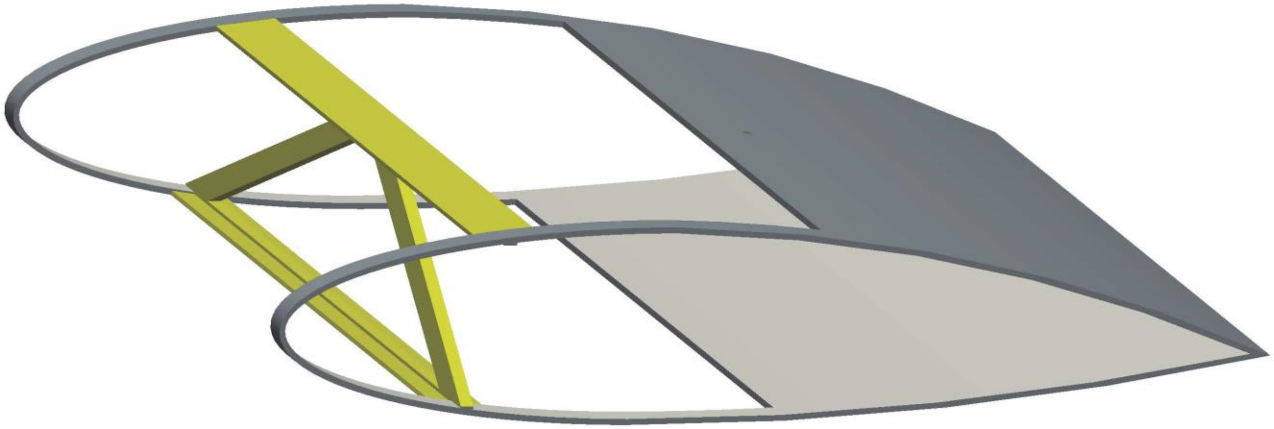
Element	RELM (m)	Twist (deg)	Chord (m)
1	2.8667	13.308	3.542
2	5.6	13.308	3.854
3	8.3333	13.308	4.167
4	11.75	13.308	4.557
5	15.85	11.48	4.652
6	19.95	10.162	4.458
7	24.05	9.011	4.249
8	28.15	7.795	4.007
9	32.25	6.544	3.748
10	36.35	5.361	3.502
11	40.45	4.188	3.256
12	44.55	3.125	3.01
13	48.65	2.319	2.764
14	52.75	1.526	2.518
15	56.1667	0.863	2.313
16	58.9	0.37	2.086
17	61.5	0.106	1.419

NACA 64	
(x-coordinate)	(y-coordinate)
1	0
0.95012	0.00564
0.90024	0.01188
0.85033	0.01849
0.80039	0.02518
0.7504	0.03176
0.70038	0.03799
0.65033	0.04375
0.60025	0.04891
0.55014	0.05333
0.5	0.05689
0.44985	0.05938
0.39968	0.06059
0.34951	0.0601

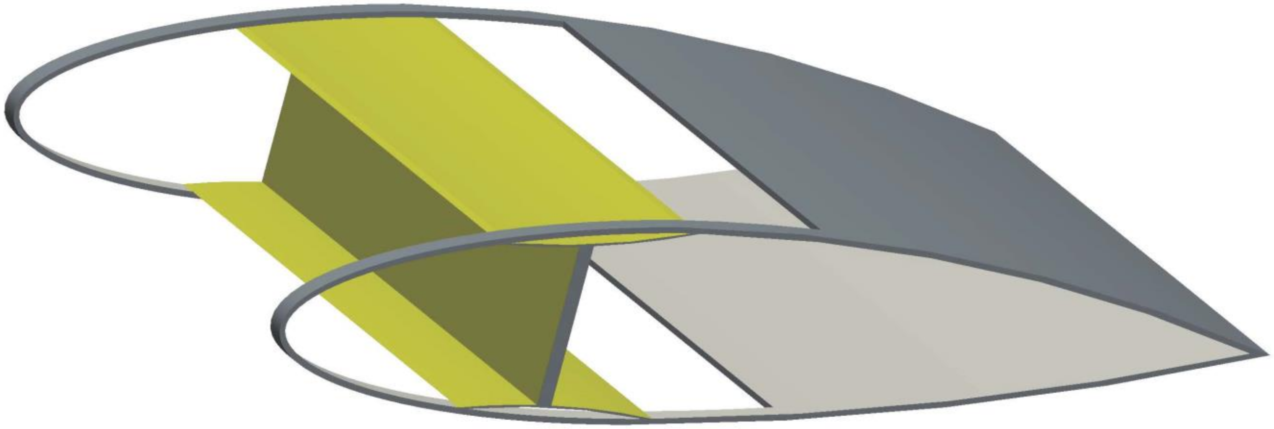
0.29934	0.05836
0.24919	0.05533
0.19905	0.05097
0.14894	0.04514
0.09887	0.03736
0.07387	0.03248
0.0489	0.02656
0.02401	0.01884
0.01163	0.01354
0.00673	0.01056
0.00431	0.00867
0	0
0.00569	-0.00767
0.00827	-0.00916
0.01337	-0.0114
0.02599	-0.01512
0.0511	-0.02024
0.07613	-0.024
0.10113	-0.02702
0.15106	-0.03168
0.20095	-0.03505
0.25081	-0.03743
0.30066	-0.03892
0.35049	-0.0395
0.40032	-0.03917
0.45015	-0.03748
0.5	-0.03483
0.54987	-0.03143
0.59975	-0.02749
0.64967	-0.02315
0.69962	-0.01855
0.7496	-0.01386
0.79962	-0.00926
0.84968	-0.00503
0.89977	-0.00154
0.94988	0.00068
1	0

Appendix C: Design CAD

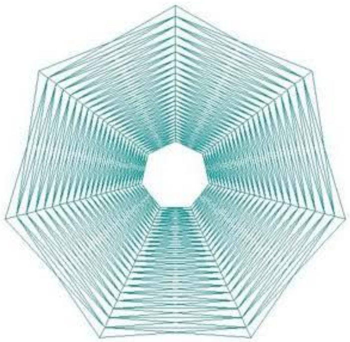




PROJECT NAME		SCALE	SHEET
Taller Turbine		0.06	1 of 1
PART NAME	PART NUMBER		REVISION
Internal Truss	DSGN. 2		0
DRAWN BY		DATE	
Team 25		17 October, 2014	



PROJECT NAME		SCALE	SHEET
Taller Turbine		0.06	1 of 1
PART NAME	PART NUMBER		REVISION
Single Post	DSGN. 3		0
DRAWN BY		DATE	
Team 25		17 October, 2014	

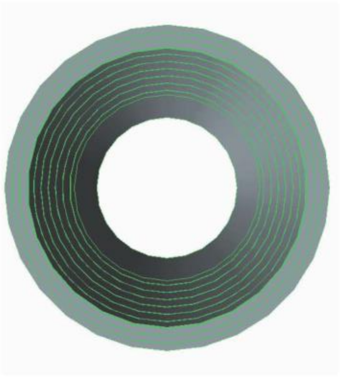


PROJECT NAME	SCALE	SHEET
Taller Turbine	0.07	1 of 1
PART NAME	PART NUMBER	REVISION
Heptagonal	DSGN. 1	0
DRAWN BY	DATE	
Team 25	17 October, 2014	

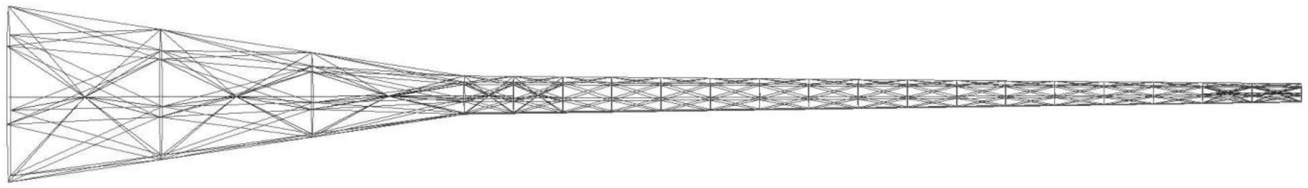
PROJECT NAME	SCALE	SHEET
Taller Turbine	0.07	1 of 1

PART NAME	PART NUMBER	REVISION
Triangular	DSGN. 2	0

DRAWN BY	DATE
Team 25	17 October, 2014



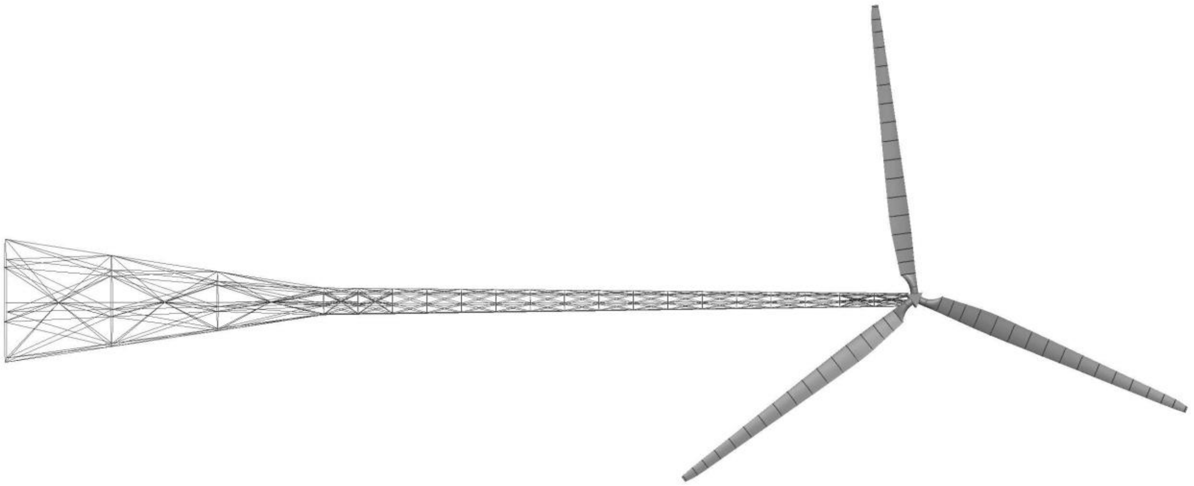
PROJECT NAME	SCALE	SHEET
Taller Turbine	0.07	1 of 1
PART NAME	PART NUMBER	REVISION
Steel Tube	DSGN. 3	0
DRAWN BY	DATE	
Team 25	17 October, 2014	



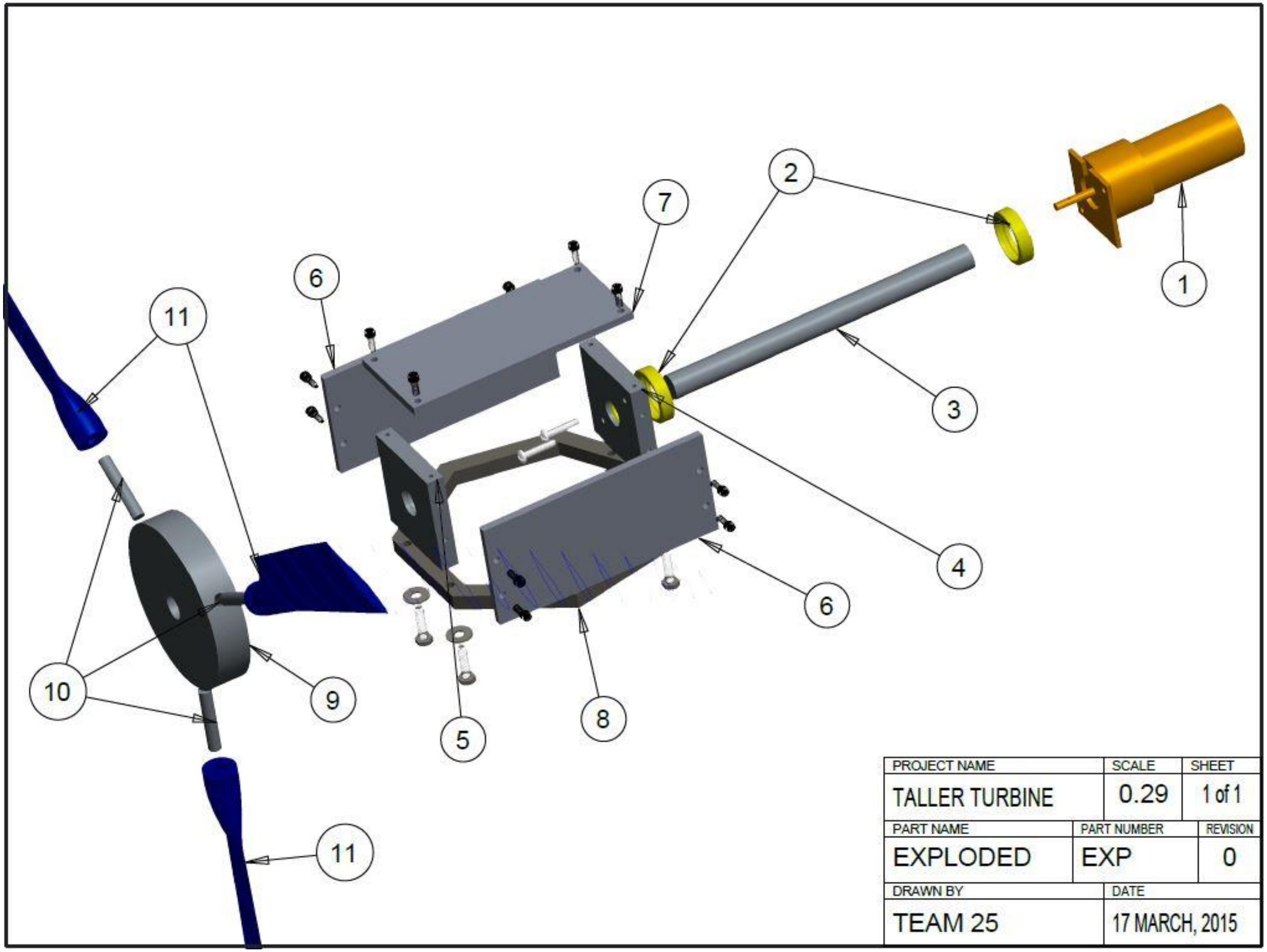
PROJECT NAME	SCALE	SHEET
Taller Turbine	0.07	1 of 1

PART NAME	PART NUMBER	REVISION
Tower	Dsgn. 4	0

DRAWN BY	DATE
Team 25	31 March, 2015



PROJECT NAME		SCALE	SHEET
Taller Turbine		0.001	1 of 1
PART NAME	PART NUMBER		REVISION
Turbine	ASM 1		0
DRAWN BY		DATE	
Team 25		21 November, 2014	



PROJECT NAME		SCALE	SHEET
TALLER TURBINE		0.29	1 of 1
PART NAME	PART NUMBER		REVISION
EXPLODED	EXP		0
DRAWN BY		DATE	
TEAM 25		17 MARCH, 2015	

Major Bill of Materials for Nacelle Model		
QTY	**Part No.**	**Item Name**
1	TWT-001	DC Motor
2	TWT-002	Roller Ball Bearing
1	TWT-003	Rotary Shaft
1	TWT-004	Rear Bearing/Motor Toter
1	TWT-005	Front Bearing Toter
2	TWT-006	Wall Sides
1	TWT-007	Nacelle Top
1	TWT-008	Top Tower Rung
1	TWT-009	Rotor
3	TWT-010	All-Thread
3	TWT-011	Turbine Blades

Appendix D: Model Purchases List

McMaster-Carr

QTY	Part No.	Description	Cost ($)	Pack Size	
1	1610T48	5x1" Dia Round Shaft	18.09	1	18.09
2	6383K49	3/4" Steel Ball bearing	7.48	1	14.96
2	6436K16	3/4" Clamp-on Collar	5.48	1	10.96
1	8974K11	3/4"x1' Alum Shaft	5.13	1	5.13
1	93410A912	3/8" All-thread (1ft)	11.03	1	11.03
1	8975K443	1/4"x8" Alum Sheet	17.23	1	17.23
1	8975K513	1/2"x3" Alum Plate	14.28	1	14.28
1	91247A548	1/4"-20x 1 3/4 Bolts	12.50	100	12.50
2	95615A120	1/4"-20 LockNuts	4.35	100	8.70
3	91081A129	1/4" Washers	2.65	100	7.95
1	91251A242	10-24x1/2" Socket head	10.27	100	10.27
1	92865A542	1/4"-20x1" Bolts	9.75	100	9.75
1		Shipping	8.64		8.64
					149.49

Fibre Glast

QTY	Part No.	Description	Cost ($)	Pack Size	
1	241-A	3yd - 2oz Fabric	18.65	1	18.65
1	2020-A	Epoxy Hardener (20 min)	21.95	1	21.95
1	2000-A	Epoxy Resin (2lbs)	44.95	1	44.95
1		Shipping	9.95		9.95
					95.50

Metals Depot

QTY	Part No.	Description	Cost ($)	Pack Size	
3	T11116	1X1" Sq Tube	19.92	12ft	59.76
3	T13416	3/4x3/4" Sq Tube	22.32	24ft	66.96
7	A1121218	1/2x1/2"x1/8" Angle	19.60	20ft	137.20
1	P1316	3/16" Steel Plate	24.30	1x2ft	24.30
1		Shipping	149.36		149.36
					437.58

UPS Store

QTY	Part No.	Description	Cost ($)	Pack Size	
1		3 Prototype Blades	547.20		547.2
					547.20

Home Depot

QTY	SKU	Description	Cost ($)	Pack Size	
1	0000-661-780	15pc. Brush Set	9.97	15	9.97
1	1000-538-380	80 grit sandpaper(9x11")	3.97	4	3.97
1	0000-802-594	Clear Rubber Gloves	9.98	100	9.98
1	0000-671-010	12"x3/8 - 16 Threaded Rod	1.37	12"	1.37
1	0000-157-510	9x12' Clear Plastic Drop Cloth	1.98	9x12'	1.98
2	0000-311-245	2" plastic putty knife	0.98	1	1.96
1	0000-451-723	Plastic Bondo Spreaders	3.97	3	3.97
1	0000-253-870	Shop Towels	6.28	3	6.28
4	1000-994-482	9" paint tray	0.98	1	3.92
1		Sales Tax (School Discount)	0.00		0.00
					43.40

Home Depot #2

QTY	SKU	Description	Cost ($)	Pack Size	
2	20066779283	Rustoleum What Spray Paint	3.76	1	7.52
1	30699331512	#10-32 Machine Screw	1.18	3	1.18
1	30699476985	Cotter Pin (3/32"x1 1/2")	0.72	4	0.72
1		Sales Tax	0.71		0.71
					10.13

Amazon

QTY	Part No.	Description	Cost ($)	Pack Size	
1		5mm Blue LED w/ Resistors	5.55	30	5.55
1		400-point Breadboard w/ wires	9.69	1	9.69
1		0.1uf 50v Ceramic Capacitors	4.23	30	4.23
1		Krylon Gray Primer 12oz	7.07	1	7.07
1		Sales Tax (School Discount)	11.95		11.95
					38.49

Online Fabric Store

QTY	Part No.	Description	Cost ($)	Pack Size	
5	PPBWHI	White PVC-Coated Polyester	5.55	600x300	27.75
2	D1000100C	10 gauge clear	3.30	1	6.60
1		Shipping	45.79		45.79
					80.14

Amazon #2

QTY	Part No.	Description	Cost ($)	Pack Size	
1		Darice Hook & Loop Strip	18.82		18.82
1		Tax	0.00		0.00
					18.82

Total Budget	2000
Used	1420.75
Remaining Budget	**579.25**

Bio

Biography

The team is composed of four senior mechanical engineering students and two senior civil eningeering students. All students attend Florida State University.

Steven Blanchette is currently in the Mechanical Engineering BS-MS program and will graduate in May 2016. He currently serves as the Treasurer of Pi Tau Sigma, a Mechanical Engineering honor society. After graduation Steven has the opportunity to return to N.L. Racing Technologies, a NASCAR Engineering firm.

David Delie is a current senior in Mechanical Engineering at the FAMU-FSU College of Engineering. Once he graduates he plans to find a job relating to material science. He also has aspirations of obtaining an MBA after a few years in industry.

Kimberly Martinson is a civil engineering student anticipating to graduate Spring 2015. After graduation, she plan to pursue her master’s degree as well as a career in structural engineering. Her goal is to contribute to the development of sustainable buildings in order to reduce waste and create a cleaner environment.

Jeremiah McCallister is undergraduate Mechanical Engineering student graduating in Spring of 2015. After he graduates from Florida State he will be attending graduate school to get a PhD. in Materials Science and Engineering and work in a National Lab as a researcher on the next generation of renewable energy.

Abigail McCool is seeking her Bachelor’s of Science in Mechanical Engineering. She currently serves as the Vice President of Pi Tau Sigma, a Mechanical Engineering honor society. After graduation, Abigail plans on seeking a job in industry.

Theo Meros is a senior Civil Engineering student graduating in May 2015. Theo has worked at Bridge Engineering firm but has interest in the design of other large-scale architectural structures. After graduation, he plans on working at a structural design firm and achieving a Master's of Science degree online.