Collegiate Wind Competition Market Team
Final Proposal

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EXECUTIVE SUMMARY

In 2008, the Department of Energy (DOE) published a report called *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply,* which detailed the predicted growth of the wind energy industry. The Collegiate Wind Competition 2018 was created by the DOE and the National Renewable Energy Lab to give undergraduates experience in this rapidly expanding industry. The competition has multiple parts, including building and testing a prototype wind turbine, generating a business plan for a deployable wind turbine, and completing a bonus wind farm siting project. The CWC18 Market team must design a theoretical wind turbine that matches the business plan and meets the requirements of the competition.

This report describes the Market team's process in designing a utility scale wind turbine. First, the team researched various existing wind turbine technologies to better understand the current market. Next, the team generated customer and engineering requirements from the research, given completion information, and help from the faculty advisors. Then the team generated 11 wind turbine concepts. The concepts were narrowed down using the customer and engineering requirements as judging criteria. The final concept is a utility-scale, direct-drive, horizontal axis wind turbine with active pitch and yaw systems. The turbine components are described in further detail in the report.

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1 BACKGROUND

1.1 Introduction

Northern Arizona University (NAU), along with twelve other schools, has been chosen to compete in the Collegiate Wind Competition 2018 (CWC18) held by the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL). The competition has three parts: A small scale turbine to be tested in a wind tunnel, a business marketing plan and a technical design for a large-scale wind turbine, and a siting challenge. The Market Team is a group of six mechanical engineers working on the technical design of the utility-scale wind turbine and the siting of a 100 MW wind farm. This report focuses on the objectives, research and design of the Market Team's turbine.

The team must fully design a hypothetical utility-scale wind turbine and its subcomponents. The team will be working in tangent with a team of students from the W.A. Franke College of Business, to create a business plan for the turbine. This design and business plan will compete at the CWC18 in May.

1.2 Project Description

The project description is given by the CWC18 Rules and Requirements:

> *"Teams participating in the 2018 Collegiate Wind Competition will be expected to research and design a turbine for a grid scenario with a high contribution of renewables. The turbine should be able to operate in islanded mode."* [1].

The Collegiate Wind Competition Market Team is responsible for creating a wind turbine design for a market plan developed by four students from the W.A. Franke College of Business at Northern Arizona

University. The business plan and technical design will be compiled into a report that will be judged at the competition in May.

1.3 Original System

Wind turbines take the kinetic energy in the wind and convert it to rotational energy. Early windmills converted this rotational energy directly into mechanical energy, while modern day turbines produce electricity through a generator.

1.3.1 Original System Structure

There are several important components on a utility scale wind turbine (Figure 1). These main components include: blades, hub, drive shaft, generator, braking system, yawing system, and tower [2].

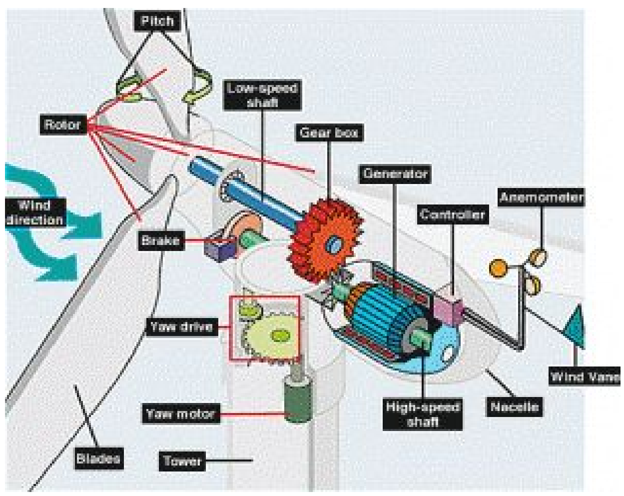


Figure 1: Components of a utility-scale wind turbine [3]

Blades – The blades are the main that interfaces with the wind. Lift based blades turn in a circular motion when the wind hits them and are often made with a mild steel beam frame and a glass-fiber and epoxy combination.

Hub – The hub is the cone-shaped piece in the middle of the rotor that holds the blades on the drive shaft. It is typically made of a polyester cone and a steel frame.

Drive Shaft – The drive shaft is a spinning circular rod attached to the rotor that connects to the gearbox or generator and is typically made of rolled steel.

Braking System – The braking system is a disk brake connected to the drive shaft. The brakes are used to stop the turbine when it is under maintenance, or when wind speeds reach the cut-out wind speed of the turbine.

Generator – The generator converts the rotational mechanical energy from the drive shaft into AC or DC current depending on the size and use of the turbine.

Yawing System – The yawing system is used to keep the rotor in the direction of the wind. In an active yawing system, a wind vane determines the direction of the wind and sends a signal to the computer controls, which send a signal to the yawing gear in the nacelle to turn the turbine in that direction. In a passive yawing system, a tail on the back of a turbine is pushed in the wind direction using skin drag.

Tower – The tower is the structure that the nacelle rests on. Typically, it is mounted to the ground using a concrete foundation and the tower is made of steel to withstand the moment and torque that is created from capturing the wind energy.

1.3.2 Original System Operation

A wind turbine can integrate its energy with a grid, micro-grid, or energy storage system. A turbine can only produce power at certain speeds. The "cut-in speed" is the value at which a turbine starts spinning. The power then increases as the wind velocity increases at a cubic rate. At a certain velocity called the "rated wind speed", the turbine reaches its "rated power". It maintains this power over a range of wind speeds until it reaches the "cut-out speed" where the braking system activates and stops the blades from spinning. The brake engages so that the high wind velocities will not spin the blades too fast and produce enough force to break the turbine. An anemometer is used to detect the speed of the wind and relay the information to the braking and pitching systems. These areas of function are shown on a basic power curve of a wind turbine (Figure 2).

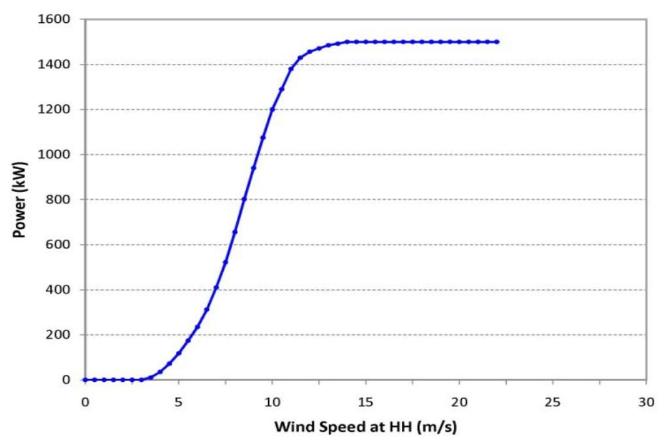


Figure 2: Basic power-curve for a utility-scale wind turbine [4]

A wind vane is used to determine the direction of the wind [3]. This information is transferred to the yawing system (in an active yawing system) which will then rotate the turbine, so it is facing the wind for maximum performance.

1.3.3 Original System Performance

The performance of a wind turbine is dependent on several factors including the coefficient of performance, power curve, and the amount of wind. These factors often depend on, the hub height, rotor diameter, and the generator.

In this section, the team looked at the GE 3.2-103 Wind Turbine [5]. This is a 3.2 MW turbine with a hub height of 85-98 meters. The blade diameter is 120 meters with each blade being 60 meters long.
These will be comparable specifications to the turbine presented in this report.

1.3.4 Original System Deficiencies

The original system did not meet the customer requirements because the competition requires an original system. Although the GE 3.2-103 Wind Turbine meets the power output requirement, the turbine needed to be an original design. Although the design in similar to modern wind turbines, the project requires an original design that has not been made before by previous CWC capstone groups.

2 REQUIREMENTS

The Market team is responsible for communicating with the business team to design a utility scale marketable turbine that meets the requirements of the competition. To accomplish this, the team must identify the customer requirements and generate a set of measurable engineering requirements. Both these requirements are placed in a House of Quality matrix to rank the requirements in order of highest importance.

2.1 Customer Requirements (CRs)

The market team generated seven CR's (Table 1) through interpreting the CWC18 challenge statement, and interviews with David Willy and Karin Wadsack. These requirements are awarded weights regarding their importance relative to the success of the project. These weights are used in the House of Quality, which can be observed in Section 2.3 of this report.

Table 1: CR's

Customer Requirement	**Description**	**Weight**
Competitive Levelized Cost of Energy (LCOE)	This requirement ensures the project is financially feasible by evaluating the system's costs in a lifetime divided by a system's total energy production over the lifetime.	15%
Wind focused power system	From the CWC18 Rules and Regulations regarding the development of a power system composed of multiple generation methods including wind power.	20%
Grid connected	Turbine must be connected to the grid as per the competition guidelines. This could either be a large city based electrical grid or a micro-grid scenario.	10%
High Renewable Energy Penetration	Power system must encompass a high percentage of renewable energy in its total power production.	15%
Operate in islanded mode	A system operating in islanded mode must supply power to a micro-grid while disconnected from the larger grid, and thus will require an energy storage component.	20%
Comparable to test turbine	Compare the designed turbine with the test turbine, and explain all discrepancies between designs.	10%

Complement the business plan	Turbine design must complement the business proposal, and its associated market.	10%

2.2 Engineering Requirements (ERs)

ER's complement the CR's, and offer the team measurable parameters to judge the generated concepts. The Market team developed a total of nine ER's (Table 2).

Table 2: ER's

Importance	**ER**	**Target Tolerance**
1	Placed within an area with a minimum wind speed average of 6.5m/s.	Between 5 and 8 m/s.
2	Located within 20 miles of grid tie-ins.	± 10 miles.
3	Minimum power coefficient of 0.35.	≤ 0.59.
4	Able to provide power in islanded mode for 4 hours.	≥ 4 hours.
5	3.5MW Rated Power	± 25%.
6	Withstand wind speeds of 20 m/s.	≥ 20 m/s.
7	Wind energy accounts for 30% of total power output.	± 10%.
8	3 Blade Turbine	± 1
9	Minimum tower height of 100m.	± 20%.

Implementing a system in an area of minimum mean wind speed of 6.5 m/s has earned the top ranking among the team's ER's. This is because the efficiency and LCOE values will suffer greatly if the turbine is not placed in an area with appropriate resources. Through interviews with David Willy, the team decided 6.5m/s was the minimum average wind speed for optimal performance. Having the turbine within 20 miles of grid tie ins reduces capital costs relating to infrastructure and results in a lower LCOE. A minimum power coefficient of 0.35 is in place to vet out any poorly performing concepts. The system's ability to operate a minimum of four hours in islanded mode using an energy storage system meets the islanded mode customer requirement. A turbine with a 3.5MW rated power will complement the current state of the business plan which requires a utility scale power system. A power system where wind energy accounts for 30% of the total power production fills the CR's for a wind focused power system and high renewable energy penetration. The value of 30% ensures a large amount of the energy in the system is from a renewable source. The system must make an impact on the percentage of power coming from renewable sources to have high renewable energy penetration, and have a competitive LCOE; these are met by a turbine with a power coefficient greater than or equal to 0.35. A system which operates with three blades will make this power coefficient an achievable goal. Creating a tower with a height of 120m will place the blades of the turbine into an optimal wind resource, and be rigid enough to not be concerned with reliability and durability issues. Durability is a key factor in designing a turbine that can withstand wind speeds of 20m/s. The team's success relies heavily upon following these ER's during concept evaluation and selection.

2.3 Testing Procedures (TPs)

To thoroughly test each engineering requirement, the below testing procedures were developed, and implemented. Mathematical, Visual, and Financial software packages make up the entirety of the team's testing procedures because this project is entirely theoretical, and we will not be building a functioning physical prototype.

2.3.1 Matlab

Utilizing Matlab the team developed several code blocks to test certain engineering requirements. The largest of them being Blade Element Momentum iterator which allows the team to test the performance characteristics of turbine blade systems. This code allows the team to see what kind of coefficient of performance their design is operating in, and to choose the best airfoil for their design. This allows the team to meet the engineering requirement of having a minimum coefficient of performance of 0.35. Other code blocks include analysis of the design's shaft, mainframe, yawing system and tower. These alternate code blocks help to ensure the durability of the team's design by allowing the team to experiment with different material properties within their design parameters. Utilizing these results the team is able to meet the engineering requirement of withstanding minimum wind speeds of 20 m/s.

2.3.2 QBlade Analysis

Once the team was confident in the outputs of the Matlab BEM iterator, the code in conjunction with QBlade to complete the rotor design. QBlade allowed the team to further test the capabilities of the selected airfoils, and generate an overall blade model. QBlade was used to test the engineering requirement of a 3.5MW rated power system. The number of blades will also be tested within QBlade to appease the engineering requirement of having a three blade system. FEA analysis for the rotor was completed in QBlade.

2.3.3 Solidworks

Designed components were subject to Finite Element Analysis (FEA) in Solidworks. FEA analysis for the tower, shaft, and mainframe was completed using Solidworks. Through this FEA the team tested the engineering requirement of being able to withstand minimum wind speeds of 20 m/s. A tower height of 120m was also tested using Solidworks FEA to see the effects of the forces present on the tower and whether or not the system was be able to withstand such heights.

2.3.4 NREL's System Advisory Model

Siting decisions will be made with the input of NREL's System Advisory Model (SAM). SAM will allow the team to see what kind of renewable impact their design will have, as well as what wind speeds the possible area is dealing with. SAM allows the team to properly test the engineering requirement of being located within 20 miles of major grid tie-ins, as well as the engineering requirement of implementing our system in an area with a wind resource of 6.5m/s. This aids in the capacity decisions of the project, as well as insuring the lowest LCOE possible. The team has generated an LCOE for a proposed site in the western region of Texas. This was to follow the guidelines in the business proposal generated by our business team.

2.4 House of Quality (HoQ)

The team's HoQ uses the CR's to determine which ER's have the highest technical importance (Table 3). This helps guide the team in further research, concept generation, and design selection. The team rated these requirements using values of either 3,6, or 9, and these values were then multiplied to the weight of their corresponding CR's and summed to get the requirements Absolute Technical Importance (ATI). Once all ATIs were tabulated the requirements were then ranked 1-9 in order of Relative Technical Importance (RTI). All ER's will be verified through testing procedures one through four, which are discussed in detail in section 2.3.

Table 3: House of Quality											
Customer Requirement	**Weight**	**Engineering Requirement**	Located within 20 miles of grid tie-ins.	An area with a minimum wind speed average of 6.5m/s.	Able to operate in islanded mode for 4 hours.	Wind energy must account for 60% of total power out.	Minimum power coefficient of 0.35.	Withstand wind speeds between 0-20m/s.	3.5MW Rated Power	Minimum Tower Height of 100m	Number of Blades
1. Wind focused power system	0.20		9	9	3	9	9	9	9	0	6
2. Competitive LCOE	0.15		9	9	0	3	3	3	6	6	6
3. Must be grid connected	0.10		9	0	3	3	0	0	0	0	0
4. High renewable energy penetration	0.15		6	9	6	3	9	3	6	0	0
5. Must operate in islanded mode	0.20		0	0	9	0	0	0	0	0	0
6. Comparable to the testing turbine	0.10		0	6	0	0	9	9	0	0	9
7. Complement the business plan	0.10		6	6	9	6	3	3	9	9	0
Absolute Technical Importance (ATI)			5.55	5.7	4.5	3.6	4.8	3.9	4.5	1.8	3
Relative Technical Importance (RTI)			2	1	4	7	3	6	5	9	8
Target ER values			20 miles	6.5 m/s	4 hrs.	60%	0.35	20 m/s	1MW	100m	3
Tolerances of Ers			± 10miles	5-8m/s	≥ 4hrs.	± 10%	≤ 0.59	≥20m/s	± 25%	± 20%	± 1
Testing Procedure (TP#)			4	4	4	4	1,2	1,2,3	1,2	1,2,3	1,2

3 EXISTING DESIGNS

An increased demand for renewable energy solutions has created a market for the design and manufacture of utility-scale wind turbines. Most of wind power generation is produced by commercial horizontal axis wind turbines (HAWT) in wind farms [6]. The team focused research and concept generation on these turbines because they are manufactured nationally and advertise high reliability and performance. Various subsystem components including turbine blades, towers, generators, and drivetrains were researched to aid in the development of a wind turbine that best fits the ER's.

Existing designs were analyzed by benchmarking commercial HAWT's. This model has a high efficiency or coefficient of performance (C_p) making it a promising solution to meet the design goal [6]. The manufacturer specifications of three distinct wind turbines are compared in Section 3.2. Individual turbine subsystems were researched to further analyze wind turbine options that meet the ER's.

Even though HAWT's are promising due to the high efficiency and ability to produce power, there are opportunities for improvement. Some problems are related to the foundation, grid connection, and maintenance. Usually, direct drive generators are preferred because failure and maintenance of the gearbox is avoided [7]. A direct drive generator substitutes the need for a gearbox in the nacelle of the turbine. Avoiding a gearbox not only results in improved reliability (assuming good generator efficiency and reliability) but improved performance due to a decrease in frictional losses in the gearbox. Another system component crucial to the power produced by the turbine is the blades. Blade design is a critical area of focus due to the significant impact on wind turbine performance.

3.1 Design Research

The team assigned individual areas of research to each team member. The areas explored include a full design comparison, blade research, tower research, and powertrain/generator comparison. The system level research was performed by finding turbine specifications from official sites of the turbine manufactures (Siemens, Vestas and Envision), see References [8] through [10]. Blades were researched by use of an article released by Siemens, an online blade comparison from popularmechanics.com, a report from windsystemsmag.com, and information from LM Wind Power, a GE Renewable Energy Business. For blade research resources see References [11] through [14]. Turbine towers were researched by use of online sources and two US patents related to turbine tower geometry, see References [15] through [17]. Generators and turbine drivetrain was researched by use of sources from the IEEE online library. The articles used to research drivetrain components were published documents from credible sources such as IEEE Transactions on Industry Applications, IEEE Transactions on Industrial Informatics, and IEEE Transactions on Applied Superconductivity, see References [18] through [20].

3.2 System Level

This section benchmarks existing wind turbines of similar rated powers and wind classes, reference Table 4.

Table 4: Benchmarking of three existing HAWT systems

Company	**Siemens Gamesa [8]**	**Vestas [9]**	**Envision [10]**
Product Name	Gamesa 3.3 MW	V126-3.45 MW	3.0-120
Rated Power (MW)	3.3	3.45	3
Cut-in Wind speed (m/s)	2	3	3
Cut-out wind speed (m/s)	25	22.5	25
Rated wind speed (m/s)	11	20	11
IEC Wind Class	IIA, IIB	IIA, IIB	IIA
Rotor Diameter (m)	132	126	120
Hub heights (m)	84, 94, 114, 134, and site specific	87, 117, 137, 147, 149, 166	90
Gear box	3 stages	Two planetary stages and one helical stage	Directly driven

All compared turbines have a rated power between 3 and 3.45 MW, and all are in IEC Wind Classification II. This rated power was chosen because this is the average value of most utility scale turbines being produced today. The specifications for the Siemens Gamesa, Vestas, and Envision wind turbines were found at the company websites.

3.2.1 Existing Design #1: Siemens Gamesa 3.3 MW

The Gamesa 3.3 MW wind turbine was first deployed in 2016 [8]. Its rated power is 3.45 MW, and is built for both IIA and IIB LEC wind classifications. It has the lowest cut-in wind speed of 2 m/s, a cut-out wind speed of 25 m/s, and a rated wind speed of 11 m/s. The rotor diameter is 132 m, and the hub heights range from 84 to 134 m. According to the company, the Gamesa 3.3 MW turbine is optimized for low LCOE and noise emission levels [8].

3.2.2 Existing Design #2: Vestas V-126-3.45 MW

The Vestas V-126-3.45 MW Wind turbine has the highest rated power and is also for LEC wind class IIA and IIB winds. It's cut-in wind speed is 3 m/s, cut-out wind speed is 22.5, and rated wind speed is 20 m/s. The hub heights range from 87 to 166 m, and the rotor diameter is 126. Vestas claims that this turbine produces "exceptional profitability in areas with low wind" [9].

3.2.3 Existing Design #3: Enivsion 3.0-120

The Envision 3.0-120 is designed for IIA wind class, and was first released in 2015 [10]. This turbine has a cut-in speed of 3 m/s, a cut-out speed of 25 m/s and a rated wind speed of 11 m/s. It has a 120 m rotor diameter and a 90 m hub height. This is the only turbine out of the three compared, that is directly driven.

3.3 Functional Decomposition

The design function tells the team what the product must do; and through what paths energy, material, and information must flow. Understanding these steps, and their interfaces, aids the design team in identifying design problems during concept generation.

3.3.1 Black Box Model

The black box model (Figure 3) simplifies the function of the wind turbine. The model assumes that matter, energy, and signals flow in and out of a black box. In this instance, the inputs include air, kinetic energy of wind, and orientation of the turbine relative to the wind. The outputs include air, electricity, and proper alignment of the rotor.

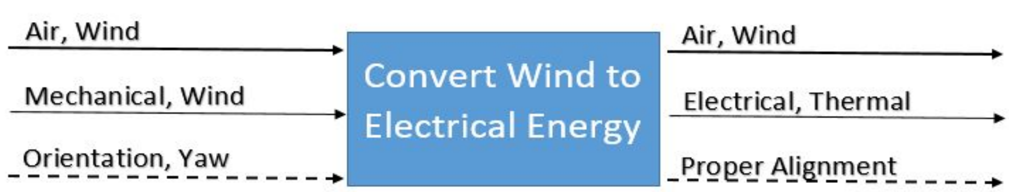


Figure 3: Black Box Model

3.3.2 Functional Model

The primary function of a wind turbine is to transform wind energy into usable electrical energy. Wind incident upon the rotor is converted to rotational energy. This rotational energy is transmitted by a low speed shaft, into a gearbox. A high-speed shaft out of the gearbox, is connected to an induction generator where the rotational energy is converted to electricity. The electricity can be transmitted to the grid or an energy storage system. Figure 4 shows the functional decomposition of a downwind lift-based HAWT, with an active yaw, a gearbox, and an induction generator.

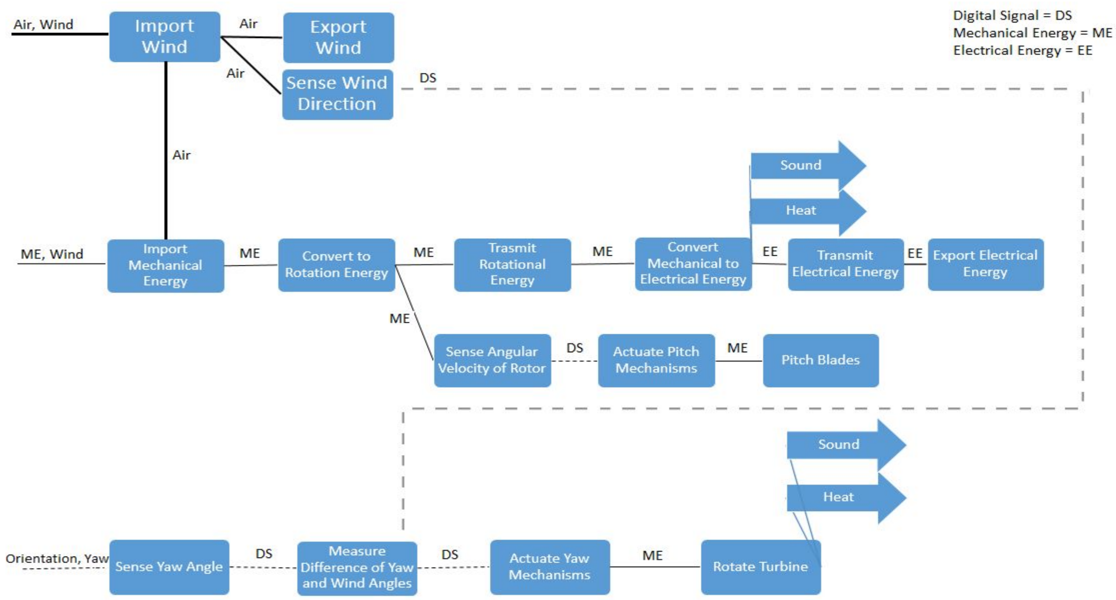


Figure 4: Functional Decomposition Model

Energy from the wind not transmitted through the rotor shaft is dissipated in the rotor wake, or converted to bending and torsional stress in the tower and its linkages. Energy that is lost between the rotor shaft and gearbox output shaft dissipates thermally through friction and hysteretic damping. Energy lost in the generator dissipates thermally. Energy lost in transmission lines dissipates thermally, and is proportional to the square of the current multiplied by the resistance.

3.4 Subsystem Level

This section analyzes current wind turbine designs on a subsystem level. The subsystems researched were blades, towers, and generators.

3.4.1 Subsystem #1: Blades

Blades are an important and unique aspect of wind turbine design. The blades collect power from the wind, and have the largest impact on total turbine efficiency. Since the goal of this design is to have a high efficiency, it is important to know what is being done with current blades in order to produce the highest efficiencies for modern turbines.

3.4.1.1 Existing Design #1: Siemens' Dinotail

The DinoTail is a blade add-on device designed to reduce noise of wind turbines. The design was inspired by the jagged edge an owl's wing and uses a serrated design to create wind vortices which reduce the noise generated by airflow [11]. Test results of the product show that the design reduces noise emissions of wind turbines at all wind speeds without affecting annual energy production. Adding a design such as this can allow the blade design to focus more heavily on capturing wind power without worry of local noise restrictions. This would be advantageous for a turbine that would be close to populated areas.

3.4.1.2 Existing Design #2: WhalePower

The company, WhalePower, has created a new fin design for turbine blades that uses a series of ridges to increase annual electrical production by as much as 20% [12]. The design is based on bumps on the fins of humpback whales called tubercles. This fin design prevents stalling and allows for steeper angles on blades, increasing the amount of wind power the blade can capture. Test results show that this design can help push back the stall angle by as much a 40% [12]. This would be a very beneficial design for any utility scale turbine and possibly any small-wind turbine as well, seeing that it adds an overall increase to the turbine efficiency by allowing it to collect more power from the wind.

3.4.1.3 Existing Design #3: LM 88.4 P

The LM 88.4 P is the world's longest blade at 88.4 m in length [13]. The blade is primarily designed for offshore wind turbines with an expected life of 25 years. Due to its immense size, the amount of power it can collect is much larger than most turbine blades, capable of producing 8 MW. One method the company used to create such a large and economical design was using a “Pre-Bend” design. This design uses a ductile blade material and applies a stress hardening process during manufacturing for higher strength at a cheaper cost [14]. Applying this manufacturing method could possibly allow the design to use cheaper material without losing strength or efficiency.

3.4.2 Subsystem #2: Tower

The tower is the structure that raises the turbine above the ground into higher wind speeds. Since wind speed increases with height, it is important to find a tower design capable of lifting a wind turbine as high off the ground as possible. It is also important that the tower is strong and sturdy enough to support a heavy wind turbine in harsh weather conditions such as thunderstorms, heatwaves, and extreme wind speeds. A strong tower with a large height would be very beneficial to this design in terms of increasing the overall wind speed and, henceforth, power output of the design,

3.4.2.1 Existing Design #1: MARS

The Mageen Air Rotor System (MARS) is a unique turbine design that has no tower. Instead, the turbine system is lifted off the ground with helium gas and tethered with power lines. This unique design allows the turbine to reach heights up to 1000 m. This design is still in the prototype stage, however Magenn has 10 to 25 kW turbine designs and plans to pursue a 100 kW model in the future [15].

3.4.2.2 Existing Design #2: Hexagonal Tower System

This patented tower design from Iowa State University uses a hexagonal shaped tower structure assembled from a series of concrete columns and panels. The columns and panels, made from high performance concrete, can be assembled together to create a tower ranging from 80 to 100 m high while withstanding all necessary loads including heavy winds and earthquakes. This tower has many advantages over the conventional steel tower, from cheaper material costs to easier transportation and to easier assembly [16]. Applying this to the design would be greatly beneficial in terms of manufacturing cost.

3.4.2.3 Existing Design #3: Reinforced Wind Tower

This patented design from Gamesa innovation & Technologies is a structural support system for the interior of a cylindrical tower. The design uses a series of longitudinal reinforcement elements attached to the inner surface of the tower's hollow body. The result is a taller tower with a smaller diameter, and cuts in material and manufacturing costs [17].

3.4.3 Subsystem #3: Drivetrain/ Generator

The drivetrain and generator of HAWT's have a significant impact on the performance and reliability of the system. A turbine design must have an appropriate drivetrain and generator to reduce maintenance costs and improve the overall system performance.

3.4.3.1 Existing Design #1: Direct Drive Generator with gearbox

The wind turbine gearbox transmits mechanical energy into the generator at a high speed. The gearbox suffers heavy loads, transient impulses of brakes, and dust corrosions; and accounts for about 59% of total wind turbine failures [19]. It is important to design a gearbox with easily replaceable parts, and carefully considered factors of safety because of the frequency of failure.

3.4.3.2 Existing Design #2: Generator without Gearbox

Direct drive systems are beneficial because they lower the maintenance costs of replacing gear boxes; however, the required generators can be expensive because they must function at a range of low angular speeds. This system is particularly suitable for installations where minimized maintenance is a crucial requirement [18].

3.4.3.3 Existing Design #3: Superconducting Generator

The superconducting generator is a type of direct drive generator that is smaller and lighter than other direct-drive generators. Superconducting generator technology is developing rapidly due to its promising attributes of efficiency and reliability [20]. This type of generator is relevant to wind turbine design because it reduces the weight and size of the nacelle, and decreases surface drag. A decrease in weight lessens the loads on the yawing system and tower, and aid in easier installation.

4 DESIGNS CONSIDERED

The team generated 11 wind turbine designs. The top five designs from the Pugh Chart are shown in Figures 5-10, the rest of the designs are described in the Appendix.

4.1 Design #1: Downwind with Shroud

Design 1 (Figure 5) is a downwind, three bladed turbine with a shroud. The design has a 40m hub with a direct drive shaft to a generator providing 500kW power. The shroud provides a passive yawing system, and a low-pressure area behind the turbine which accelerates the flow of the wind through the blades.

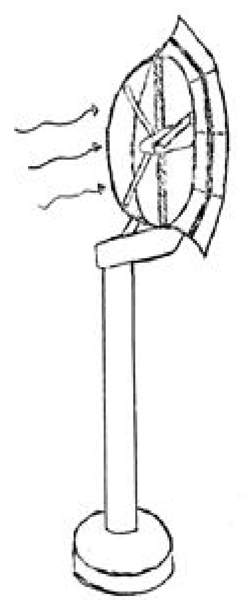


Figure 5: Downwind Turbine with Shroud to increase flow velocity through blades.

Pros:

- High efficiency

- Always in the optimal direction for wind capture
- No gearbox

Cons:

- Complex design
- Better for small-scale systems
- Not aesthetically pleasing
- Low durability

4.2 Design #2: Two Blade with Passive Yaw

Design 2 (Figure 6) is a two blade, variable pitch, 30m wind turbine. The variable pitching allows for lower cut-in speeds and able to stall at cut-out speeds. The low speed shaft goes into a planetary gear box which allows for a cheaper generator that spins at a high speed. The fin acts as a passive yawing system and the turbine can always be pointed in the direction of the wind.

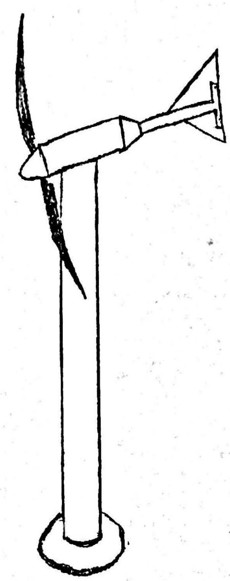


Figure 6: Two bladed small-scale wind turbine with passive yawing system

Pros:

- High efficiency
- Always in the optimal direction of wind capture
- Low generator cost

Cons:

- Gearbox will need maintenance
- Complex design
- Low durability
- Not aesthetically pleasing

4.3 Design #5: Three Blade Turbine with Planetary Gearbox

Design 5 (Figure 7) includes three blades, a pitching blade mechanism, a software controlled yaw system, a planetary gearbox, and a power generator. The turbine is intended for an IEC wind class level II. There are preferred features with this design that correlate with the identified ER's but there is also room for improvement.

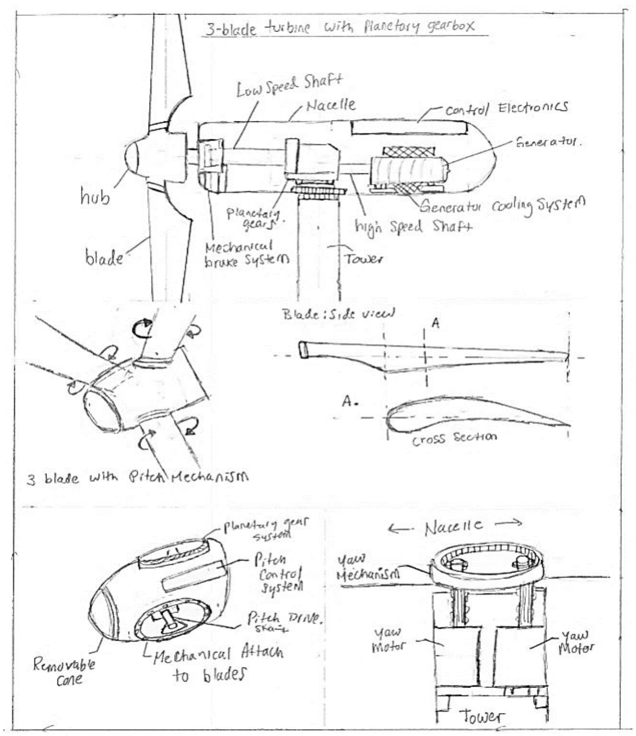


Figure 7: Utility scale turbine with planetary gearbox

Pros:

- Moderate efficiency
- Designed for utility scale systems
- Aesthetically pleasing
- High durability/ longevity
- Low generator cost

Cons:

- High maintenance costs due to the gearbox
- Frictional losses due to the gearbox
- High number of components to maintain

4.4 Design #6: Three Blade Direct Drive Wind Turbine

Design 6 (Figure 8) includes three blades, a pitching blade mechanism, a software controlled yaw system, and a direct drive power generator. The turbine is intended for an IEC wind class level II. There are preferred features with this design that correlate with the identified ER's but there is also room for improvement.

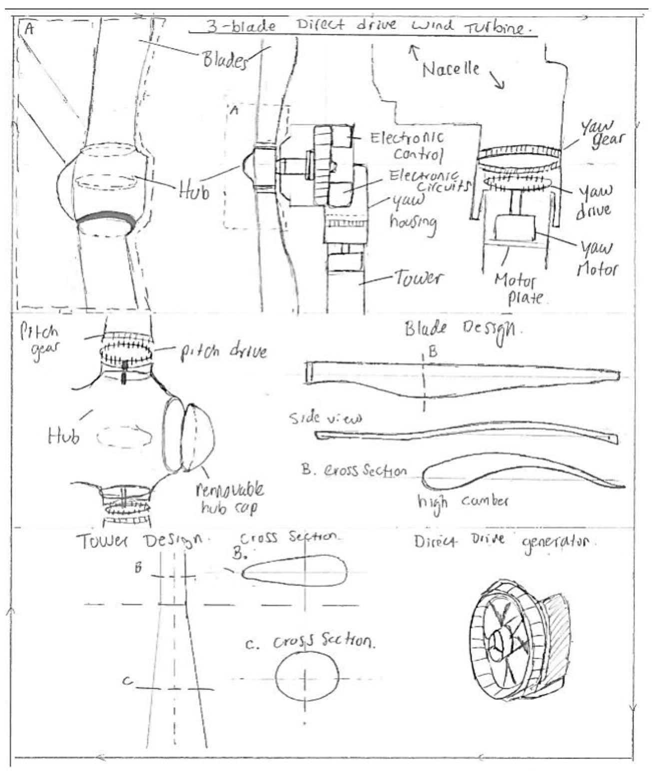


Figure 8: Utility-scale turbine with direct drive

Pros:

- High efficiency
- Reduced frictional losses (as compared to design #5) due to the elimination of the gearbox
- Designed for utility scale systems
- Reduced number of components (as compared to design #5) to manufacture and assemble

● Smaller nacelle (as compared to design #5) and esthetically pleasing.
● High durability

Cons:

● Complex design
● High generator cost

4.5 Design #11: Down-Wind HAWT with Truss tower

Design 11 is a HAWT and down-wind configured turbine, see Figure 9. The turbine's tower is constructed from a series of faired trusses. The generator is a direct drive permanent magnet system. The rotor blades are composed of composite material, and are shaped as an S800 series, and include vortex fences to mitigate span wise blade flows. This turbine is stall regulated.

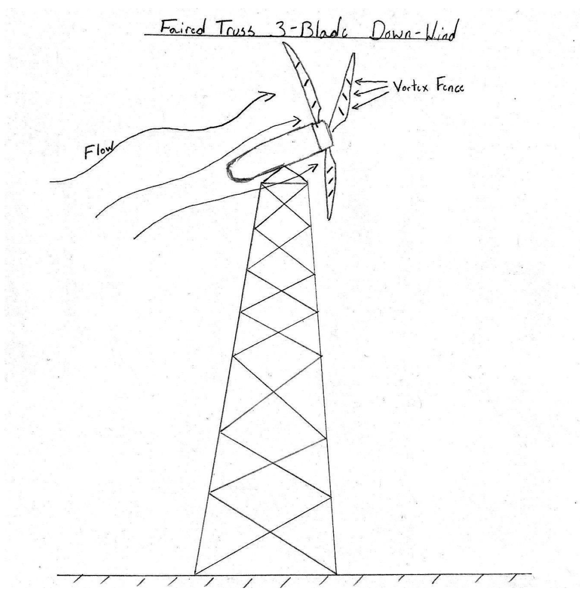


Figure 9: Downwind turbine with truss tower and vortex fenced blades

Pros:

● No gearbox
● Always in the optimal direction for wind capture
● No gearbox
● High durability

Cons:

● Low efficiency
● Complex design
● Better for small-scale systems
● Not aesthetically pleasing

- High generator cost

4.6 Design #3: Upwind HAWT with Shroud

Design 3 (Figure 19 in Appendix) is HAWT, upwind, four bladed turbine with a wind shroud. The system is also directly driven. The wind shroud acts as a passive yawing system.

Pros:

- High efficiency
- Always in the optimal direction of wind capture
- No gearbox

Cons:

- Complex design
- Better for small-scale systems
- Not aesthetically pleasing
- Low durability
- High generator cost

4.7 Design #4: Eight Bladed Downwind Turbine

Design 4 (Figure 20 in Appendix) is a small-scale. eight bladed, downwind turbine. It has a 3-stage gearbox and is stall regulated.

Pros:

- Always in the optimal direction of wind capture
- Simple design
- Better for large-scale systems
- Low generator cost

Cons:

- Low efficiency
- Gearbox will need maintenance
- Not aesthetically pleasing
- Low durability

4.8 Design #7: HAWT with Vertical Axis Wind Turbine

Design 7 (Figure 21 in Appendix) is a combination of a HAWT and a vertical axis wind turbine. The HAWT is an up-wind system with a passive yawing, and 3-stage gearbox. The vertical axis turbine is integrated into the tower to provide additional power generation from the wind passing below the top turbine.

Pros:

- High efficiency
- Low generator cost
- Aesthetically pleasing

Cons:

- Gearbox will require maintenance
- Complex design
- Low durability

4.9 Design #8: Floating Turbine

Design 8 (Figure 22 in Appendix) is a floating wind turbine tethered to the ground using power cables. The funnel-style kite design, accompanied by helium filled sacks on the outside would keep the turbine afloat while forcing it to face the direction of the wind. Serrated edges on the backs if the blades would help to prevent stalling of the turbine and allow it to capture more energy.

Pros:

- High efficiency
- Aesthetically pleasing

Cons:

- Complex design
- Low durability
- Better for small-scale systems

4.10 Design #9: Horizontal Axis, 3-Blade Upwind, Guyed Tower

Design 9 (Figure 23 in Appendix) is a three blade, upwind HAWT. The uniqueness of this design comes from its telescoping guyed tower which would allow for easy transport and implementation. This design has a tower height of 40 meters a blade length of 17 m, and a rated capacity of 300kw.

Pros:

- High efficiency

Cons:

- Better for small-scale
- Complex design
- Low durability
- Not aesthetically pleasing

4.11 Design #10: Vertical Axis, 2-Blade, Multi-generator

Design 10 (Figure 24 in Appendix) is a 40 m tall, vertical axis, multi-generator wind turbine which has varying blade lengths at each 2-blade subsystem. Due to the nature of this design all control and power electronics would have to be encased in a separate area near the turbine structure.

Pros:

- Always in the optimal direction for wind capture
- Simple design
- Aesthetically pleasing

Cons:

- Low durability
- Low efficiency
- Better for small-scale systems

5 DESIGN SELECTED

This section contains the rationale for the selection of Design #6. This design was the highest ranked in a decision matrix due to its preferred characteristics that meet the engineering design requirements.

5.1 Rationale for Design Selection

All 11 generated concepts were qualitatively ranked in a Pugh chart (Table 5). The datum for the Pugh chart is the Siemens Gamesa 3.3 MW wind turbine. This turbine is a common off the shelf turbine intended for utility scale wind power plants.

Table 5: All Designs Pugh Chart

	Wind Turbine Concepts												
Selection Criteria	1	2	3	4	5	6		7	8	9	10	11	12
Cost	+	+	-	-	0	-		-	-	-	-	+	0
Simplicity	-	+	-	-	0	+		-	-	0	-	0	0
Efficiency	+	-	+	0	0	+		+	-	+	-	0	0
Aesthetic	+	0	+	+	+	0		+	+	-	+	-	0
Safety	-	+	-	-	0	0		-	-	-	-	0	0
Durability	-	-	-	-	+	+	Datum	-	-	-	-	+	0
Eco. Impact	+	0	-	+	0	0		+	-	0	-	0	0
Sum +'s	4	3	2	2	2	3		3	1	1	1	2	0
Sum 0's	0	2	0	1	5	3		0	0	2	0	4	7
Sum -'s	3	2	5	4	0	1		4	6	4	6	1	0
Net Score	1	1	-3	-2	2	2		-1	-5	-3	-5	1	0
Rank	2	2	6	5	1	1		4	7	6	7	2	3

The top five designs from the Pugh chart entered a decision matrix with weighted criteria, (Table 6). Designs #5 and #6 were the highest ranked due to their preferred attributes to meet or exceed the predetermined ER's. Efficiency, energy output, cost, and durability are important requirements that the system must meet or exceed.

Table 6: Top Five Designs Decision Matrix

Decision Matrix for Top Five Wind Turbine Designs											
Criteria	Weight	Design 1		Design 2		Design 5		Design 6		Design 11	
		Score (1-5)	W-Score	Score (1-5)	W-Score	Score (1-5)	W-Score	Score (1-5)	W-Score	Score (1-5)	W-Score
Efficiency	0.2	4	0.8	2	0.4	4	0.8	5	1	4	0.8
Asthetics	0.05	3	0.15	2	0.1	3	0.15	3	0.15	1	0.05
Durability/Maint.	0.35	2	0.7	1	0.35	3	1.05	5	1.75	2	0.7
Energy Output	0.2	4	0.8	3	0.6	4	0.8	4	0.8	4	0.8
Cost/Material	0.2	3	0.6	4	0.8	4	0.8	3	0.6	2	0.4
Total	1		3.05		2.25		3.6		4.3		2.75

Based on the criteria designs #5 and #6 are competitive with current wind turbine technologies. Design #6 ranked higher than others because of the lack of gearbox. As previously discussed, the gearbox accounts for most failures and maintenance required for wind turbines. Therefore, eliminating the gearbox reduces the energy losses (due to friction) within the system, and lowers the maintenance costs. Design #6 is the best fit to meet the customer needs and ER's due to its reliable and efficient, low cost design.

5.2 Design Description

The proposed turbine for the business plan consists of a mechanical design of a utility scale turbine. Power electronics and performance will be addressed at a future revision of this document. The mechanical design is composed of blades, a hub, a pitching system, a low speed drive shaft, nacelle, yawing system, and a tower (Figure 10).

Figure 10: Solidworks model of the design

The wind turbine was designed to provide a minimum power output of 3.5MW. The following sections provide further detail on the components and their analysis.

5.2.1 Tower Design Description

The final tower design selection is a tapered concrete-steel tower (Figure 11). This design was chosen over a regular steel tower due to being cost efficient. These hybrid towers are cost effective past 100 meters because of the ease of construction on site and using less steel. The tower height will be 120 meters. For ease of transportation and cost of manufacturing, the tower is divided into 20 meter sections. These sections have flanges at each section break that have 80 holes for bolts. The bolt analysis is yet to be done, but the bolts will be at least 0.2m in depth to go through the flanges and receive a bolt. The width of the bolts will be dependent on a finite element analysis to be able to withstand extreme conditions. The base of the steel section of the tower can be seen in Figure 11 below.

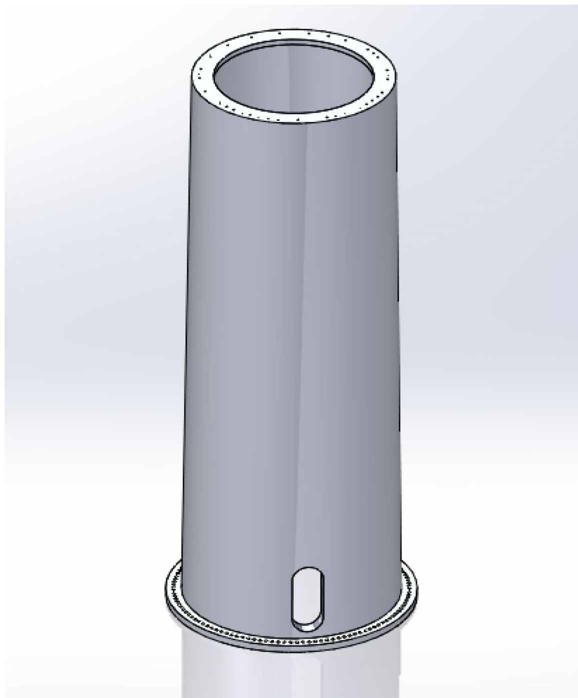


Figure 11: Base section of the tower design

The base of the tower also has a flange at the bottom that will allow for it to be bolted down to the concrete base of the tower. The concrete base is a tapered design treated as a tall foundation. It is 40 meters tall. This concrete base is shown in Figure 10 above. This will have 120 bolts since there isn't a space or access like the flanges within the tower. As with the bolts within the tower, the length and width required has yet to be determined. The hole in the base will be a door that allows access to the control systems within and a ladder that will go up to the nacelle. The material used for this tower design will be S500 Grade Structural Steel. This is a material used in most modern skyscrapers. This material is expensive, but when used in a large structure such as this turbine, it is cost effective and can use less material.

5.2.2 Blade Design Description

The selected blade is based on extruded profiles of S811, S809, S810 and a circular airfoil (Figures 11-13). The S811 and circular airfoils will be used to design the blade sections near the root of the blade.

Note that these profiles show a larger blade thickness as compared to the S809 and S810 airfoils. The larger blade thickness at the root is necessary to provide sufficient structural support for the large loads.

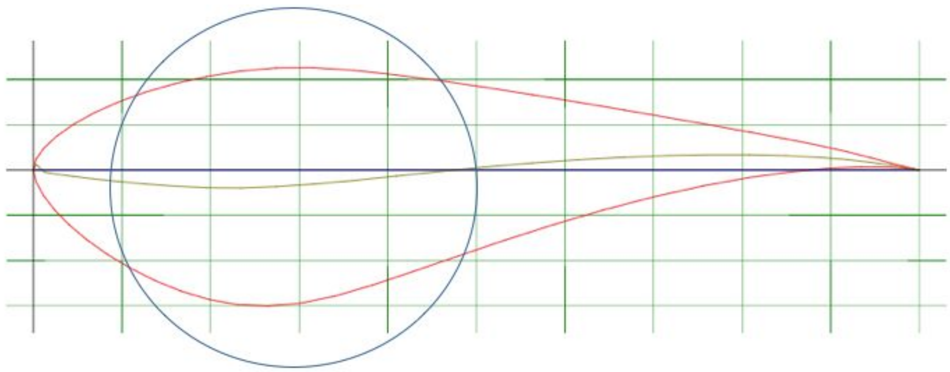


Figure 11: S811 and Circular Profile (Blade Root) [21]

The blade length was calculated to be 70m. This creates a 140m diameter rotor with sufficient swept area for a 3.5MW turbine. The primary length of the blade will be designed based S809 airfoil (Figure 12). The S809 airfoil has a smaller thickness than the S811 airfoil for improved performance along the primary length of the blade. Also, the stress concentrations will be larger at the root of the blade therefore requiring it to be larger at root. The stresses along the rest of the blade are not as large so the primary concern is performance.

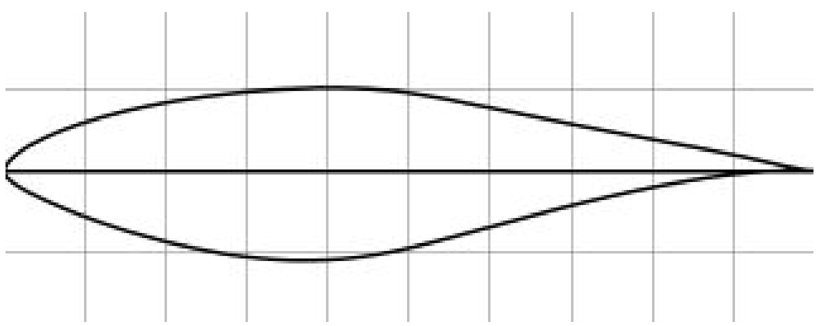


Figure 12: S809 Airfoil Profile (Primary Blade Length) [21]

The blade section near the tip of the blade will be designed based on the S810 airfoil (Figure 13). Note that the left edge of this profile is thinner than the previous two profiles. The thinner profile allows for better performance at the tip of the blade. Also, the tip of the blade carries little load for which structural strength is not a concern.

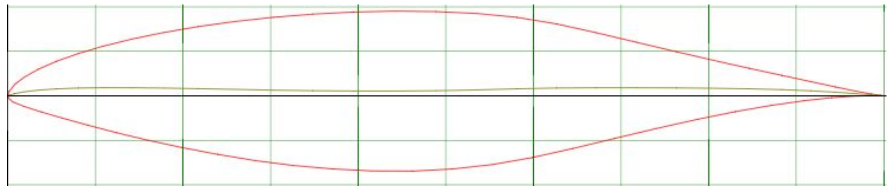


Figure 13: S810 Airfoil Profile (Blade Tip) [21]

To withstand blade stress concentrations which result from bending and centrifugal forces, the root section of the blade's length is lofted from a root circle to an S810 airfoil. An analysis based on Blade Element Momentum (B.E.M.) theory was implemented and performed in the MatLab programming environment. The initial blade iteration was estimated to have a power coefficient of about 0.2. Utility scale turbines possess power coefficients that range from 0.4-0.5. Therefore, we recalculated blade parameters, resulting in changes of chord length, twist angle, and length of cylindrical root loft. The revised blade design possesses a power coefficient of 0.4771, well within the expected range of a utility scale blade design.

Finite Element Analysis (F.E.A.) was performed in the Solidworks CAD environment. We estimate thrust on each blade at wind speeds of 24 meters per second to be approximately 9500 N. The blade model is shown in Figure 14.

$$T = \frac{1}{2}\rho A V^2$$

$$where\ T = Thrust, \rho = density, A = area, and\ V = wind\ speed$$

Assuming the blade is composed of a Derlin 2700 NC010 acetal copolymer composite, the maximum von Mises stress is 142 KPa, well within the material's yield strength of 63 MPa, reference Figure 15.

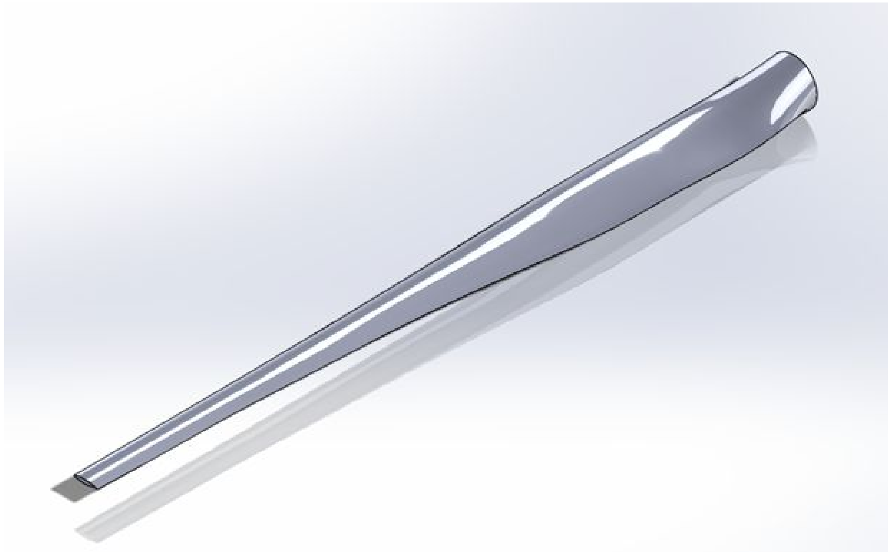


Figure 14: 3.5 MW Blade Model

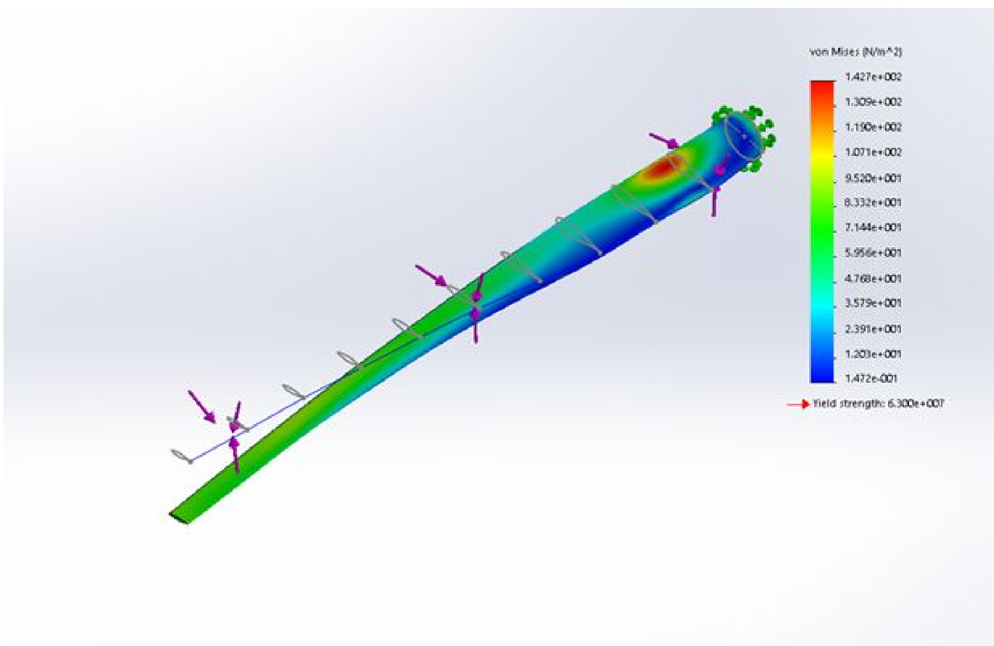


Figure 15: 3.5 MW Von-Mises Stress Concentrations

Many adjustments to design parameters remain to be determined. For example, we have yet to decide on the geographic setting in which this turbine will operate, and hence are not familiar with the design wind regime. As more business and siting decisions are made, the team will have more information upon which to make blade design decisions. The aforementioned decisions may affect the dimensioning of turbine components. When the geometry of the blade design is complete, the team will conduct another F.E.A., which will account for centrifugal as well as expected thrust loads.

5.2.3 Hub Design Description

The hub was designed to accommodate three blades of diameter 4 meters at the root, reference Figure 16. The hub-blade attachment dimensions were driven by the designed blade. The hub will be secured to each balde by use of 50 large bolts. The hub also allows for the shaft to be attached at a 3.5 meter diameter, reference Figure 17. The attachment to the shaft will also consist of 100 large bolts. The material selected for the hub is AISI 4130 Steel, annealed at 865 degrees Celsius and aluminum for the front end of the hub. The steel was selected based on its desired yield strength of 460 mpa and relatively low mass density of 7850 kg/m^3 as compared to other steels of similar yield strength. Aluminum was selected for the front end of the hub since this does not need to withstand large loads and the material helps reduce the weight. It is essential for the hub to be able to withstand the loads from the blades and also the shaft; Therefore, a high yield strength material is required for this part. The mass density is also important since this part will need to be delivered to the top of the turbine tower via a crane.

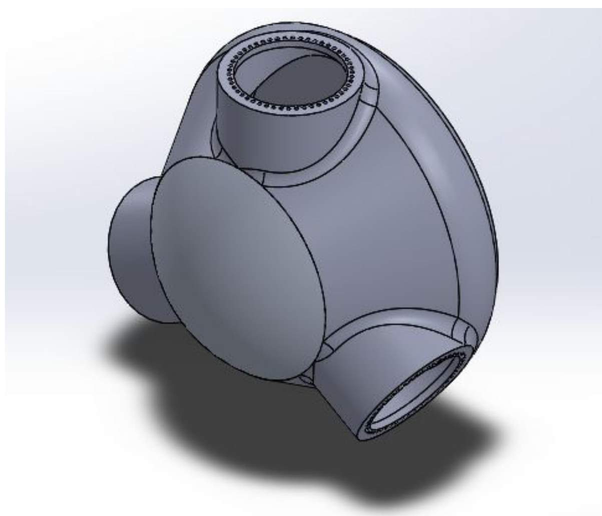


Figure 14: Hub-Blade Attachment

Figure 15: Hub-Shaft Attachment

5.2.4 Yaw Design Description

An active yawing mechanism was determined to be the best fit for the selected scale. A slewing ring bearing with an internal gear will be attached to the nacelle base and mounted to the tower tip mounting station. Two motor gears will be attached to the nacelle and link up with the teeth along the inside of the bearing. The wind direction will be tracked using a wind vane sensor. Every ten minutes, a circuit board will analyse the wind direction data of the wind vane and determine the average direction of the wind. The circuit board will then turn the motors linking the nacelle to the bearing and rotate the turbine to that direction.

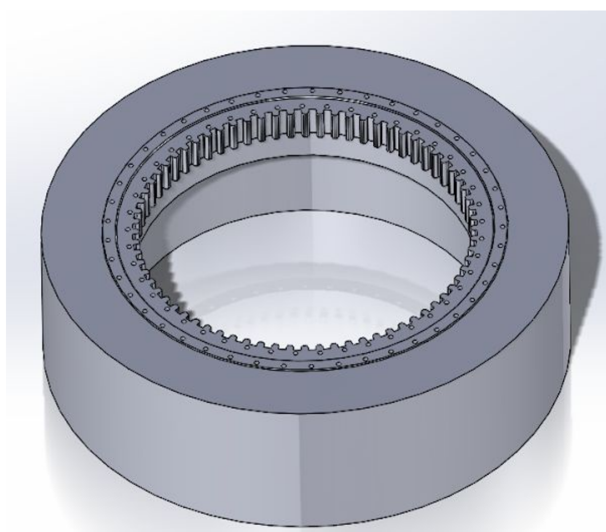


Figure 16: Tower Tip Mounting Station

The tip of the tower will have a plate extended along the interior to act as a mounting station for the slewing ring bearing. The inner ring of the bearing will be mounted along the bars of the tower mounting station while the external ring will be bolted to the nacelle.

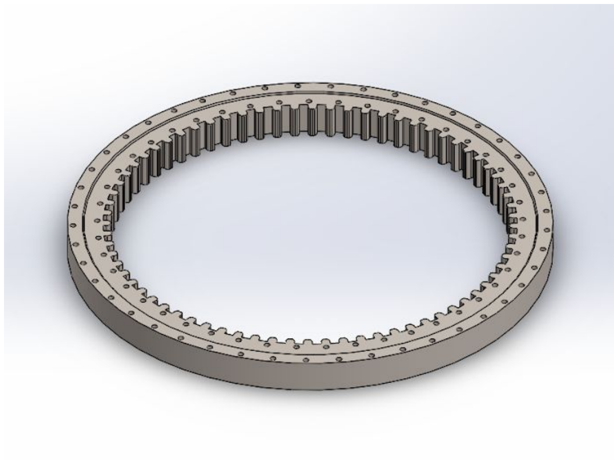


Figure 17: Yaw Bearing

The bearing displayed in figure 17 is a top-level design of the bearing that was selected for the turbine. The bearing chosen for this design was a triple row cylindrical roller combined slewing bearing. This bearing was chosen because the design would be able to most effectively support the weight of the nacelle while adequately reducing the force needed for rotation.

5.2.5 Shaft Design Description

A wind turbine's shaft transmits the torque generated from the blades to the generator. There are two ways to transmit this torque, through a gearbox, which converts the torque into a higher speed, and through a directly driven system. We chose a direct drive system because of the high maintenance costs associated with gearbox replacements (Figure 17).

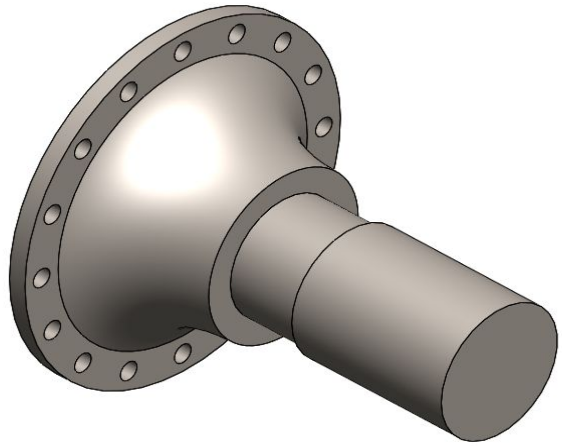


Figure 17: Shaft Design

This first iteration design is made from AISI 1040 steel because of its desired properties. This design has a fatigue factor of safety of 1.03, and a yield factor of safety of 1.29, where these values were found in an excel algorithmic workbook. The exact dimensions of the groove thicknesses and bolt holes will be finalized with a FEA in SolidWorks. This will also help improve the factors of safety of the final shaft design.

5.2.6 Nacelle Design Description

The nacelle main frame is the backbone of the full design. The mainframe will be constructed from AISI 1020 plate steel. This material was chosen utilizing the mainframe analysis conducted using Matlab. The analysis allowed the team to adjust material, as well as dimensions to review maximum shear and bending moments on the mainframe. Through this analysis the team found that the AISI steels yield strength of 352 MPa performed best, while still keeping cost low. AISI 1020 can be ordered as sheet steel with the appropriate thickness for the base plate. This allows for the team to keep manufacturing cost low as well. The mainframe has a length of 15 meters, and is 7 meters at its widest part, and features a cover which is constructed from 1060 aluminium to keep weight down, while still being structurally sound (Figure 18). This current design also incorporates a single mount for the shaft's support bearings, in order to accommodate the system's direct drive set-up.The mainframe attaches to the yawing system via forty M30 bolts to minimize structural deformation from the forces exhibited on the component.

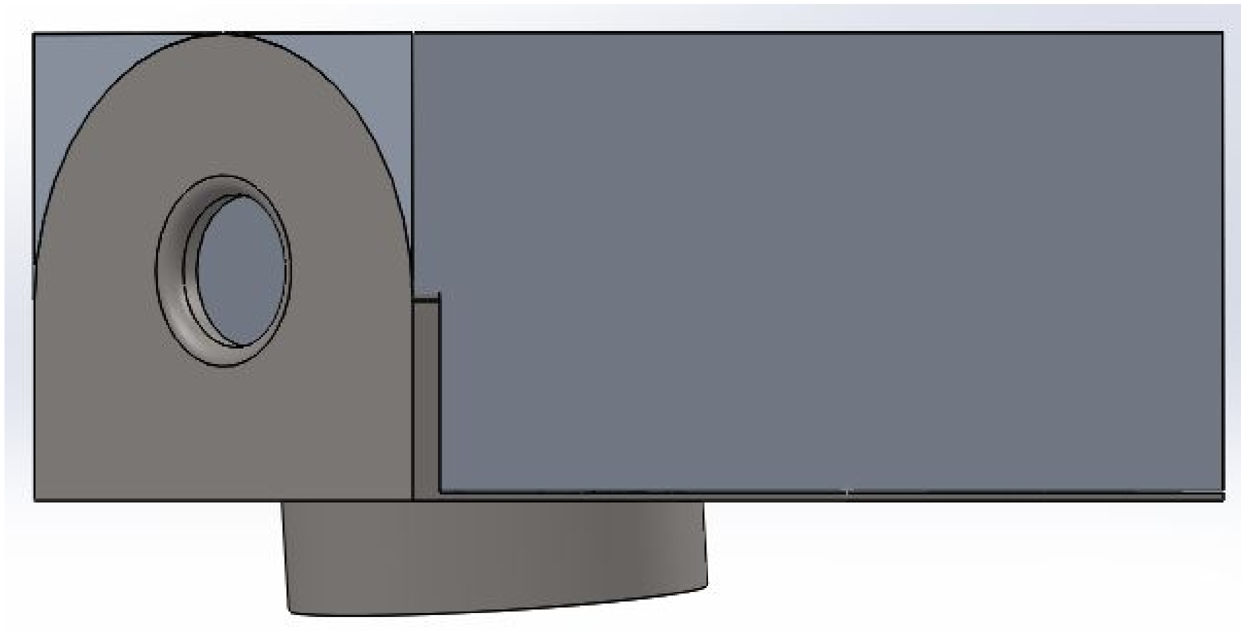


Figure 18: Mainframe Design

6 PROPOSED DESIGN

The market team is designing a utility scale turbine that meets the needs of a market. The proposed design is a 3.5MW turbine to be deployed in a location in Texas. With this conceptual design, a scaled prototype will be created showing the primary mechanical components of the design. Components that will be modeled include the blades, hub, nacelle, tower and yawing mechanism. The prototype will be used as display during the competition in Chicago, and will appear similar to the first iteration design (Figure 19). Depth analysis of the primary mechanical components will be performed to ensure viability of the designed turbine. Analyses to be completed include FEA for mechanical components and performance analysis of the blades by use of a BEM analysis.

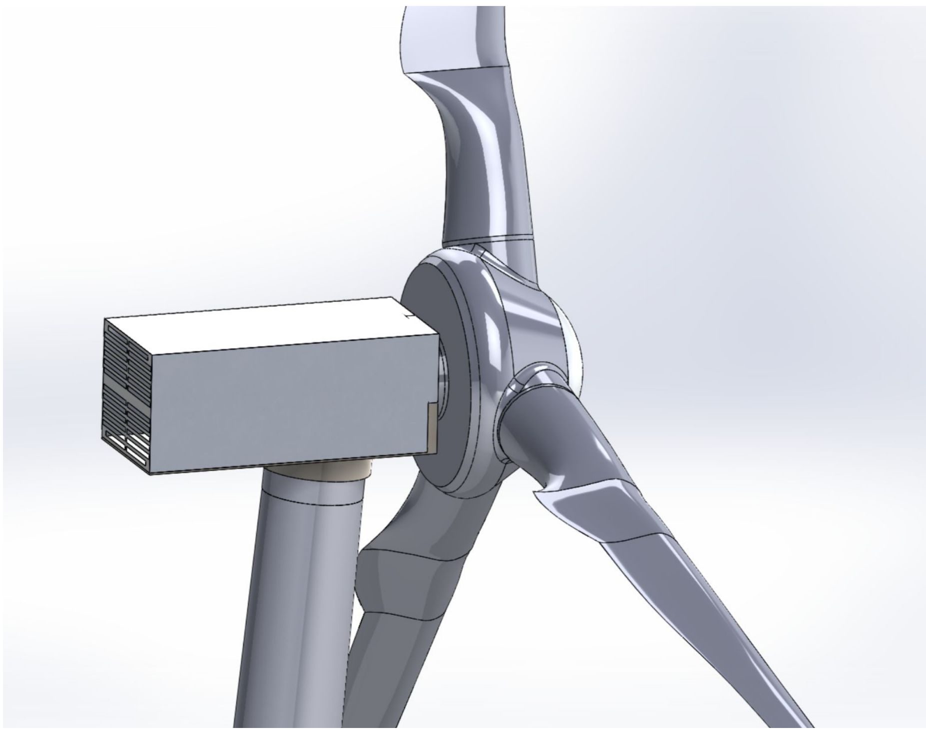


Figure 19: Hub View of the scale model

The prototype model will not be functional, but instead be a physical representation of the mechanical components as viewed from the outside of the turbine. This model will be made of four components: The blades, hub, nacelle, and tower (Figure 20).

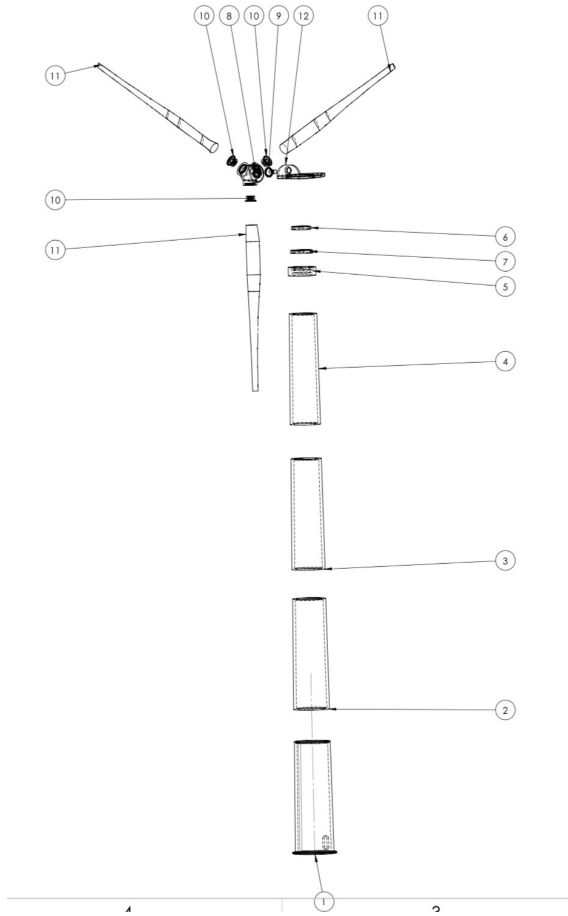
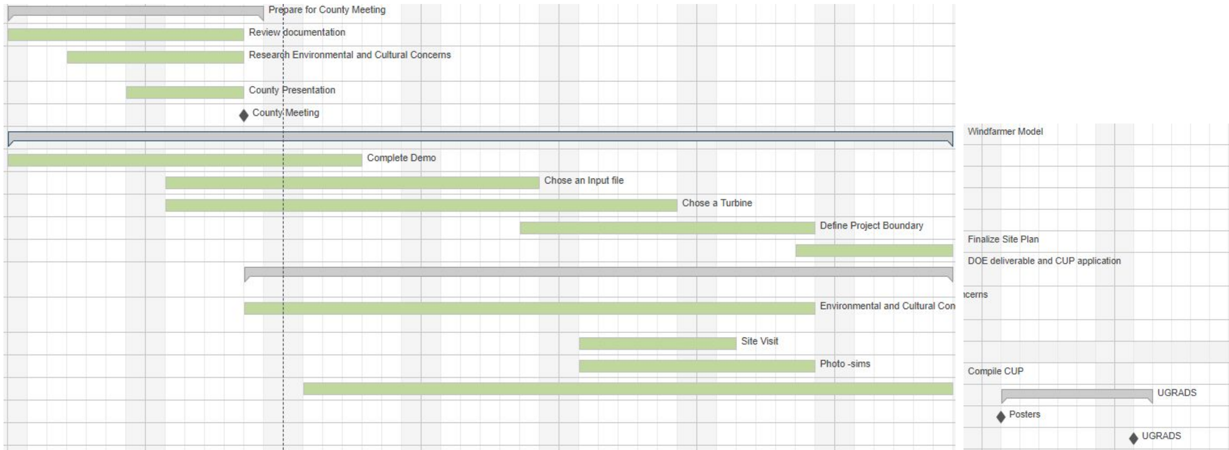


Figure 20: Exploded View of Prototype Assembly

Once the prototype is finalized, the team will begin to work on material and manufacturing selection for the small-scale display. This will most likely be made by 3D printing the parts and gluing them together. If possible, other options will be chosen to make the parts move. The 3D printing process will take place at the Cline Library's MakerBot studio which charges $0.10 per gram of filament used. The total price of the prototype will be dependent on the volume and scale decided next semester. The team will also start to research and design the electrical components and power electronic equipment needed to use a utility scale wind turbine. These electronics will allow the pitching and yaw systems to move as well as turning the mechanical rotation to usable electricity. The power electronics will also allow the electricity to be put into the grid and the decided storage component for the competition.

6.1 Schedule and Budget

A schedule for implementation of the project has been created with the ultimate goal being the Siting Challenge to be delivered to the Department of Energy. The Gantt Chart in Tables 7 give details regarding all tasks that will need to be completed to accomplish the main deliverable for the project.



Tabe 7: Gantt Chart for Spring 2018

A budget has also been created for the market team. The major expenses for the team will be the 3D printing of a scaled prototype (Table 8) and travel expenses for the competition (Table 9). The scale prototype will be used for demonstration purposes at the competition in Chicago.

Table 8: Market Team Prototype Expense

3D Print Model Costs		
ABS (g/cm^3)		1.05
Print Cost ($/gram)		0.10
Volumes		Units
Blades (3)	600	cm^3
Nacelle	200	cm^3
Tower	628.32	cm^3
Base Plate	96	cm^3
Hub	62.83	cm^3
Total Volume	**1587.15**	**cm^3**
Total Cost	**166.65**	**$**

The overall cost of the prototype is anticipated to be $166.65. A total of $400 was allocated to the 3D printed model from the DOE fund for this year's competition. Fundraising events are ongoing to cover the remainder of the travel costs.

Table 9: Market Team Travel Budget

Travel Budget Collegiate Wind Competition Market Team 2018					
Description	**Type**	**Unit Cost**	**Quantity**	**Amount**	**Notes**
Flight on Delta/United	Transportation	$256.00	3	$ (768.00)	3 Students: depart 5/7, return evening of 5/10
Hotel at least expensive official conference hotel available ($240/night including tax)	Lodging	$240.00	2	$ (1,440.00)	3 students, 2 Students per room, 2 rooms total:
Flag to PHX shuttle and return shuttle to Fla	Transportation	$ 96.00	3	$ (288.00)	3 Students
shuttles or trains in Chicago	Transportation	$ 80.00	3	$ (240.00)	Per person estimate: 3 students train to Hotel Monday and shuttle back to airport Thurs
Food not covered by event	Food	$120.00	3	$ (360.00)	$30 per day per student, 4 days (Mon -Thurs)
Total Cost				**$ (3,096.00)**	
ASNAU AWARD				**$ 750.00**	
Balance costs				**$ (2,346.00)**	
Undergrad student travel award (3 teams going to		$1,100		**$ 366.67**	Award is being shared in 3 equal parts.
ME Department travel award		$200		**$ 600.00**	$200 being awarded per student
Karin's Travel Fund		?		**?**	
Fundraising at Bigfoot and Pay n' Take		?		**?**	
Remaining Costs to Cover				**$ (1,379.33)**	

7 Implementation

7.1 Utility Assessment

In order to better understand how the proposed design will behave on an electrical scale, two simulink models are under construction that will simulate two situations. The first will be a simulation of how the proposed wind farm will interact with its local grid, and the second will be a simulation of the wind turbine's electrical system topology.

7.1.1 V2G Power Grid

In order to create a grid simulation for the business proposal, the team has been studying an example model pre-programmed into simulink that shows a small grid system that implements a wind farm, a solar PV farm, and a diesel generator to provide electricity to a load represented by a small town. The original V2G model can be seen in Figure 21 below. The example was chosen because the simulation also implements a vehicle-to-grid (V2G) electric car charging system, a system that explores the idea of using electric vehicles as batteries for the grid. The V2G element of the example held no significance to the proposal, however the pre-programmed electric vehicle charging system proved a great help in creating the simulation. To adjust the V2G example into something that more closely matches the business plan, the V2G element of the charging system is able to be disabled. Since the business proposal also doesn't include photovoltaics, the PV farm is able to be set to 0% efficiency or deleted. The power inputs and outputs from the generating stations and load can also be adjusted to suit the proposed destination of west Texas.

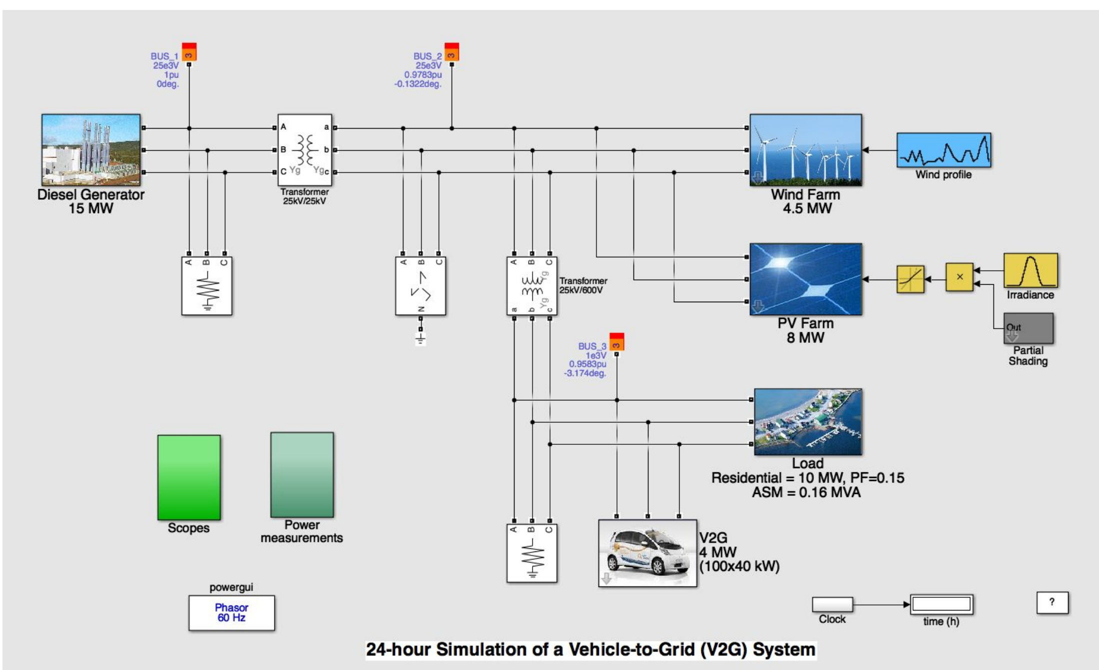


Figure 21: Simulink Grid Simulation

The next step in the process was to make assumptions and apply them to the simulink model for western Texas. The first assumption made was that the proposed wind farm would be connected to an isolated grid, when in reality the energy from this farm would be sold to different locations throughout Texas as well as other states. The next assumption was that the non-renewable energy from the grid system was strictly coal and diesel power supplies. This assumption allowed for the ability to ramp the power plants up and down as they are treated as asynchronous machines. It also allowed for a more simple model rather than trying to design nuclear power plants, hydro plants, etc. After these assumptions were made, the characteristics of the grid had to match the assumed population. The population was set to about 200,000 homes which uses about 150MW of power. This assumption allowed for the load block of the model to be set to 150MW. The other block modifications included 1000 electric vehicles with varying characteristics if the vehicle battery storage is desired, a 100MW wind farm, 200MW of coal and diesel power generation, and no generation from PV farms. The modifications to the grid can be seen in Figure 22 below.

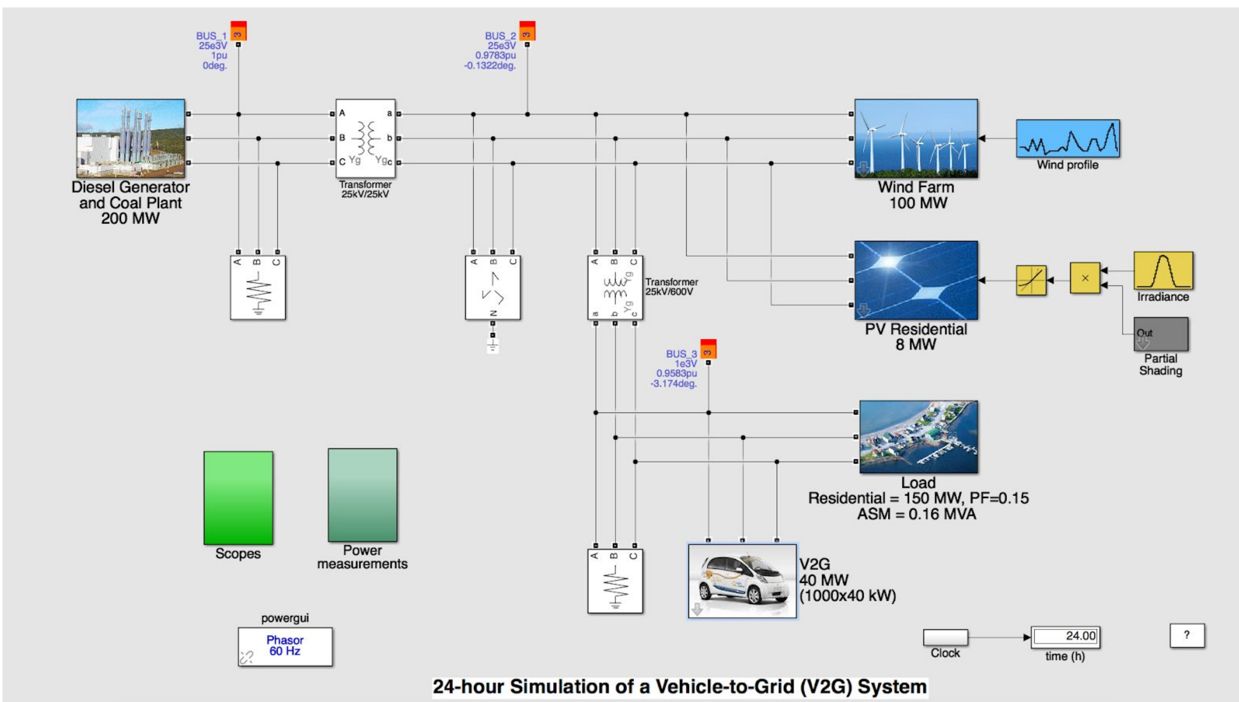


Figure 22: Modified Simulink Grid Simulation

There are several issues occurring with modifying the grid. The first implication is that the transformers and electrical line limits are too low. This means that the transmission lines on the grid are not rated high enough for the amount of energy transferring through. The other problem with this is that the transformers are stepping down the voltage too much. Fixing these errors are part of the tasks still in progress. Once the grid is working without errors, the next step is to understand what the outputs and scopes mean. These diagnostics and understanding are set to be complete by March 25

7.1.2 Electrical System

In order to predict the necessary electrical components for constructing the wind turbine, a simulation of the turbine's electrical system will be constructed using simulink. The simulation will follow the flow of energy as it travels from the generator, through any inverters and transformers that may be needed, and into the grid. The market team will be working closely with the electrical engineers on the test team in order to create this simulation. Construction for this simulation is still in the preliminary stage and is expected to start on March 26, 2018.

7.2 Resource Assessment

To understand how the proposed design will behave on the selected deployment location, a resource assessment of the site was performed. The selected site for deployment is west Texas as shown in Figure 23. The site has a wind resource averaging wind speeds of about 9m/s at a height of 80m above ground. The resource assessment was used in conjunction with the turbine's performance data to understand the power output of the proposed design.

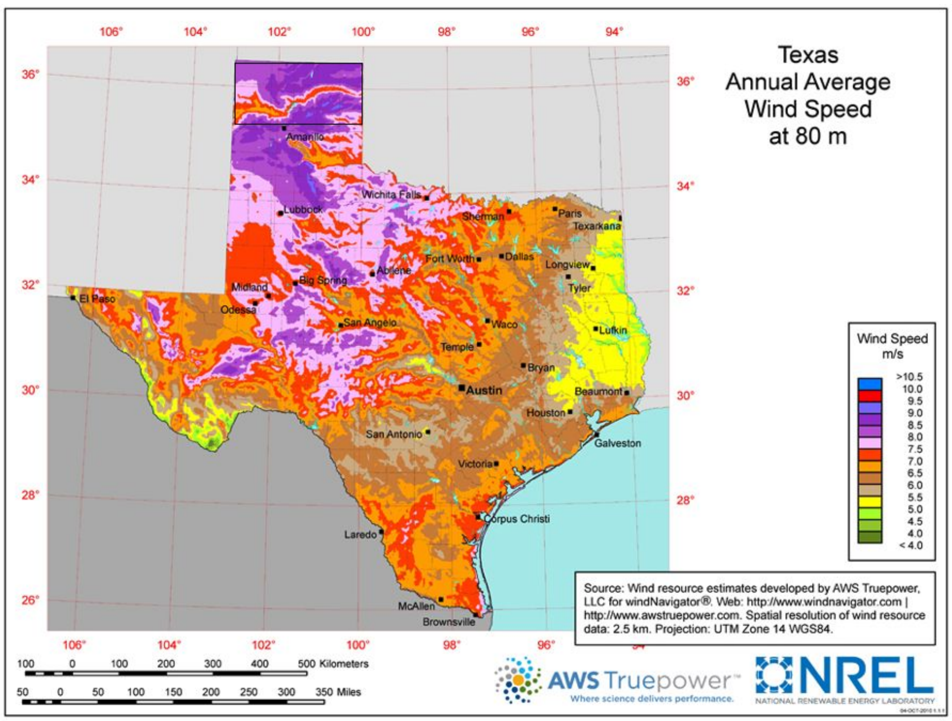


Figure 23: Turbine Deployment Location [22]

7.3 Turbine Performance

A Cp vs Tip Speed Ratio curve was created to understand the system's power coefficient, reference Figure 24. The curve indicates a maximum power coefficient of 0.45 when the tip speed ratio is about 7.5. To elongate the life of the turbine, reduce noise impact, and reduce impact to flying wild life the turbine will be limited to a maximum tip speed ratio of 6 (Cp=0.39).

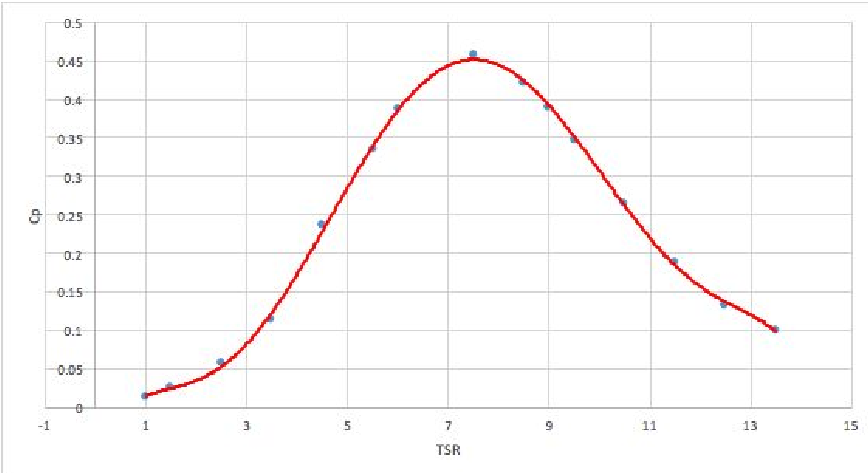


Figure 24: Cp vs Tip Speed Ratio for 3.5MW Turbine

Given the design tip speed ratio of 6 and Cp value of 0.39, a power curve was created for various wind speeds (Figure 25). The power curve demonstrates a rated power of about 3.9MW after reaching wind speeds of 10m/s. Given the resource assessment in Figure 22 at a height of 80m, average wind speeds of about 10m/s are achievable at a hub height of 120 meters. After reaching average wind speeds of 10m/s, the system operate at the rated power (by braking) to prevent damage to the trubine.

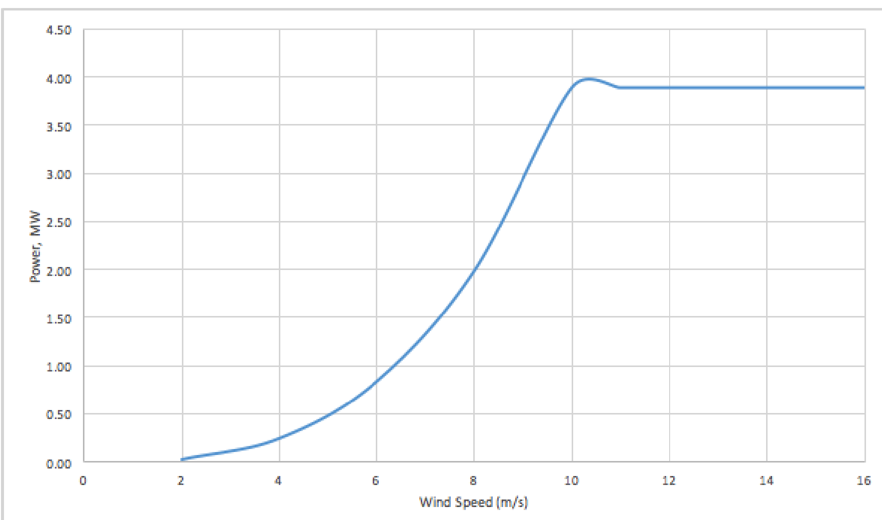


Figure 25: Power vs Wind Speed

8 Testing

9 Conclusions

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9 APPENDIX: Designs considered figures

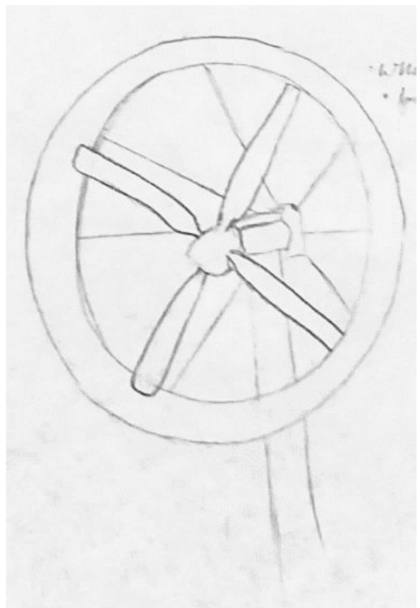

Figure 21: Upwind HAWT with wind shroud

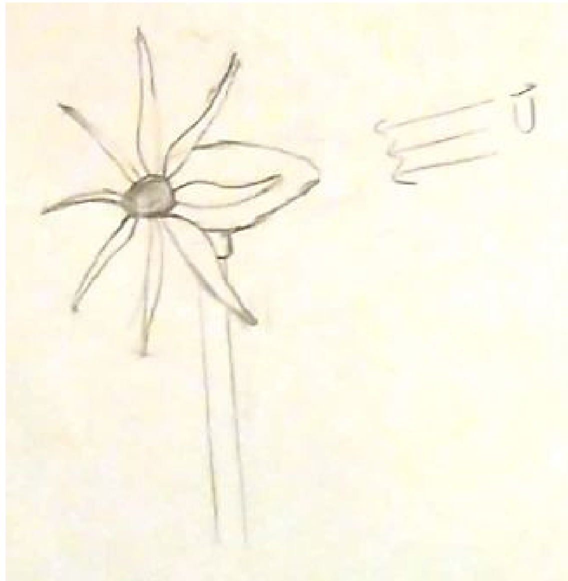

Figure 22: Eight blades, downwind, with 3-stage gearbox

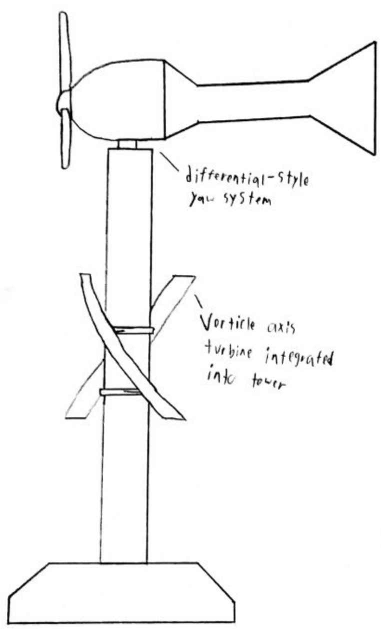

Figure 23: HAWT with Vertical Axis Wind Turbine

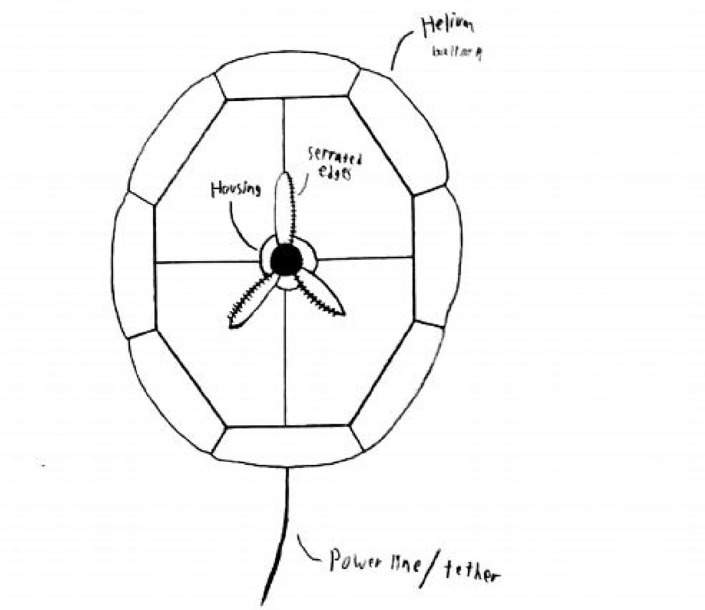

Figure 24: Floating Turbine

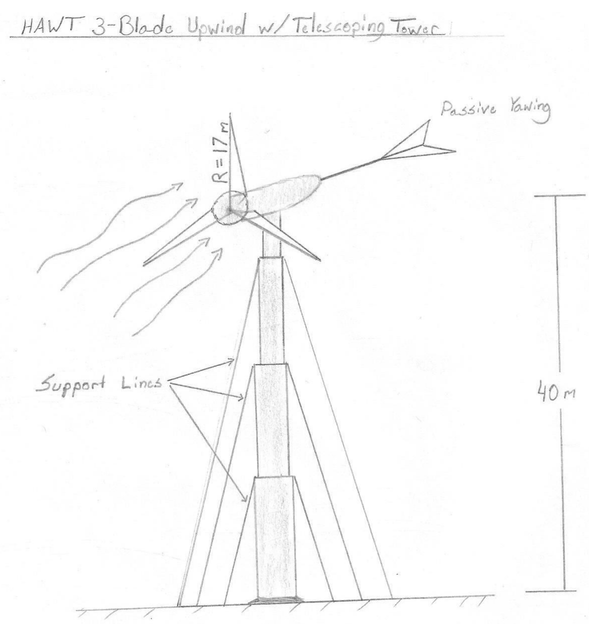

Figure 25: Horizontal Axis, 3-Blade Upwind, Guyed Tower

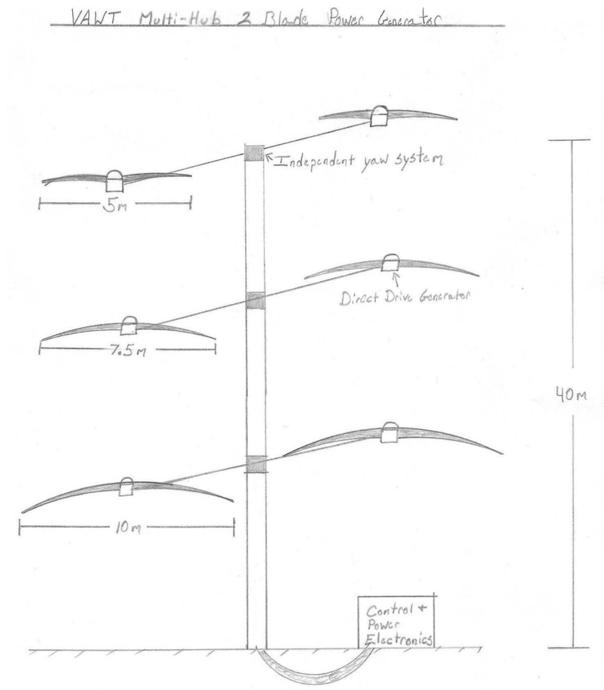

Figure 26: Vertical Axis, 2-Blade, Multi-generator