Collegiate Wind Competition: Deployment Team

Final Proposal

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DISCLAIMER

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1 BACKGROUND

1.1 Introduction

Wind power is continuing to grow and gain popularity in the United States and internationally. By the beginning of 2015, approximately 66 gigawatts of wind energy capacity had been installed in the U.S., enough to power 18 million homes. This equates to wind constituting 4% of the nation's energy supply, with continued growth predicted in the future. Some states, such as Iowa and Minnesota, have up to 20% of their energy needs met with wind power today. With this large penetration of wind and continued growth in the future, qualified individuals are needed to fill jobs both nationally and internationally.

In order to help facilitate the creation of these qualified individuals, the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) partnered to create the Collegiate Wind Competition (CWC) in 2014. The goal of the competition is to, "catalyze the timely, material, and efficient transformation of the nation's energy system, secure the United States' leadership in clean energy technologies, and maintain a vibrant domestic effort in science and engineering as a cornerstone of economic prosperity" [1]. In simpler terms, the competition was created to give college students from multiple disciplines real-world experience to prepare them for work in the nation's wind industry.

After competing in the inaugural competition in 2014, Northern Arizona University (NAU) has again been giving the opportunity to compete in 2016. Thus, a team of engineering and business undergraduate students have been formed as the representative team for NAU. This large team is broken into three groups; the tunnel team will build a scaled down turbine for testing, the deployment team will develop a small wind turbine design for market, and a marketing team will develop a business plan for the deployment turbine. This specific report is in regards to the work done by NAU's deployment team.

Specifically, the deployment team is designing a small scale wind turbine that is marketable to either an existing or new business market, as selected by the team. A small scale wind turbine generates power in range of 1-100 kilowatts (kW). The specific generation size of the turbine will be dependent on the selected market. As such, the deployment team is responsible for performing market research to determine a feasible market, then design a turbine specifically for sale in that area.

1.2 Project Description

Following is the original project description from the organizers of the competition, the DOE, located on page 3 of the rules and regulation document provided for the competition [1].

> *The competition challenges interdisciplinary teams of undergraduate students from a variety of academic programs to offer unique solutions to complex wind-energy-related problems. To fulfill the requirements, each team must perform the following multifaceted tasks:*
>
> ***•Develop and deliver a market-research-supported business plan that shapes the design and development of the team's turbine and load into a marketable wind power system.***
>
> ***•Prepare a deployment strategy by identifying a project site for the team's power system and developing a plan based on siting constraints and expected challenges.***
>
> ***•Design, build, and present a unique, wind-driven power system based on market research*** *and test the wind turbine and corresponding load in an on-site wind tunnel.*

> ***The Collegiate Wind Competition 2016 focuses on the design and construction of a wind-driven power system that can supply electricity to non grid-connected device(s).*** *Specifically, competition participants will need to create:*
>
> *•A mechanical, electrical, and aerodynamic turbine design that is safe, reliable and effective.*
>
> *•A load system that represents a real-world need, can match the power being generated, and visually indicates the power being generated. The competition does not prescribe a power system market or wind regime.*

Note that the bold sections in the provided project description are the items relevant to the deployment team. This is because the deployment team's purpose is to develop a turbine design for marketing. To accomplish this, the deployment team, which consists primarily of engineering students, will work closely with a team of business students. Some collaboration will need to occur between the deployment team and the tunnel teams as well. The tunnel team will be building a turbine prototype for testing in a wind tunnel at the competition, which must be linked mathematically to the deployment turbine. Further requirements for the project will be discussed in Section 2.

1.3 Original System

This project involved the design of a completely new wind turbine system. Although NAU had designs from previous competitions, some key changes in the rules and regulations for the competition in 2016 prompted a completely new design. Because the past designs did not function properly in their final iterations, they are only being used in preliminary research.

The previous turbines utilized a horizontal axis 3 blade design, which will be emulated in this design of the turbine. Some problems encountered with the past designs will also be taken into consideration, such as the failure of the power electronics systems, high cut-in speeds, and mechanical/blade failures that occurred during the testing. Such input will hopefully help the team avoid such issues in this design.

2 REQUIREMENTS

2.1 Customer Requirements (CRs)

In order to create a successful product design for the competition, the deployment team will be responsible for designing and modeling a wind turbine that could be marketed upon completion of the project. This will include the utilization of various software packages to analyze expected loads and factors of safety on the turbine design, as well as expected turbine output at different wind speeds. Breaking down these requirements, the following list of customer requirements (Table 1) is created with weights corresponding to their importance in the successful completion of the project. Customer requirements refer to what the customer (in this case the DOE) wants out of the final product. Because of the competition nature of this project, the specific customer requirements were developed by students to best meet the general requirements given by the DOE as well as help the design appeal to the targeted market.

Table 1 – Customer requirements for NAU deployment team

Customer Requirement	Weight (total = 250)	Description/Importance
Mathematically linked to tunnel team's prototype turbine	49.5	This ensures that the tests performed on the prototype turbine can have some importance to the business plan, thus linking the whole project together
Energy production estimation	36.25	Will show how much power the turbine will produce under different wind conditions, determining turbine placement for profitability
Wind flow modeling	31.25	Will show the loads on the turbine components and tower, showing safe usage conditions of the turbine
Climate establishment	31.25	Determines the climate that the turbine will be operating, to better design for possible weather or climate effects on the turbine
Uncertainty in wind resource assessment	27.5	How often does the wind vary from year to year? This will help determine the profit of the turbine throughout its lifespan
Installation of turbine	26.5	Ease of installation of the entire turbine system will reduce initial costs for the buyer, making the design more desirable
Turbine operation and maintenance	21.25	Ease of turbine maintenance and operation again reduces costs to the buyer making it more desirable. (i.e. it can be serviced by a local rather than a specialist)

These requirements are based off of the rules and requirements for the competition. As the school year continues, we expect these initial requirements to evolve as the team's understanding of key concepts and components involved in the project improves.

2.2 Engineering Requirements (ER's)

Section 2.5 depicts the House of Quality (HoQ). A HoQ is used to prioritize engineering requirements based on the customer needs. Each need is weighted by the correlated importance of the customer need. Thus, the engineering requirement can be better understood. This thereby places the engineering requirement in a cue for importance when the designing process is commenced. Below is Table 2 which shows the arrangement of each engineering requirement in the proper order of importance, where 1 has the highest priority. Each engineering requirement has a tolerance between in which values can fall and still meet the needed requirements. Tolerances are important, as in manufacturing there will always be slight deviations in parts created, and the tolerance tells if they fall within a useable range or not. Importance is calculated for each engineering requirement using the following equation:

$$\sum_{i=1}^{n}(customer\ requirement)_i * (engineering\ requirement)$$

Where i represents a weight in the list of customer requirements and starts at the beginning of the list and ends at n, which represents where the list ends. Each weight is then multiplied by the corresponding importance regarding the customer weight. This final sum represents the relative importance of the engineering requirement. Each engineering requirement can then be interpreted by the designer as to the absolute importance of the requirement.

Table 2 –Engineering requirements

Importance	Engineering Requirements	Target Tolerance
1	Tower height	60 m
2	Wind climate deviation	5 %
3	Rated wind speed	11 m/s
4	Efficiency loss	30 %
5	Mathematical model with QBlade	72.5 %
6	Cut in wind speed	4 m/s
7	Cut out wind speed	28 m/s
8	Aerodynamic efficiency	40 %
8	Number of blades	3
8	Tip Speed Ratio (TSR)	7
11	Component efficiency loss	18.5 %
12	Capacity factor	30 %
13	Installation cost	$900
14	Leveled cost of energy	6 ¢/kWh
15	Rated power	3 kW
16	Lease agreement	5 years

According to the table above tower height is the most important engineering requirement. This is because the height of the wind turbine will dictate how much power will be available to the turbine. A general wind profile for anywhere in the world is that the closer to the ground you are, the more wind turbulence will be encountered and less strong the resource will be as a whole. Second is wind climate deviation, which is wind profile the turbine will be subject to. Third, the rated wind speed, is the speed of wind the wind turbine blades are designed to operate at. Higher rated wind speed means the turbine produces more in high winds, but may take longer to start up in lower speeds. Next are wake effects, which are the reduction in wind speed and increase in turbulence that occurs downstream of a wind turbine. In projects involving more than a handful of turbines, wake effects typically reduce power production by anywhere from 3% to 15% per turbine.

Moving on to modeling with Q-blade, this software is used to calculate loads on the turbine blades during operation and the effects of wake on the turbine's performance. As such, the models used in this software will be a huge driving factor behind design decisions and must be accurate.

Next is cut in wind speed. This is the wind speed necessary for a wind turbine to start producing energy from stop. In the lower wind speeds seen by small-scale turbines, this cut in speed becomes a critical factor in determining the profitability of the turbine. The cut out wind speed on the other hand is the wind speed at which the turbine will stop functioning so components are not damaged from excessive wind speeds. The aim is to make the cut out speed as high as possible without causing any damage to the turbine.

Then the aerodynamic efficiency, also known as the coefficient of power (C_P), must be considered. This C_P describes how much energy the design can efficiently extract from the wind. This efficiency is governed by the Betz limit, which states that the max power that can be extracted from the wind by any wind turbine design is 59%. Most turbines fall into the range of 30-40% efficiency due to mechanical and electrical losses. A greater number of blades can increase this aerodynamic efficiency to get closer to 59%, but also adds significant cost. As such, the smallest number of blades possible for proper performance will be used.

Tip speed ratio (TSR) is the ratio of the tip of the blade's speed to the incoming free-stream wind speed. The higher the tip speed ratio, the closer the coefficient of power (C_P) can approach the Betz limit of 59%. The total efficiency is the aerodynamic efficiency with loss factors taken into account. Losses occur in both mechanical and electrical aspects of the turbine, and are used to calculate total efficiency with the following equation.

$$L_{total} = 100\% - (100\% - L_1)(100\% - L_2)(100\% - L_3)\ldots$$

The capacity factor is the average power generated divided by the maximum power the turbine could produce. This relates to the profit margin of the wind turbine, as a higher capacity factor means the turbine is closer to producing its maximum power regularly. Also included in the profit calculations is the installation cost, which is the initial price for installation. Reducing this upfront cost maximizes the investment return on the design. Lastly are the leveled cost and rated power. Leveled cost is how much each kW generated by the turbine is worth monetarily, while the rated power is what the power output of the wind turbine expected to be at its rated wind speed. The higher the rated power, the lower the leveled cost of energy is for the consumer, which is why large scale turbines are generally more popular than small scale.

2.3 Testing Procedures (TR's)

To satisfy the engineering requirements, testing procedures were developed. The testing procedures included various software packages for mathematical, visual, and financial modeling.

2.3.1 Matrix Laboratory by MathWorks (MATLAB)

Matrix laboratory is a programming language that allows mathematical manipulations. This program was utilized to understand the various mechanics involved in the turbine. Matrix laboratory was programed with the following aerodynamic theories: Betz optimum rotor design with wake rotation and the Blade element momentum theory (1) [2].

Betz optimum rotor design allowed the team to choose the desired tip speed ratio, angle of attack, rotor radius, induction factors, amount of blade sections, and number of blades. By using the freedom of the Betz optimum rotor design with wake rotation, the team was able to calculate the following characteristics for each section of the blade, chord lengths, angles of relative wind, twist angles, section pitch angles, and solidity ratios (see Appendix-B for equation details). However, the Betz optimum rotor design with wake rotation does not account for all loss factors and is not perfectly accurate with aerodynamic coefficients. Thus, the blade element momentum theory was also programed and used.

Full utilization of the blade element momentum theory included using the chord lengths and twist angles from the Betz optimum rotor design with wake rotation. By using the ideal chord lengths and twists angles, the blade design could be optimized. The programed theory was used as an iterator, which will converge on an answer before yielding the proper coefficients of lift, drag, power, thrust, and induction (see Appendix-B for equation details). The obtained results are then compared to the QBlade analysis.

2.3.2 QBlade Analysis

In terms of blade analysis, QBlade will be used. QBlade is a graphical source interface (GUI) that simulates wind turbine blades under various design scenarios. QBlade also uses the blade element momentum theory with adjustable variable inputs (2).

The use of QBlade consisted of importing the MATLAB coding output of chord lengths and twist angles from the betz optimum rotor design into the program. Outputs from the QBlade analysis yielded similar results to the MATLAB version of the blade element momentum theory, validating the output of both.

In accordance to the blade element momentum theory, the von Mises stresses acting on the blade will be analyzed through the QBlade program. The visual representation of these stresses show how the turbine will respond to operational loads. These stresses will also be validated through comparison of von Mises stresses (FEA) preformed in SolidWorks. Figure 1 shows a von Mises stress distribution from QBlade.

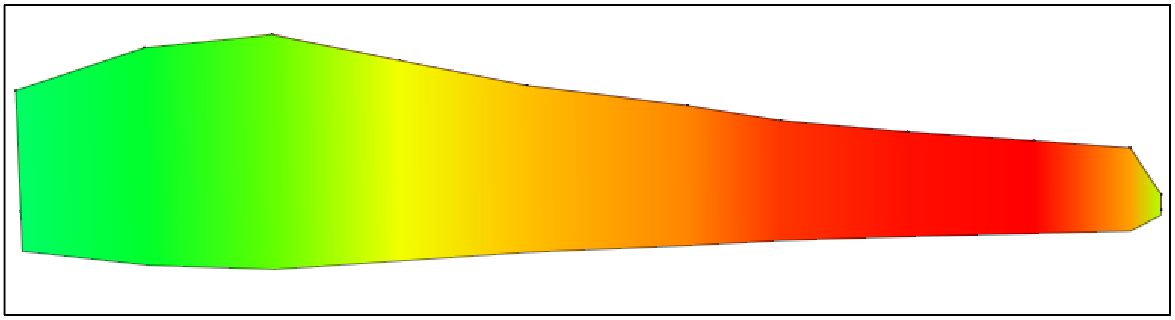

Figure 1: Von Mises stresses in QBlade

2.3.3 SolidWorks Analysis

Structural analysis will be performed with SolidWorks. SolidWorks is a computer-aided design (CAD) program that can perform von Mises stress analysis (FEA) on a created object, as well as produce manufacturing drawings. To perform the stress analysis on the blade design, the file from QBlade will be imported into SolidWorks. By importing the file into SolidWorks, the dimensions of the design will be consistent, thus yielding a more reliable comparison (3).

2.3.4 System Advisory Model (SAM)

Next, financial analysis will be performed in SAM. NREL's SAM program performs analyses for performance and financial capabilities for renewable energy devices or systems. For the performance and financial modeling analyses: dimensions materials, rated wind speed, and wind speed variations are used. These values coincide with outputs from QBlade analysis and MATLAB calculations. The wind speed variations are obtained from the meteorology and dynamics software (Meteodyn) (4).

2.3.5 Meteorology and Dynamics (Meteodyn)

Lastly, wind resouces assessment will be performed with meteodyn. Meteodyn is a software that uses computational fluid dynamics (CFD) to accurately measure wind speeds at various locations. The purpose of Meteodyn is to obtain the various wind speeds at the turbine's deployment location (5).

2.4 Design Links (DL's)

To ensure that engineering requirements are met a comparison of the results with the engineering requirements is performed. Note that the DL's below are numbered based on their relationship with the engineering requirements.

2.4.1 Tower Height

Tower height has been met at 60 meters by reviewing the heights of the telecommunication towers in India that the turbine will be placed on (1) [3].

2.4.2 Wind Climate Deviation

Wind climate deviation is still in review while the specific telecom sites are considered.This specific requirement requires analysis of every season at the telecom site to determine wind patterns and possible turbine output. These calculations will be provide in the final draft of the report (2).

2.4.3 Rated Wind Speed

Rated wind speed has been selected as 11 m/s. The value is plugged into MATLAB and QBlade for their analysis (3).

2.4.4 Efficiency Loss

Preliminary calculations have confirmed that the efficiency losses have been met at a loss of 20.69%. The calculation was performed using the percent error analysis with the design’s optimum coefficient of power at 11 m/s with the Betz optimum coefficient of power (4).

2.4.5 Mathematical Modeling

Mathematical modeling has been performed and met in the preliminary design. However, the tunnel turbine has yet to be completed. Since the tunnel turbine is still in development, a mathematical link between the two turbine designs cannot be established at this time (5).

2.4.6 Cut-in Wind Speed

Cut in has been calculated to occur at a velocity of 4 m/s. The engineering requirement was met by means of mathematical modeling as discussed in sections 2.3.1 and 2.3.2 (6).

2.4.7 Cut-out Wind Speed

Cut out wind speed has been estimated to occur at 25 m/s. However, this is currently not sufficient to meet the requirement. Further development will be done to add sufficient breaking and/or furling mechanisms to insure cut out wind speed requirement will be met (7).

2.4.8 Component Efficiency

Component efficiency loss has yet to be determined. Full analysis will be performed once additional components of the turbine are chosen and manufacturers specified (8).

2.4.9 Number of Blades

The number of blades was determined to be 3. This decision is explained later in the report, but this number of blades provides decent turbine performance without adding a huge initial cost to the design (9).

2.4.10 Tip Speed Ratio (TSR)

For the purposes of MATLAB and QBlade analysis, a max tip speed ratio of 5 was selected (10).

2.4.11 Overall Efficiency

Overall efficiency has yet to be determined, as it depends on components selected for the turbine. Once all components are selected for the turbine, an overall efficiency will be calculated (11).

2.4.12 Capacity Factor

Capacity factor has not yet been determined. The capacity factor will be calculated once a manufactured generator has been sufficiently match to the blade design. This will occur over the winter break (12).

2.4.13 Installation Cost

An installation cost has been estimated to be $840.00. The calculation was performed using SAM and meets the engineering requirement (13).

2.4.14 Leveled Cost of Energy

Once final siting parameters have been established and all components have been priced, SAM will be used for the calculations (14).

2.4.15 Rated Power

The initial rated power of the turbine has been calculated in QBlade to be 3.6 kW. This value meets the established engineering requirement (15).

2.4.16 Lease Agreement

The lease agreement rate has yet to be determined. Once the location perimeter is fully established, this will be clearly defined. This will occur near the end of the school year (16).

The next section, Section 2.5, contains the full house of quality and is located on the next page.

2.5 House of Quality (HoQ)

Customer Requirements	Weight	Engineering Requirement	Blades (#)	Tip Speed Ratio (TSR) (#)	Overall Efficiency (%)	Component Efficiency (%)	Capacity Factor (%)	Cut-in Wind Speed (m/s)	Rated Wind Speed (m/s)	Cut Out Wind Speed (m/s)	Rated Power (Watts)	Installation Cost ($/kW)	Leveled Cost of Energy (¢/kwh)	Mathematical Modeling (%)	Lease Agreement (yrs)	Efficiency Loss (%)	Wind Climate Deviation (%)	Tower Height (m)
1. Computer Modeling	5		9	9	9	9	9	9	9	9	9	9	9	9	0	9	9	9
2. Land Lease	3		0	0	0	0	0	0	0	0	0	9	0	0	9	0	0	9
3. Wind Flow Modeling	4		9	9	0	9	0	9	9	9	0	0	0	9	0	9	9	9
4. Uncertainty in Wind Resource Assessment	3		3	3	9	3	9	3	9	9	0	9	9	9	0	9	9	9
5. Energy Production Estimation	4		9	9	9	9	9	9	9	3	9	0	3	9	0	3	9	9
6. Climate Adjustment	4		9	9	0	9	0	9	9	9	0	0	0	9	0	9	9	9
7. Turbine Operation and Maintenance	2		0	0	0	0	0	0	0	0	0	0	0	3	0	9	9	9
8. Installation of Monitoring Stations	2		0	0	3	0	0	9	9	9	3	0	3	1	0	9	9	9
Tolerance(s)			3	#5-8	17-20%	40-59%	≥25%	≤5 m/s	± 2 m/s	± 3 m/s	± 2 kW	≤($)1100	± 4¢	±10%	5 yrs	± 10%	4-6%	60m
Target(s)			3	7	18.50%	59%	30%	1m/s	11m/s	28m/s	3 kW	$ 900.00	6¢	73%	5yrs	30.00%	5%	60m
Absolute Technical Importance			162	162	114.00	162.00	108.00	180.00	198.00	174.00	87.00	99.00	90.00	188.00	27.00	192.00	216.00	243.00
Relative Technical Importance			8	8	11	8	12	6	3	7	15	13	14	5	16	4	2	1
Testing Procedure (TP#)			1,2	1,2	4	1,2,3	4	1,2	1,2	1,2	1,2,3	4	3,4	1,2	NA	1,2,3	5	NA
Design Link (DL#)			9	10	11	8	12	6	3	7	15	13	14	5	16	4	2	1

3 EXISTING DESIGNS/MARKETS

3.1 Design Research

In order to research current designs in the wind industry, the team first had to narrow down the large span of markets that wind energy is involved in. Utility scale wind turbines provide power to the electricity grid, which residential homes draw from. These turbines can range from 1 megawatt (MW) to 10 MW of generating capacity. In comparison, small wind has a generating capacity of 1 - 100 kilowatts (kW). These turbines are often placed near residential homes or businesses to provide supplemental electricity to lower monthly bills.

The scope of this project focuses on the small wind market, which has numerous locations, technologies, and applications. Thus, the team performed market research within the scope of the small wind field. This was done using two textbooks. The first, “Wind Energy Explained; Theory, Design, and Application” by J.F. Manwell, J.G. McGowan, and A.L. Rogers [2] was used to gain an understanding of turbine component design to understand what information was needed in a target market. The second book, “Wind Resource Assessment” by Michael C. Bower [4] was used for a better understanding of how to determine the placement of a wind turbine and the data needed, again to help with background research of possible markets. Finally, Ross Taylor, an employee of Xzeres (a small wind company), provided input to the group as to potential markets that should be researched. With an idea of the knowledge that needed to be gathered, the team delved into market background research, primarily utilizing web sources.

3.2 System Level

The markets selected for the background research included off-grid wind in Hawaii, tele-communication tower energization in India, and rural village energization with no specific location. Each of these markets was chosen based on their ability to use small wind to meet current needs. In order to successfully market any product, there must first be a need for the product. Then, there must be some profit margin in that area for the business plan to make sense. Each of markets will be looked at in this sense below.

3.2.1 Existing Market #1: Off-Grid Hawaii

The first market that was researched was small wind, off-grid application in Hawaii. Hawaii has the most expensive average electricity bill in the U.S. as 91% of their energy comes from imported sources (i.e. heavy oil). The island chain produces approximately 788 GWhr of electricity, of which 660 GWhr come from imported fossil fuel, either petroleum or coal. Because of this, the islands have seen a large increase in rooftop solar systems over the past few years, as incentives and high electricity prices made project financing extremely affordable. However, recently the local government has put a stop to rooftop solar growth due to the high strain it puts on the grid with lots of power during the day, and none at night.

Despite this cutback, Hawaii has recently passed a plan that includes a push for full renewable energy by 2045. Small wind could be an answer to Hawaii’s plan while also not straining the grid as much as solar. Hawaii has an excellent wind resource due to the coastal winds in the region. Utility scale wind (greater than 100 kW) will have a hard time breaking into this market because they will be an eyesore on the coast line, but small wind would have less of a problem in this area. This, coupled with a large movement by Hawaii residents towards off-grid homes, will allow for small wind (1-100kW) to have a competitive advantage in this area. Also, wind in this area tends to blow day around, thus it won’t strain the grid as much as solar energy.

3.2.2 Existing Market #2: Tele-Communication

The second market researched was tele-communication tower energization. Currently in India telecommunication towers are powered by diesel generators, which produce greenhouse gases and are expensive to run. Recently president Modi, the president of India, has enacted stricter clean air policies to keep up with the new UN standards. While many of these existing telecommunication towers could be kept on diesel generator use, it would be more cost efficient to have a wind turbine power the tower. Wind power would reduce or eliminate the cost of fuel and having it transported to the tower.

Diesel generators are currently the main power source for telecomm towers, and are costly, inefficient, and emit high levels of carbon dioxide (CO_2) [5]. With wind energy, emissions will be reduced to zero and there is no fuel or fuel transport costs involved. Within the year 2015 there is a plan to install 1000 new telecommunication towers [6]. The goal is to retrofit these new towers with wind turbines to reduce pollution, provide free energy, and help to move the entire market in a renewable energy direction. With the large expansion planned for India's telecommunication industry, there is a great market for getting wind turbines to power telecommunication towers.

3.2.3 Existing Market #3: Village Energization

Providing rural villages in large population countries with electricity using wind energy is another market to consider. A small wind energy system has a high potential to generate power in off-grid systems. Since wind power is simple and fast to install, it will be ideal to use for rural villages. Atlantic islands of Canary, Azores and Cape Verde, are successful examples of small wind energy systems. China is another country that invested in wind energy to provide rural villages with electricity. China invested around $690 million in a program to supply 989 rural villages with electricity. This program is called the "Township Electrification Program" and it helped to supply 842,737 people with electricity. Note that 340,404 people out of the 842,737 got their electrical energy using photovoltaics and wind systems in 2008 [7]. Also, wind power growth rates increased by more than 100% in China between 2006 and 2009 [8]. Despite this, it should be considered that from a business standpoint, a village energization market is hard to justify. This is because such projects are normally funded out of goodwill, and as such cannot be considered a source of good revenue for a company.

3.3 Subsystem Level

In order to best serve one, or all, of these markets, the team must look at the key components that will need to be designed for the wind turbine system to operate effectively. These components consist of the turbine generator, blades, and control system. Blades are responsible for converting kinetic energy of the wind into mechanical energy, while the generator converts the mechanical energy into electrical energy. Lastly is the control system, which is responsible for the safe operation of the turbine and how the turbine relays power to the load. Depending on the target market, the design constraints for each of the components will change based on local climate, weather, and other factors. Figure 2 below shows the general layout of a horizontal wind turbine design. Note that in this specific picture, the rotor is directly connected to the generator.

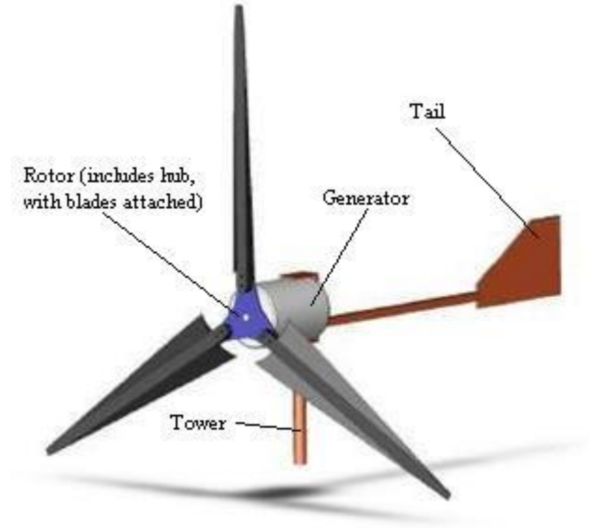

Figure 2: General turbine layout [9]

3.3.1 Subsystem #1: Blades

Blades are the most important component on a wind turbine, as they convert energy in the wind to mechanical energy. They are primarily made from composites, such as fiberglass or carbon fiber reinforced plastics (GRP or CFRP), but sometimes wood and epoxy laminates are used. The primary role of the blade is to harness the wind's kinetic energy and convert it into mechanical energy. When it comes to types of wind turbines, there are three main kinds: drag, lift, and mixed. In respect to the deployment team, the blades must be designed similar the tunnel team's in this regards, but designed for a larger scale turbine. Figure 3 below shows how the turbine blades generally work.

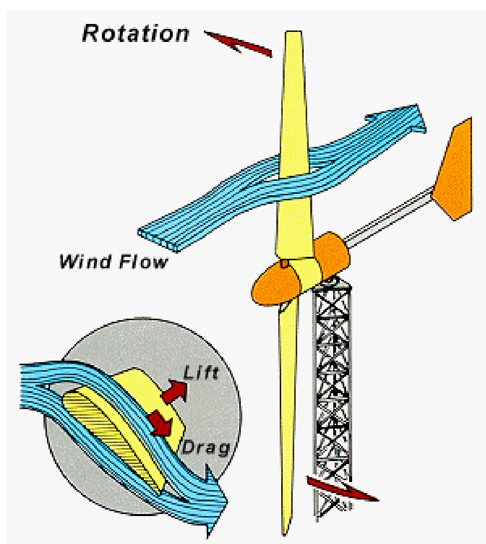

Figure 3: Principles of wind turbine aerodynamic lift

The drag turbine blades rely heavily on the angle of attack (pitch) and the width (chord length) of the blades. Reliance on these two areas increases the drag coefficient (C_D) which increases the power coefficient (C_P) of the design. Drag turbines also have a better ability to start up with less wind speed compared to the other types. However, when wind speeds are relatively high (around 18 m/s) drag turbines have an extremely poor C_P value compared to lift style turbines [2].

Turbine blades that rely on lift perform well in high wind speeds. The high performance and efficiency for these types of turbines are due to a larger lift coefficient (C_L). The high aspect ratio of the blade design of being long and slender yields a faster and more reliable tip speed ratio and local tip speed ratio, resulting in a better C_P value.

In addition, mixed turbine blades use particular combinations of lift and drag designs to maximize the performance. These blades approach the Betz limit while also improving the start-up capability of the blade [2]. In other words, a mixed design combines the best aspects of lift and drag based blades.

3.3.1.1 Existing Design #1: Xzeres Skystream

The Skystream is an off-grid turbine designed originally by Southwest Windpower for homes and businesses. The turbine blade design was developed for low wind speed and encompasses a small swept area of 115.7 ft^2. The blade is constructed of fiberglass reinforced composite material and has curved blade tips, giving the turbine a rated power capacity of 1.8 kW. The design of the blades to include curved blade tips reduces the noise when the turbine is operating at higher speeds. The cost for a Skystream 3.7 is approximately $12,000.00 to $15,000.00 to both purchase and install. The generator itself costs $5,400.00 in this turbine. Depending on the tower and installation costs, average wind speed, rebates and local electricity costs, a Skystream 3.7 can pay for itself in as little as 5 years [10].

3.3.1.2 Existing Design #2: Primus Energy

Primus Energy offers a selection of five off-grid wind turbines which have varying max power output. The output depends on the application, as their five turbine products are specifically designed for various off grid applications [11]. Applications for their turbines range from inland and coastal residential use to marine use. The cost of their premier turbine is $ 1,139.00 without installation [12]. This wind turbine in particular has a power rating of 30 kWh/month at 5.8 m/s (13 mph), and is intended solely for marine use because of the durability of the components.

3.3.1.3 Existing Design #3: Bergey

Bergey turbines have blades designed for off-grid applications as well. The price range for these turbines is $23,000-$30,000 depending on the model. Looking at the various models, the highest rated power capacity is 8.9 kW at 11 m/s, and the swept area is typically 415.48 ft^2.The blades are drag dependent, meaning that the blades will perform well in low speed applications. The estimated startup speed is 3.4 m/s and have a max wind speed of 60 m/s. However, the design of the Bergey wind turbines do not account for wind cutout speed. The wind cutout speed is essential in wind turbine blade design. For instance, if the wind speed exceeds 60 m/s the blades and/or the generator can be damaged or fail entirely.

3.3.2 Subsystem #2: Generators

Generators are the component in the turbine responsible for producing the actual electricity used by consumers. Mechanical energy enters the generator via a rotating shaft. This mechanical energy is then converted to electrical energy through the use of a rotor and stator. The rotor produces a rotating magnetic field as it moves around the stator, inducing a voltage difference between the different windings in the stator. This in turn is responsible for the production of electricity out of the generator. There are currently 4 commonly used generator types in wind turbines: doubly fed induction generators (DFIG), squirrel cage induction generators (SCIG), wound rotor generators (WRSG), and permanent magnet generators (PMSG). Each of these has unique characteristics. For this turbine design, we will look more in depth at DFIG's, SCIG's, and PMSG's.

3.3.2.1 Existing Design #1: Squirrel Cage Generator

The first design is the squirrel cage induction generator (SCIG). This consists of a rotor with internal conductive bars (usually copper or aluminum) connected on the ends with shorting rings forming a cage shape, as seen in Figure 4. This design has the advantage of being rugged while still having a lower initial and maintenance costs. These types of generators are commonly used in 1 MW and up turbines, and as such are readily available for such uses. Downsides to this generator is that it consumes reactive power from the grid and is limited to high-speed operation only. For these reasons, this generator is not well suited for a small scale, off-grid wind turbine design, as the operational wind speed will be lower than what the generator needs.

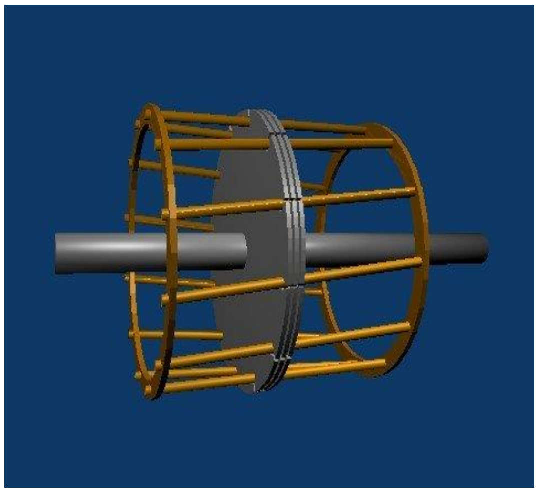

Figure 4: Squirrel Cage Inductive Generator (SCIG) [13]

3.3.2.2 Existing Design #2: Doubly Fed Induction Generator

The second generator design is the doubly fed induction generator (DFIG). This type of generator has windings on both the stator and rotor, both of which produce power when the shaft rotates. The stator itself is directly connected to the grid because it has a fixed AC frequency, while the rotor is connected to a three-phase converter because it has a variable frequency. The benefit to this design is that the rotor operates well in variable speeds, the generator has high torque starting capability, and the output power is easier to control. That said, this generator type also has a high initial and maintenance cost because the slip rings involved in the design need regular care. Although the high cost is something the team would wish to avoid, this generator would be useable in a small wind application due to its ability to operate well at variable speeds.

3.3.2.3 Existing Design #3: Permanent Magnet Super Conducting Generator

The last generator design is the permanent magnet generator (PMSG). This type of generator utilizes magnets attached to the rotor to create the magnetic field as the magnets pass the coils in the stator, as seen in Figure 5. This generator type is fairly rugged, but has a high initial cost due to the cost of the magnet material. Also, because of the weight of the magnets used, a low speed PMSG can be extremely heavy. That said, these generators also have a high reliability and efficiency, and have high and low speed generation capacity. Despite the high cost, early research would suggest that this generator is the best suited for use in a small wind turbine in off-grid applications. Despite the high initial cost, the generators are efficient and reliable, which means less maintenance for the turbine owner.

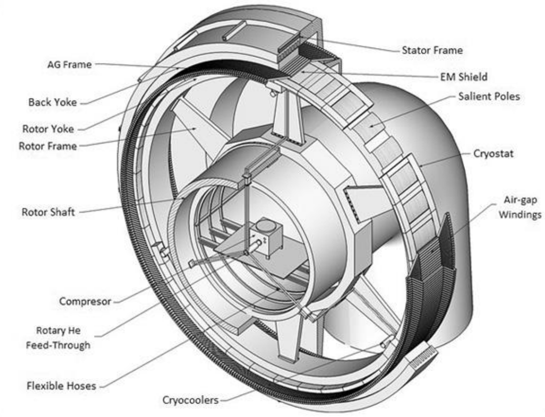

Figure 5: Permanent Magnet Super Conducting Generator (PMSG) [14]

3.3.3 Subsystem #3: Controls

The wind turbine control system connects the operation of all subsystems together. This includes wind speed measurement, component monitoring, operation of brakes, and closing contactors to connect the turbine to the grid or load. The controls also adjust blade pitch settings and generator torque to control power output and turbine speed in high winds. Control systems in a wind turbine are important because they add safety, reliability, and efficiency to the device.

3.3.3.1 Existing Design #1: Yaw System

A yaw orientation system is required to keep the rotor shaft properly aligned with the wind. Its primary component is a large bearing that connects the turbine itself to the tower. An active yaw drive, always used with upwind wind turbines and sometimes with downwind turbines, contains one or more yaw motors, each of which drives a pion gear against a bull gear attached to the yaw bearing. This mechanism is controlled by an automatic yaw control system with its wind direction sensor usually mounted on the top of the wind turbine. Sometimes yaw brakes are used with this type of design to hold the nacelle in position, when not yawing. However, in small wind systems free yawing used. This means that the turbine can self-align with the wind using a tail fairing. This is popular in small wind because it does not include the extra cost of yaw motors that draw power from the generator.

3.3.3.2 Existing Design #2: Power Electronics

The control system for a wind turbine is important with respect to both machine operation and power production. A wind turbine control system includes the following components.

- <u>Sensors</u> - speed, position, flow, temperature, current, voltage…etc.
- <u>Controllers</u> - mechanical mechanisms, electrical circuits
- <u>Power amplifiers</u> - switches, electrical amplifiers, hydraulic pumps, and valves
- <u>Actuators</u> - motors, pistons, magnets, and solenoids
- <u>Intelligence</u> - computers, microprocessors

3.3.3.3 Existing Design #3: Pitch System

The pitch control is used to set the wind turbine blades at the optimal angle to the wind. This optimal angle of attack will have great effect on how efficient the wind turbine will be.

Full span pitch control is used for aerodynamic torque and controls through rotor geometry. It requires rotation of the blade about its long axis. The pitch control system can only be used on a large scale wind turbine. Full span pitch can be used to regulate aerodynamic torque by either pitching the bale inward or outward to adjust for optimum power production.

4 DESIGNS CONSIDERED

4.1 Focus of Designs

The main focus of designs 1-4 is the combination of various airfoil designs and types of generators. Focusing on these two components of the design will help optimize the customer needs and engineering requirements as the design is implemented. In contrast, designs 5-10 look at different components of the wind turbine considered to yield a broad spectrum of cost, maintenance, reliability, and stability.

Designs 5-10 will focus more on the following components: structure, load, pitch and yaw controls, and blade materials. The generator and blade design will be held constant during these design considerations. For ease of considering these designs, only the horizontal axis turbine layout will only be considered. This is because the horizontal axis turbine layout is significantly more efficient than the vertical layout. In the vertical layout, a blade will always be spinning back into the oncoming wind, limiting the power production, where as a horizontal layout does not have this limitation.

Once final decisions on the airfoil and generator are selected, a fully optimized turbine will be implemented. Until then (finalized report), an iterative process will be performed for each parameter.

4.2 Design #1

In this design, a wound rotor super conducting generator paired with the NACA 6040 airfoil will be considered. The designated parameters for type of turbine (horizontal), structure, load, pitch and yaw controls, and blade materials are as follows (refer to appendix Tables A-G for Pugh chart computations)

Table 3 - Design 1 parameters

Support	Load	Pitch Type	Yaw Type	Blade Material
Telecomm tower	Telecomm equipment	Fixed	Free	Fiberglass composite

The wound rotor super conduction generator (WRSG) has high-torque operation, is independent of the pitch and yaw controls, and eliminates the need for a gearbox. High-torque operation allows the generator to operate at higher wind speeds without having to brake or power down the turbine. The high-torque operation also allows the generator to be independent of pitch and yaw controls, meaning that these controls are not needed. With the absence of the gearbox’s frictional factors, the overall maintenance of the turbine is reduced significantly.

Drawbacks of this generator include high capital and maintenance costs, required additional excitation circuit, and needed frequent maintenance for slip rings. Reasoning for high capital cost and maintenance cost is the complexity of the generator. Additional excitation for the circuit is needed because the generator can operate at high-torque. The high torque capability induces greater force needed, which in return creates the need for high excitation.

The NACA 6040 has a max coefficient of lift to drag ratio (C_L/C_D) of 92.7 at an angle of attack of 6.6 degrees [15]. Having a high angle of attack allows the airfoil to operate in higher wind speeds. The angle of attack also increases the area in which the wind hits the turbine blade, thus creating more force acting on the blade and subsequently higher torque on the shaft.

Combination of the NACA 6040 and the WRSG do however have drawbacks. A lower C_L/C_D value yields a lower power coefficient (C_P) when compared to other designs. The power coefficient is proportional to the ratio of C_L/C_D, thus the lower the ratio the lower the power coefficient will be. This concept is based off of the Blade Element Momentum Theory (BEM), which is highly used in turbine blade design [2].

4.3 Design #2

Next, a permanent magnet superconducting generator (PMSG) with the NACA 6041 airfoil will be considered. The designated parameters for type of turbine (horizontal), structure, load, pitch and yaw controls, and blade materials are as follows (refer to appendix Tables A-G for Pugh chart computations):

Table 4: Design 2 parameters

Support	Load	Pitch Type	Yaw Type	Blade Material
Telecomm tower	Telecomm equipment	Fixed	Free	Fiberglass composite

PMSGs have high power density and reliability, no need for excitation and gearbox, and lower losses and high efficiency. High power density occurs from the greater flux density the magnets generate. The flux generated constantly induces a change in directional flow of electrons. The change in direction induces an alternating current (AC), which is constantly iterating a sinusoidal output. This form of output is more natural to the flow of electrons and thus makes the power density high. The generator is more reliable since it has less moving parts such as a gearbox.

Drawbacks for this generator are high cost for permanent magnet (PM) material, possible demagnetization of the PMs, and the heavy weight of generator. For magnets there is a natural decay for magnetization. This will occur over time and will lead to high costs in replacements. With the higher weight of the generator, installation costs are relatively higher as different machinery is needed to put the turbine in place.

The NACA 6041 has a max C_L/C_D of 89.2 at an angle of attack of 3.5 degrees. With the lowest C_L/C_D of all the designs considered, this airfoil design is optimized for low speeds. The smaller the C_L/C_D ratio, the more drag force is applied to the turbine blade and the better the start up speed (torque) will be. The combination of the airfoil design and generator allows for higher C_P values and more power at low wind speeds. However, at higher wind speeds this airfoil will not perform as well as some of the other designs, and as such will not provide the generator with as much mechanical energy at these speeds.

4.4 Design #3

This design will examine the permanent magnet superconducting generator (PMSG) and the NACA 6042 airfoil will be considered. The designated parameters for type of turbine (horizontal), structure, load, pitch and yaw controls, and blade materials are as follows (refer to appendix Tables A-G for Pugh chart computations):

Table 5: Design 3 parameters

Support	Load	Pitch Type	Yaw Type	Blade Material
Telecomm tower	Telecomm equipment	Fixed	Free	Fiberglass composite

From previous design discussion, the pros and cons for the PMSG have been evaluated (refer to Design #2).

The NACA 6042 airfoil has characteristics of a max C_L/C_D of 117 at an angle of attack of 3.5 degrees. Combination of the PMSG and NACA 6042 will allow the generator to pull more power from the wind at higher speeds. This is correlated to the lower angle of attack and a high C_L/C_D ratio. As such, this a great air foil for use in high speed operation or near the tip of the blade where a higher speed is seen.

4.5 Design #4

Next, a doubly fed induction generator (DFIG) with the NACA 6043 airfoil will be considered. The designated parameters for type of turbine (horizontal), structure, load, pitch and yaw controls, and blade materials are as follows(refer to appendix Tables A-G for Pugh chart computations):

Table 6: Design 4 parameters

Support	Load	Pitch Type	Yaw Type	Blade Material
Telecomm tower	Telecomm equipment	Fixed	Free	Fiberglass composite

DFIGs allow rotor power to operate at variable wind speeds, high starting torque capability, and flexible reactive power control. The variable wind speeds coincide with high starting torque capability that is similar to the wound rotor superconducting generator. This will allow the generator to be place in locations were winds oscillate throughout the year. The flexible reactive power control yields safer power over load situations. These situations may include brake failure and or sudden weather changes.

Drawbacks for the DFIGs are high initial and maintenance costs, low-power factor at light loads, and slip rings needing regular maintenance. The low-power factor at light loads refers to low wind speeds. For example, if the cut in wind speed is 5 m/s, the power produced will be relatively insignificant at this speed. This limits the location of the turbine to higher local wind speed areas.

The NACA 6043 airfoil has characteristics of a max C_L/C_D of 133.3 at an angle of attack of 4 degrees. This airfoil has the highest C_L/C_D ratio of all the designs considered. Thus, it will be the most efficient airfoil at high operational speeds, but will have the worst start up speed of the air foils considered.

Combination of the DFIG and the NACA 6043 airfoil will allow the turbine to be placed in locations with higher wind speeds (above 10 m/s). This is due to the higher angle of attack and C_L/C_D within the blade design. However, because the generator and blades will have a hard time producing power at lower wind speeds, the overall power production and profitability of the turbine will lack compared to other designs.

4.6 Design #5

With the possible blade and generator designs now examined, we will look at each of the control mechanisms involved in the turbine's maintenance. The first thing we will discuss is pitch control. As explained earlier, pitch control is what allows the blade to rotate along an axis to change its angle of attack with the wind. Pitch control normally has two forms, controlled or fixed.

A controlled pitch utilizes either electric motors or hydraulics to rotate the blade to change the angle of attack as needed. This provides a way for the turbine to regulate its speeds and power production in high wind speeds. Also, in dangerous winds, the pitch control can rotate the blades to be parallel with the wind, which stops the turbine from spinning all together. Controlled pitched is normally used on large scale wind turbines, as the components draw a decent amount of power when rotating the blades and are fairly expensive when implemented in small wind compared to large wind.

Small wind turbines almost exclusively use fixed pitch. Fixed pitch is when the blade is held in blade and does not have the ability to rotate. Although the angle of attack can't be change to regulate power as well as a controlled pitch, there are less expenses involved in this system and it does not detract from the power being generated by the generator.

4.7 Design #6

Similar to the pitch system is the yaw system. This can be either fixed, free, or motor controlled. A fixed yaw means that the turbine in essence is bolted straight to the tower. This does not allow the turbine to move or follow the wind. This is used on a very limited basis by testing turbines that know what direction the wind will be coming from during their test. The problem with using this fixed system commercially is that the turbine cannot follow the wind direction, and as such will only produce power at very specific wind directions.

A free or natural yaw system is one that is able to freely rotate on the tower without being regulated. This is often used in small scale wind turbines for the same reason fixed pitch is used, high relative cost. Natural yaw systems will often have some sort of slip ring and bearing involved in its construction and operation, but that is it component wise. The turbine itself is directed into the wind by using a tail vane or other such device that the wind is able to push until it is parallel to the flow. As the wind pushes the tail vane, the yaw system simply allows the turbine to rotate in that direction.

Lastly is controlled yaw, which uses motors to regulate the yaw of the turbine. A sensor, normally on top of the turbine itself, tells the motors which direction the wind is coming from. These motors then engage and rotate the turbine into the wind. Once the wind direction is matched, yaw brakes engage and hold the turbine in that position until the wind again changes direction. This system is used commonly in commercial scale wind, as it is more feasible than a large tail vane and provides better control of the turbine's actions. However, the brakes and motors need regular maintenance, add cost to the design, and are harder to use in the small-wind sector.

4.8 Design #7

The last design consideration is the power electronic controls. These controls encompass everything from sensors to computers to energy regulators. Although a majority of this designing will occur next semester as the deployment team will be selecting these parts from manufacturers, we will discuss some of their functions here. Perhaps most important is the micro-controller/computer, which makes decisions on how to operate the turbine given sensor input. In large scale turbines, these computers control the pitch, yaw, generator output, controlling while monitoring the entire system for any problems. Should a problem be recorded by a sensor, the computer will initiate an emergency shut down of the turbine to ensure no extra damage is done to the machine. In small wind, these controllers are still present but less involved. Because most small wind turbines utilize free yaw and fixed pitch, these systems do not need to be controlled. However, the generator's output power is still recorded and controlled to ensure a safe and reliable stream of electricity leaves the turbine. These microcontrollers can be as simple as an Arduino chip used by many of the engineering students at NAU.

Moving on to sensors, the various performance aspects of wind turbines are often monitored. In large scale wind, the most important sensors are the anemometers, which record the wind speed and direction at each turbine. This in turn tell the computer which direction to turn the turbine and how to pitch the blades. These large scale turbines also include sensors that monitor vibrations and performance of almost every component involved in the operation of the turbine. Should one of these sensors detect a problem, they emergency stop of the turbine is initiated to prevent further damage until it can be repaired. In regards to small wind, sensors are still used to monitor system performance, but on a limited basis. For the most part, the only system that is monitored regularly is the generator in these turbines because of the simplified design. However, they still have the same purpose of shutting down the turbine to avoid damage if a problem is detected, while also giving information to the computer to help regulate the generators performance.

The exact sensors and micro-controllers that will used in our turbine design will be listed next semester, as the focus this semester was to design the blades and select a generator type.

5 DESIGN SELECTED

5.1 Rationale for Design Selection

Through a qualitative analysis of each component of the turbine designs considered (refer to appendix Tables A-G for Pugh chart computations), a quantitative analysis was performed. This analysis was performed with structure, load, and pitch and yaw controls. To perform this analysis a decision matrix was created, weighted, and evaluated. Table 7 shows the decision matrix of the blade design, while Table 8 shows the decision matrix for the generator selection. Lastly, Table 9 shows the decision matrix for the pitch and yaw systems. Detailed analysis and selection of the power controls will be completed next semester.

Table 7: Blade design decision matrix

Decision Matrix: Blade Design									
Criteria	**Weight**	**NACA 6040**		**NACA 6041**		**NACA 6042**		**NACA 6043**	
		Score	W-Score	Score	W-Score	Score	W-Score	Score	W-Score
Low Speed Energy Production	.33	7	2.31	8	2.64	4	1.32	3	.99
High Speed Energy Production	.33	4	1.32	3	.99	7	2.31	8	2.64
Overall Efficiency	.34	5.5	1.87	5	1.7	5.5	1.87	5	1.7
Total	**1**		**5.5**		**5.33**		**5.5**		**5.33**

In the case of the blade airfoil design decision, no clear decision could be made. This is because each airfoil has its benefits and limitations for different applications, whether high or low speed. Because a wind turbine has to operate in variable wind speeds, both high and low speed performance is applicable. As such, all four will be implemented into the blade design to utilize their strengths. The low speed airfoils will be used in the first third of the blade starting at the base. This will help with initial startup of the turbine, and during high speed operation the inboard portion of the blade does not affect the blade's performance much compared to the outboard portion. As such, the outboard two thirds of the blade will utilize the high speed airfoils. This is because the outboard area influences high speed operation a high amount. Also, the further out you move along the blade, the faster the rotational speed, and as such the high speed airfoils will thrive in that area of the blade.

Table 8: Generator design decision matrix

Decision Matrix: Generator Type							
Criteria	**Weight**	**WRSG**		**PMSG**		**DFIG**	
		Score	W-Score	Score	W-Score	Score	W-Score
Energy Production	.23	6.5	1.495	9.2	2.116	6.5	1.495
Safety	.10	6	.6	7.5	.75	7.7	.77
Reliability	.27	8	2.16	9.3	2.511	8	2.16
Start Up Speed	.15	4.5	.675	7.9	1.185	4.5	.675
Efficiency	.25	8.5	2.125	8.5	2.125	9	2.25
Total	**1**		**7.055**		**8.687**		**7.35**

Reliability was weighted highest because the market demands reliable energy output from the system. If the power source is not producing power, it defeats its purpose. The weightings for efficiency and energy production were rated at 2nd and 3rd highest. For efficiency the turbine must be efficient in capturing the wind and transforming it into energy. This leads to energy production. The coefficient of power (C_P) of the turbine must be at least 30 percent, with a goal for 40 percent. Otherwise, the wind turbine will not be able to produce enough power to be considered feasible for the market.

Start up speed and safety were weighted least. Even though startup speed was weighted low it is still important in design of the turbine. Safety of a wind turbine is important as well but most of the telecomm sites that will utilize our turbines are further away from urban areas. Thus, a catastrophic failure does not put lives in danger. However, it still puts equipment of the customer in danger and needs to be considered and designed for carefully as in any engineering project.

As for the generator selection itself, the permanent magnet (PMSG) was the clear choice to design around. This is because this specific generator is durable and requires little maintenance compare to the other designs. It also operates fairly well at variable wind speeds, operates at lower rpm's in general, and has a decent start up ratio. This means that the turbine rotor can be directly connected to the generator without the need of a gearbox to increase the rpm of the system, further reducing cost. It is true that the generator itself has a slightly higher initial cost compared to the other designs due to the cost of the magnet material, however the benefits of this generator far out way the small additional cost in terms of our engineering and customer requirements.

Table 9: Pitch & yaw design decision matrix

Decision Matrix: Pitch & Yaw Controls									
Criteria	**Weight**	**Fixed Pitch**		**Controlled Pitch**		**Free Yaw**		**Controlled Yaw**	
		Score	W-Score	Score	W-Score	Score	W-Score	Score	W-Score
Initial Cost	.23	1	.23	8	1.84	3	0.69	7	1.61
Maintenance Involved	.10	1	.1	8	0.8	3	0.3	9	.9

Reliability	.27	8	2.16	7	1.89	8	2.16	7	1.89
Total	**1**		**2.49**		**4.53**		**3.15**		**4.4**

Initial cost describes how expensive the component is at the initial construction and installation of the turbine. The higher the score, the higher the expense of the component. Because this expense is passed on to the consumer, it is important to reduce it as much as possible. The maintenance involved describes how much or how often a component has to be serviced or replaced. An increase in motors, bearings, slip rings, or parts in general adds to the amount of the service needed. Reliability, the highest rated criteria, describes how much the part affects the reliability of the overall system. More maintenance and/or part failures leads to turbine down time and less reliability of the turbine as a whole.

In regards to these criteria, we look at the selection of the pitch and yaw controls. In this case, a lower total score is better, as the initial cost criteria was ranked as high being expensive and low being cheap. In this regard, the fixed pitch and free yaw systems both win their respective categories. Fixed pitch is just directly mounting the blades to the hub, and as such there is no extra cost or maintenance involved with motors as in the controlled pitch. Similarly, the free yaw requires a tail vane and bearing/slip ring assembly at the rotation point on the tower, but does not involve the motors or control components involved with the controlled yaw system. Looking at our customer requirements of keeping the turbine easy to maintain and as low in cost as possible, these systems match up perfectly.

The criteria used to evaluate the generator selection, similarly to the other requirements listed, were created by using the quality function deployment (refer to Figure A in Appendix A). Weighting for each criteria was also evaluated by using both engineering requirements and customer requirements.

Using the decisions above, the final design will have a blade consisting of all four airfoils tested, with the low speed foils used on the inboard portion of the blade and the high speed foils used on the outboard section. The generator will be a permanent magnet generator with an approximate generation capacity of 3 kW, which was determined by market research. It will also utilize fixed pitch blades and a free yaw system due to their cheaper costs and higher reliability.

5.2 Design Description

5.2.1 General Design

Figure 6 below depicts the final design of the wind turbine, shown as a side view of the system.

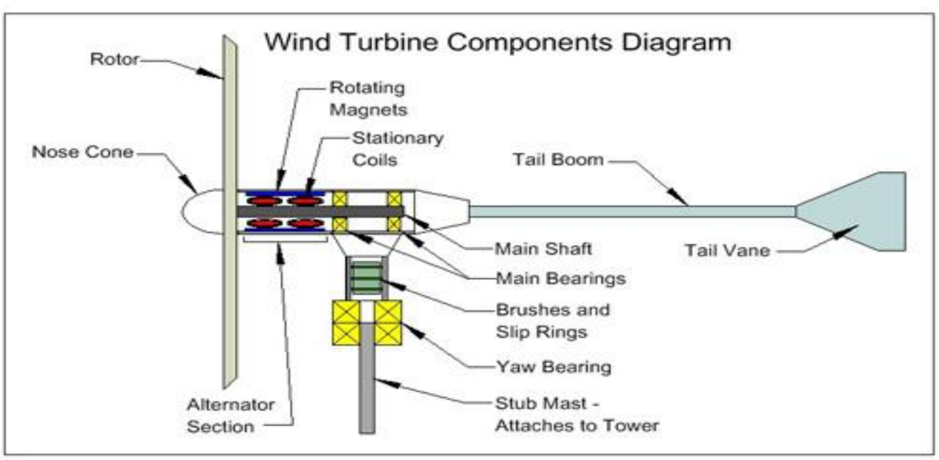

Figure 6: Final turbine design outline [15]

As mentioned the previous section, the generator will be a permanent magnet generator. The tail vail is responsible for directing the wind turbine into wind as the main bearings and slip rings allow the whole turbine to pivot about the support. The area near the nose cone, the inboard rotor, will contain the airfoils better suited for low speed operation, while the high speed airfoils will be located closer to the outside edge. This design does not contain many moving parts, and as such is expected to be both durable and easy to maintain. Also, the fewer components used, the cheaper the overall cost will be for the customer.

Material wise, we currently expect the blades to be composed of fiberglass reinforced plastics. This material is cheaper than a carbon fiber reinforced plastic and more durable than a wood/epoxy composite. The blades need to be fairly easy and cheap to replace in case of possible failure, and a cheaper but still durable material like fiberglass reinforced plastics meet this requirement. Blade material selection will be finalized next semester based on work done at Nova Kinetics by members of the tunnel team.

The remaining parts of the system will be specified next semester as well, as they are going to be purchased from various manufacturers. We will also spend next semester developing a cost of manufacturing and deployment of the turbine, including construction of any customized parts, costs of spec'd components, price of turbine shipping, and cost of installation on the telecomm towers.

5.2.2 Blade Design

With the general design in mind, and the airfoils selected, the blades were then designed. Figure 7 below shows the completed rotor design, and Figure 8 shows the blade specifications and locations of the airfoils. Not that as described above, the low speed air foils are used near the base of the blade while the high speed air foils are used closer to the tip.

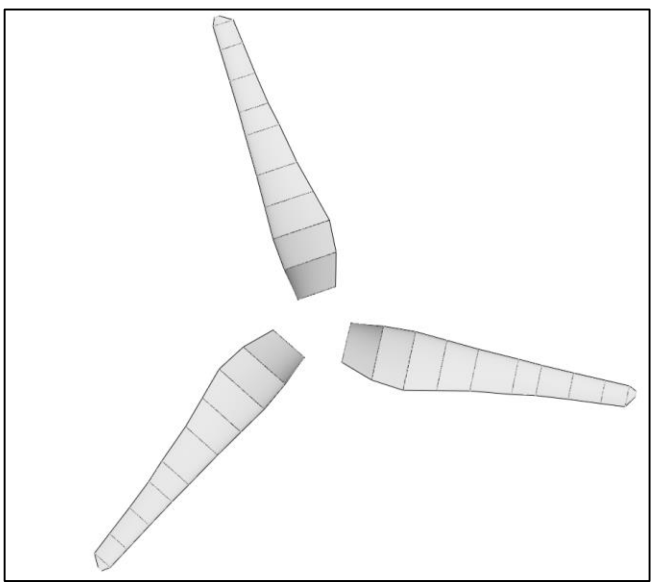

Figure 7: Current blade design

3 blades and 0.20 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Polar
1	0	0.415	52.46	SG6040	T1_Re0.408_M0.00_N9.0 36...
2	0.2056	0.4151	33.09	SG6041	T1_Re0.408_M0.00_N9.0 36...
3	0.4111	0.4029	20.45	SG6041	T1_Re0.408_M0.00_N9.0 36...
4	0.6167	0.3317	13.1	SG6042	T1_Re0.408_M0.00_N9.0 36...
5	0.8222	0.2719	8.612	SG6042	T1_Re0.408_M0.00_N9.0 36...
6	1.08278	0.2275	5.66	SG6042	T1_Re0.408_M0.00_N9.0 36...
7	1.2333	0.1944	3.59	SG6043	T1_Re0.408_M0.00_N9.0 36...
8	1.4389	0.1693	2.07	SG6043	T1_Re0.408_M0.00_N9.0 36...
9	1.6444	0.1497	0.91	SG6043	T1_Re0.408_M0.00_N9.0 36...
10	1.8	0.134	0	SG6043	T1_Re0.408_M0.00_N9.0 36...
11	1.85	0.034	0	SG6043	T1_Re0.408_M0.00_N9.0 36...

Figure 8: Blade Specifications

The chord lengths and twist angles were found using the Betz optimum rotor design with wake rotation MATLAB code developed by students involved in the project. The performance of the rotor was tested using the QBlade software package from the National Renewable Energy Laboratory (NREL). The resulting initial power curve is shown in Figure 9 below.

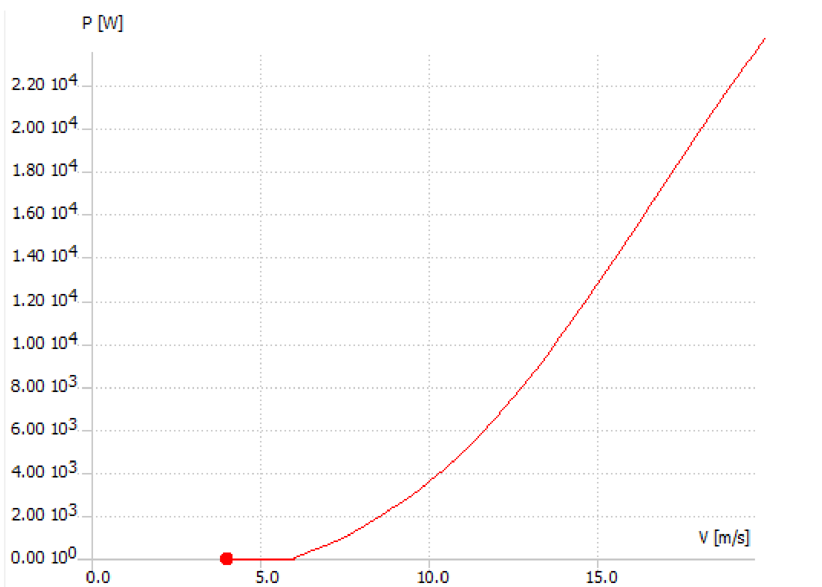

Figure 9: Initial power curve for blade design (power vs. wind speed)

This preliminary power curve of the turbine shows a startup speed of 5.5 m/s and a rate power of 3.7 kW at a wind speed of 11 m/s. It should be noted that this preliminary design uses an average Reynolds number over the entire blade rather than specific values at each blade section. In future analysis of the blade, the Reynolds number will be calculated for each blade section at the rated wind speed to add more accuracy to the turbine power curve. The start up speed is based on the amount of force needed to overcome the cogging torque of the generator to start the rotation of the shaft. This specific torque varies for different manufacturers and generators types, and in this analysis an average cogging torque of a 3kW permanent magnet generator was used. This will be refined with the final generator selection.

Figure 10 below shows the thrust load on the wind turbine, which will in turn have to be supported by the tower. Most telecomm towers are built to withstand such thrust loads, as the antennas they support have similar thrust loads. As such, mounting turbines on the telecomm towers is not expected to be a problem.

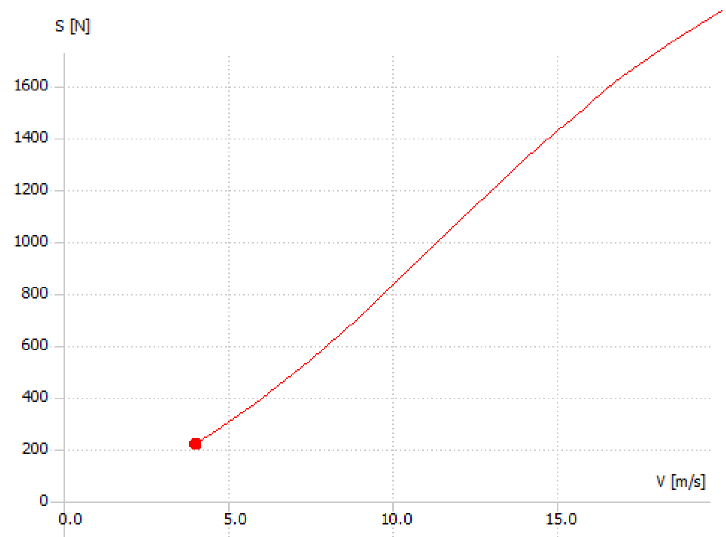

Figure 10: Thrust load on turbine vs. wind speed

6 IMPLEMENTATION

In terms of implementation, most of the deployment team's testing and design iteration will occur through the use of software packages. This is because there is a relatively high cost involved with most of the turbine components at this turbine scale that are beyond the scope of the team's budget. As such, multiple software packages, including SAM, QBlade, Meteodyn, and SolidWorks, will be used to analyze the design performance and make necessary changes to the design. Each of the software packages have been described earlier in the report, but will again be discussed as to their intended purpose in the implementation process.

6.1 Software Descriptions

6.1.1 SAM

SAM, which stands for System Advising Model, is a software that was developed by the National Renewable Energy Laboratory (NREL) with funds from the U.S. Department of Energy. SAM is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry. It makes performance predictions and cost of energy estimates for both grid-connected and off-grid power projects based on installation, operating costs, and system design parameters that the user specifies. SAM displays simulation results in tables and graphs, ranging from metrics table displaying the project's net present value, first year annual production, and other single-value metrics, to the detailed annual cash flow and hourly performance data.

6.1.2 QBlade

QBlade is an open source wind turbine design software. QBlade allows the user to design custom air foils and compute their performance, as well as integrate them into a wind turbine rotor design for turbine simulations. It is also includes extensive post processing functionality for the rotor and turbine simulations and gives deep insight into all relevant blade and rotor variables. In addition to that, the resulting software is a very flexible and user-friendly platform for wind turbine blade design.

6.1.3 Meteodyn

Meteodyn, which stands for meteorology and dynamics, is a wind modeling software that provides climate analysis. It focuses on renewable resource optimization, sustainable construction, and city planning (natural ventilation, pedestrian wind comfort, small wind, and solar radiations modelling, etc.). This software will be used for evaluating potential telecomm sites for their wind resource. The specific implementation task will be completed later in the spring semester, as final design selections and analysis need to be completed before hand.

6.1.4 SolidWorks

SolidWorks is a 3D software tool (CAD) that lets you create, simulate, publish, and manage designs. This software will be used to develop 3D models of each component involved in the construction of the turbine, and a full 3D assembly of the design. It also includes a finite element analysis (FEA) software package that allows for von Mises stress simulation and analysis of any draw parts. This will be used to determine the design's ability to withstand operational forces it encounters. Any fabrication will also be a result of this 3D modeling and creation of manufacturer drawings.

6.2 Schedule

Table 10 below outlines the predicted implementation and testing schedule for the spring 2016 semester. Note that some work will also be conducted by team members during the winter break to get a jump on the spring semester.

Table 10 - Spring 2016 schedule

#	Task	Date
1	Students meet with industry expert for generator design and selection discussion	Dec. 16, 2015
2	Preliminary Department of Energy (DOE) Document due	Dec. 17, 2015
3	-Individual research turbine structural components (ie tower, etc.) -Begin work on CAD models and array of simulations of components	Dec. 20, 2015 – Jan. 19, 2016
4	-Blade design & generator compatibilities identified -Create full array of CAD, FEA, and other models/simulations	Feb. 1, 2016
5	-Iterate design and business plan as needed -Finalize CAD and create manufacturing drawings	Feb. 2, 2016 – Mar. 1, 2016
6	-Physical prototype created -Work towards DOE presentations and final report	Apr. 10, 2016
7	-DOE final document and presentations due	Apr. 25, 2016
8	- Collegiate Wind Competition begins in New Orleans, LA at AWEA National Conference	May. 19, 2016

7 Conclusions

In conclusion, with the growing popularity in wind energy both in the United States and internationally, wind power is a growing industry with some marketing opportunities. The deployment team is currently designing a new wind turbine to break into one of these identified markets, the telecommunication industry. The new turbine design employs a horizontal axis, 3 blade design with fixed pitch and free yaw systems. After extensive qualitative research into the designs and considering optimization of all the operations of a wind turbine, the design team settled for the permanent magnet generator type and the NACA 604X series airfoils.

Moving forward, the team will be working towards the implementation steps outlined in the report. This includes properly modeling all aspects of the wind turbine for full analysis. This will allow the team to iterate the design to a great final product. The team will also be working towards their public pitch presentation at the American Wind Energy Association, which is where the final CWC competition will be held.

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APPENDICES

Appendix A

Table A

Generator Concepts					
Criteria	**Permanent Magnet Superconducting**	**Squirrel Cage Induction**	**Double Fed Induction**	**Wound Rotor Superconducting**	**High Temp-Superconducting**
Construction		+	-	-	-
Maintenance cost	D	+	-	-	-
Variable speed/ Starting capability		-	+	+	-
Reactive power control	A	-	+	-	s
Power density		-	-	-	-
Gearbox rotor losses	T	-	-	+	+
Torque operations		-	+	+	+
Size/Weight	U	+	+	+	+
Sum of +		3	4	4	3
Sum of -		5	4	4	5
Sum of S	M	0	0	0	1

Table B

Load Concepts						
Criteria	**Battery**	**Antenna**	**Health Equipment**	**Lights**	**Heating/cooling systems**	**Ships**
Manufacturing cost	D	+	-	+	-	-
Maintenance cost		-	-	-	-	-
Investment cost	A	+	+	+	+	-
Power consumption		-	+	+	-	-
Power storage	T	+	-	-	-	+
size/weight		-	s	+	-	-
Sum of +	U	3	2	4	1	1
Sum of -		3	3	2	5	5
Sum of S	M	0	1	0	0	0

Table C

Blade Design Concepts					
Criteria	**NACA 021206**	**Bio-Inspired: Dorsal Fin** **NACA 63-015A**	**Bio-inspired: Hawk** **NACA 22112-Jf**	**NACA AH 93-w-300**	**NACA AH 93-w-174**
Camber	D	-	-	-	+
Max Cl/Cd		-	-	-	+
Cut in Speed	A	+	+	+	+
Cut out speed		-	-	-	-
Noise reduction	T	+	+	+	+
Max Thickness		-	+	-	-
Sum of +	U	2	3	2	4
Sum of -		4	3	4	2
Sum of S	M	0	0	0	0

Table D

Structure Design Concepts					
Criteria	**Bio-Inspired:** **Fluid droplet**	**Bio-Inspired: Sunflower**	**Bio-Inspired: Dorsal fin**	**Cylindrical**	**Telecom tower**
Manufacturing cost		+	s	+	+
Maintenance cost	D	+	s	+	+
Feasibility		+	s	+	+
Viscous shear Resistance	A	-	+	-	-
Compressive Strength		+	-	+	-
Reliability	T	+	+	+	+
Foundation		-	+	-	+
Sum of +	U	5	3	5	5
Sum of -		2	1	2	2
Sum of S	M	0	3	0	0

Table E

Pitch Control Concepts					
Criteria	**Spring Loaded**	**Hydraulic**	**Electric Motors**	**Dielectric Polymer**	**Magnetic Shape Memory Alloy**
Manufacturing cost	D	-	-	-	-
Maintenance cost		+	+	-	-
Feasibility	A	+	+	-	-
Operation Power		+	-	S	-
Stability	T	+	+	-	+
Reliability		+	+	-	-
Sum of +	U	3	2	0	1
Sum of -		1	2	5	4
Sum of S	M	0	0	1	0

Table F

Yaw Control Concepts					
Criteria	**Electric drive**	**Hydraulic drive**	**Self-actuation**	**Shape Memory Alloy**	**Spring Loaded**
Manufacturing cost	D	-	+	-	+
Maintenance cost		-	-	-	-
Feasibility	A	+	+	-	-
Operation Power		+	+	+	+
Reliability	T	-	+	-	-
Stability		+	+	-	-
Sum of +	U	2	3	1	2
Sum of -		2	1	4	3
Sum of S	M	0	0	0	0

Table G

Blade Material Concepts					
Criteria	**Fiber glass composite**	**Carbon Fiber**	**Polycarbonate composite**	**Aluminum**	**Wood**
Manufacturing cost		-	-	-	+
Maintenance cost	D	+	+	-	-
Strength		+	-	+	-
Fatigue Resistance	A	-	+	-	+
Stiffness		+	-	+	+
Fracture toughness	T	-	+	+	+
Environmental impact resistance		s	-	-	-
Sum of +	U	3	3	3	4
Sum of -		3	4	4	3
Sum of S	M	1	0	0	0

Appendix B

Betz Optimum Rotor Design with Wake Rotation

$$\lambda_{TSR} = will\ be\ a\ chosen\ number$$
$$\#Blade_{sections} = will\ be\ a\ chosen\ number$$
$$Rotor_{radius} = will\ be\ a\ chosden\ number$$
$$\lambda_R = \lambda_{TSR}\left(\frac{\#Blade_{sections}}{Rotor_{radius}}\right)$$
$$\varphi = \left(\frac{2}{3}\right)\tan^{-1}\left(\frac{1}{\lambda_{TSR}}\right)$$
$$\#_{Blades} = will\ be\ a\ chosen\ a\ number$$
$$C_{lift} = will\ be\ a\ chosen\ number$$
$$Chord_{length} = \left(\frac{8 * \pi * Rotor_{radius}}{\#_{Blades} * C_{lift}}\right) * (1 - \cos^{-1}\varphi)$$
$$\sigma = \frac{\#_{Blades} * Chord_{length}}{(2 * \pi * Rotor_{radius})}$$
$$a = \frac{\frac{1}{1 + 4 * \sin\varphi^2}}{\sigma * C_{lift} * \cos\varphi}$$
$$a' = \frac{\frac{1}{4 * \cos\varphi^2}}{\sigma * C_{lift} - 1}$$

λ_{TSR}................................ $tip\ speed\ ratio$
$\#Blade_{sections}$..................$amount\ of\ blade\ sections$
$Rotor_{radius}$...................$desired\ rotor\ radius$
λ_R............................$Local\ tip\ speed\ ratio$
φ................................ $angle\ relative\ to\ the\ wind$
$\#_{Blades}$......................$\#blades\ for\ desired\ turbine$
C_{lift}............................$coffecient\ of\ lift$
$Chord_{length}$.................... $length\ of\ each\ blade\ segment$
σ................................ $solidity\ ratio$
a................................ $axial\ induction\ factor$
a' ....$angular\ induction\ factor$

Method 1 – solving for Cl and a

This method finds the angle of attack, lift coefficients for the center of each blade element, and empirical blade curves

$$C_{l,i} = 4F_i \sin\varphi_i + \frac{\left(\cos\varphi_i - \lambda_{r,i}\sin\varphi_i\right)}{\sigma_i'(\sin\varphi_i + \lambda_{r,i}\cos\varphi_i)}$$

$$\sigma_i' = \frac{Bc_i}{2\pi r_i}$$

$$\varphi_i = \alpha_i + \theta_{T,i} + \theta_{P,0}$$

$$F_i = \left(\frac{2}{\pi}\right)\cos^{-1}\left[\exp\left(-\left\{\frac{\left(\frac{B}{2}\right)\left[1-\left(\frac{r_i}{R}\right)\right]}{\left(\frac{r_i}{R}\right)\sin\varphi_i}\right\}\right)\right]$$

The lift coefficients and angle of attack can be found iterating graphically. The iterative approach requires an initial estimate of the tip loss factor

$$\varphi_{i,1} = \left(\frac{2}{3}\right)\tan^{-1}\left(\frac{1}{\lambda_{r,i}}\right)$$

$$\varphi_{i,j+1} = \theta_{P,i} + \alpha_{i,j}$$

$$a_i = \frac{1}{\left[1 + \frac{4\sin{\varphi_i}^2}{\left(\sigma_i' C_{l,i}\cos\varphi_i\right)}\right]}$$

If ai is greater than 0.4 we must use Method 2

Method 2 – iterative solution for a and a'

Iterating to find axial and angular induction factors using Method 2 requires initial guesses for their values. To find initial values, start with values form an adjacent blade section, values from the previous blade design in the iterative rotor design process, or use an estimate based on the design values form the starting optimum blade design

$$\varphi_{i,1} = \left(\frac{2}{3}\right)\tan^{-1}\left(\frac{1}{\lambda_{r,i}}\right)$$

$$a_{i,1} = \frac{1}{\left[1 + \frac{4\sin{\varphi_i}^2}{\left(\sigma'_{i,design}C_{l,design}\cos\varphi_i\right)}\right]}$$

$$a'_{i,1} = \frac{1-3a_{i,1}}{4a_{i,1}-1}$$

Having guesses for $a_{i,1}$ and $a'_{i,1}$ start the iterative solution procedure for the j-th iteration. For the first iteration j=1. Calculate the angle of the relative wind and the tip loss factor:

$$\tan\varphi_{i,j} = \frac{U\left(1-a_{i,j}\right)}{\Omega r\left(1+a'_{i,j}\right)} = \frac{1-a_{i,j}}{\left(1+a'_{i,j}\right)\lambda_{r,i}}$$

$$F_{i,j} = \left(\frac{2}{\pi}\right)\cos^{-1}\left[\exp\left(-\left\{\frac{\left(\frac{B}{2}\right)\left[1-\left(\frac{r_i}{R}\right)\right]}{\left(\frac{r_i}{R}\right)\sin\varphi_{i,j}}\right\}\right)\right]$$

Determine $C_{l,i,j}$ and $C_{d,i,j}$ from the airfoil lift and drag data, using:

$$a_{i,j} = \varphi_{i,j} - \theta_{P,i}$$

Calculate the local thrust coefficient:

$$C_{T,i,j} = \frac{\sigma'_i\left(1-a_{i,j}\right)^2\left(C_{l,i,j}\cos\varphi_{i,j} + C_{d,i,j}\sin\varphi_{i,j}\right)}{\sin{\varphi_{i,j}}^2}$$

Update a and a’ for the next iteration. If $C_{T_r,i,j} < 0.96$

$$a_{i,j+1} = \frac{1}{\left[1 + \frac{4F_{i,j}\sin{\varphi_{i,j}}^2}{\left(\sigma'_i C_{l,i,j}\cos\varphi_i\right)} - 1\right]}$$

If $C_{T_r,i,j} > 0.96$

$$a_{i,j} = \left(\frac{1}{F_{i,j}}\right)\left[0.143 + \sqrt{0.023 - 0.6427\left(0.889 - C_{T,i,j}\right)}\right]$$

$$a'_{i,j+1} = \frac{1}{\frac{4F_{i,j}\cos\varphi_i}{\left(\sigma'_i C_{l,i,j}\right)} - 1}$$

If the total length of the hub and the blade is assumed to be divided into N equal length blade elements then

$$\Delta\lambda_r = \lambda_{ri} - \lambda_{r(i-1)} = \frac{\lambda}{N}$$

$$C_P = \frac{8}{\lambda N}\sum_{i=k}^{N} F_i \sin\varphi_i{}^2 \left(\cos\varphi_i - \lambda_{ri}\sin\varphi_i\right)\left(\sin\varphi_i + \lambda_{ri}\cos\varphi_i\right)\left[1 - \left(\frac{C_d}{C_l}\right) cot\varphi_i\right]\lambda_{ri}{}^2$$