COLLEGIATE WIND COMPETITION
U.S. DEPARTMENT OF ENERGY

JURACAN ENERGY
Universidad del Turabo

TURABO
UNIVERSIDAD DEL TURABO
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Written Report

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1 EXECUTIVE SUMMARY

Puerto Rico has gone through one of the most catastrophic weather events leaving the island without communication, families lost their homes and electricity (which leads to lack of water, since there is no electricity for distribution pumps). With the fall of the electrical power distribution system, Juracan Energy discussed what we can do to generate energy after an event like this, hence the idea of using wind turbines to generate energy.

The dependence on fossil fuels for power generation, led the island to an energy crisis. The actual energy system on the island is unstable and extremely expensive. Currently, 51% of the generation on the island depends on fossil fuels, while 32% and 14% are natural gas and coal, and the other 3% is obtained with renewable energy systems. As a team, we want to increase the use of renewable energy sources, for the generation of energy in the country, and reduce the electric generation of non-renewable resources.

First, a study was performed to find where it would be more convenient to install a wind farm to generate and maintain stable energy for a specific region on the island. After the study was performed, it was concluded that the wind farm installation will be in Yabucoa, given that it is an agricultural area available to install a wind farm capable of a total power capacity of 100 MW, connected to the distribution system of Puerto Rico Energy Power Authority (PREPA). The idea is to provide stable power to hospitals, supermarkets and water distribution pumps.

After hurricane Maria, the standards of design and construction are believed to change in the island. Due to this fact, our design for the 2 MW turbine was to tolerate winds and gusts over 67 m/s. Part of our design is based on proven concepts, which includes a hybrid tower, a permanent magnet generator, a direct drive and a three-blade rotor. JE turbine differs from the other concept turbines, because the blades are made of Carbon Fiber Resin Polyester (CFRP) and it has a black start, which means that does not need any external energy to start the turbine.

2 BUSINESS PLAN

This section outlines the development of Juracán Energy as a start-up company. Details regarding the business overview, market opportunity, management team, development and operations, and the financial analysis are outlined here.

2.1 BUSINESS OVERVIEW

Juracan Energy (JE) is a new company located in Gurabo, Puerto Rico that focuses in the design, sales and development of large scale wind turbines. JE is composed of a group of students from mechanical and electrical engineering of the Universidad Del Turabo. The company was born to provide an alternative to help to the main grid in catastrophic situations (i.e., hurricane) and give an economic relief to high cost of electricity in Puerto Rico. JE name comes from the Taíno (i.e., Puerto Rico natives before the arrival of Cristobal Colón in 1493) word Juracán. According to the Taínos, Juracán was the "god of the wind". The origin of the name came from the taíno word "jura" (i.e., wind) and can "cán" (i.e., center). JE main product is the 2MW horizontal-axis wind turbine to provide an energy source in emergency situations. The innovation wind turbine design is particularly suited in places where the high probability of hurricane route.

2.2 JET COMPANY MISION

Create and offer renewable energy solutions to Puerto Rico, through the innovation and improvement of the wind source. Focus on help the economic development assuring security and high quality. Committed with the environmental, ***Juracán Energy***, seek to reduce the fuel consumption and change to an eco-friendly Puerto Rican perspective.

2.3 JET COMPANY VISION

Illuminate the alternatives of Puerto Rico with a clean energy source.

2.4 JET COMPANY VALUES

- **Involved** with our planet, with our people.
- **Respect** who do things differently
- **Be Accountable**, taking care of your worries
- **Social Commitment** providing a solution
- **Safety and Reliability**, trust our quality
- **Innovation,** dare to change

2.5 MARKET OPPORTUNITY

2.5.1 Problem Definition

In September 20, 2017 hurricane Maria, one of the strongest ever to hit Puerto Rico, caused unpresented damage to the island's already fragile power grid. The island has been experiencing the largest blackout in US modern history. Without electricity, there's no sources of clean water. The pumps, filtration systems and other equipment used to treat sewage and provide clean drinking water was down. After several weeks, even though US federal agencies and Puerto Rican government try to start up water distribution with diesel generators, few people had water in the island. Due to the logistics and fuel shortage, pumps in the water treatment and distribution plants were without power. By other side the hospitals, supermarkets and communications were also unable during several days.

According to statusPR, the power generation after hurricane, until April 20, 2018 is 97.27% as shown in figure 1. That means that in Puerto Rico (PR) there still people without electricity after 7 months of the hurricane. Energy in Puerto Rico has always experienced inefficiency and instability in the electrical main grid. Through the years the generating stations in Puerto Rico have not received the required maintenance, as replace important parts and materials. The current stations are not able to generate the maximum capacity, either cannot resist a hurricane.

According to the Puerto Rico Electric Power Authority (PREPA), which is the main and only supplier

Figure 1: Electrical generation after Hurricane Maria

of electricity in Puerto Rico, the highest producer of energy comes from fossil fuels, which contribute into the global pollution. Juracan Energy motivation is to approach a renewable energy generation in Puerto Rico, the currently status of renewable energy is not fully developed at the island.
According to the information provided by the government officials, Figure 2 shows the percentage energy generation in 2016 by different resources available in Puerto Rico. Highest production comes from fossil fuel with a 46.74% and the lowest production comes from hydroelectric power with 0.36%. The pie chart includes PREPA's energy generation and bought from other sources. Only the fossil fuel, hydroelectric and an amount of natural gas energy is generated by PREPA and the bought energy comes from natural gas, wind, solar and carbon. The same definition to the 2017 energy generation is shown in the figure 3. At this year there are three months with no generation, because of an atmospheric event.

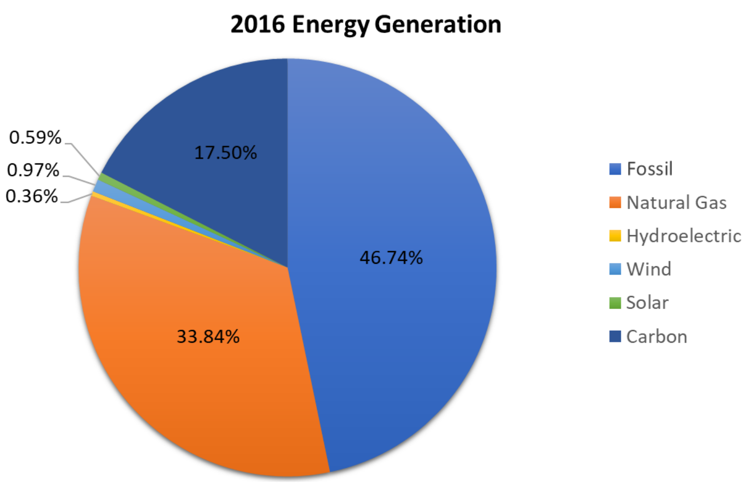


Figure 2: Puerto Rico Energy Generation 2016

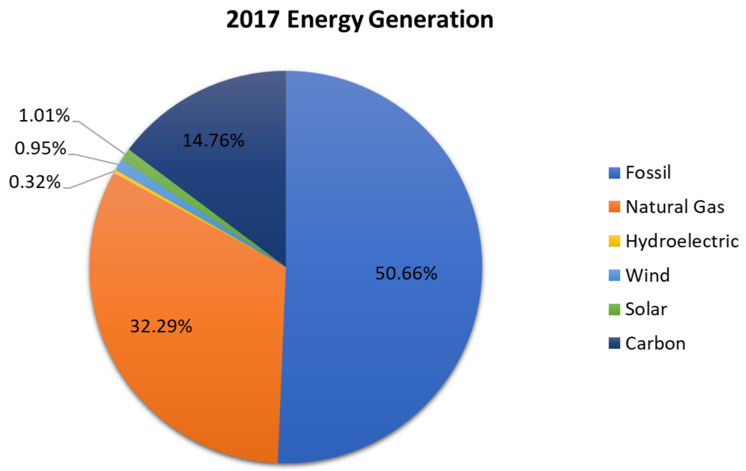


Figure 3: Puerto Rico Energy Generation 2017

Nowadays, Puerto Rico has two wind farms in Santa Isabel and Naguabo, its design did not fully consider the severe operating condition produced by hurricanes. Having in mind that we are located on Both farms are at hurricane risk with a high probability to strike the island year after year. The aim of this project is to explore the potential for wind turbines, considering this atmospheric phenomenon and reduce the fossil fuels in energy production of Puerto Rico. Minimize the dependence on fossil fuels will also reduce the contribution to environmental pollution. In fact, a 2010 law in Puerto Rico established a goal that 12% of the energy produced must be through renewable sources by 2015. As also established by the law, this percentage shall increase to 15% by 2020 and 20% by 2035. Currently, with only 2.29% of electricity produced by renewable sources, as shown in figure 3, meeting these requirements has become a remarkable challenge to the Island. According to the article VI, Section 19 of the Constitution of the Commonwealth of Puerto Rico declares as a public policy "the most effective conservation of its natural resources, as well as the greater development and use thereof for the general benefit of the community."

2.5.2 Proposed Solution

After passing one of the most atmospheric phenomenon where the whole island altered the economic situation and the Puerto Ricans lifestyle, JE compromised to bring solutions and contribute to improve the electrical system. Our objective is to change the perspective of electric generation, providing educational talks to guide communities, companies and others. Recognizing the actual energy situation in Puerto Rico, the high consumption of fossil fuels and dependence of the grid-connection, JE identified an excellent opportunity for development of renewable energy in Puerto Rico.

Juracan Energy seeks to provide a wind turbine system to supply energy in different environmental conditions for operation. In order to supply a reliable solution for energy generation, our turbine must operate land-based. Due the relative low wind speeds that are usually found inland in Puerto Rico the solution must effectively work at relatively low wind speeds (i.e., around 3 to 5 m/s). Besides the windfarm normal operation condition the turbines will be able to provide support and electricity right after a catastrophic emergency, JE would have a system of batteries backup to supply energy to water pumps, elderly centers, mini-markets and communications needs to areas near to the windfarm. Our batteries will also be convenient on local activities to provide power generation during a specific amount of time.

2.5.3 Target Client

The high consumption of fossil fuels and the actual main grid situation in Puerto Rico provide an excellent opportunity to market and sell the product in the island. JE's goal is to supply a green solution for the electric generation while reducing the use of fossil fuel sources. JE's primary target client is

Puerto Rico Energy Power Authority (PREPA) with the purpose of assist citizens of Puerto Rico near the local area.

According to the siting, the suitable city for the windfarm project will be Yabucoa. With this decision, the wind turbines will help the east area of Puerto Rico. Yabucoa have a population of about 37,665 and a total annual consumption in 2014 of 7000 (MWh). The solution will help the stability of the grid and reduce the load of the generation power plants of the country and thus increasing the percentage of renewable energy.

2.5.4 Market Size

The potential locations to install turbines are in the agricultural land since there is currently a law in which it establishes: "all potential land for the development of wind farms can be used" ACT-30. The initial development will focus on the Yabucoa area called "Valle de Yabucoa" which has 11,500 acres and the wind farm will take about 2,524 ac. It is an excellent location since the PREPA energy distribution lines are close to the site and could be connected to these lines to sell the power generation of the turbines; or in case the PREPA power plants are out of service, the turbines will help in maintaining the energy in this area. After the successful implementation of wind turbines in Puerto Rico, we could be expanded to other jurisdictions.

2.5.5 Competition

There are currently two wind farms in Puerto Rico, one of them suffered damage caused by Hurricane Maria (i.e., Naguabo wind farm) and the other with no damage but could not start generating because they need external energy for the initial start (i.e., Santa Isabel wind farm). Our design will be tested in both cases; withstand wind speeds greater than 155 mph and start generating without relying on external energy (black start).

2.5.6 SWOT Analysis

In order to further understand factors that can affect positively or negatively the business in the making Juracan Energy is developing. Both, internal (strengths and weaknesses) and external (opportunities and threats) factors are put under consideration during this analysis to help measure risks and rewards while identifying the key factors related to accomplishing the mission, shown in table 1:

Table 1: SWOT analysis

Internal Factors	
STRENGTHS (+)	WEAKNESSES (-)
Innovative design made to withstand extreme winds of up to 155mph Carbon fiber design to ensure rotor flexibility Black start, which does not rely on an outside electricity source to start generation There are previous data of functionality of wind turbines in Puerto Rico	Rely on government subsidies in order to remain competitive Lack of business experience on wind energy project development Funding difficulties

External Factors	
OPPORTUNITIES (+)	THREATS (-)
After Hurricane Maria, market for non-dependent renewable energy has grown Further product development taking into consideration various weather conditions Local government established a Law pushing forward renewable energy generation on the island to 15% by 2020	Non-renewable electricity continues to lead the market Wind farms often endure opposition from local communities debating they disrupt sights

2.5.7 Business Risk Management

From the SWOT Analysis, the following major risks were identified. A Mitigation plan was developed to assess and prepare for the possible impact of these risks and is as follows Table 2.

Table 2: Risk and Mitigation strategies

Risk	Mitigation Strategy
Rely on government subsidies to remain competitive	After completion of the first project, profits will be invested in funding for further project development making the business sustainable. Future work relies on changing the perspective of who is buying the energy produced from the wind farms by making new designs and project development as well as selling power to third parties such as industries.
Lack of business experience on wind energy project development	Hiring professionals who have business knowledge and involving the whole company to take workshops to keep updated on the wind energy market. Also, benchmarking will aid in understanding the market and how to achieve the prospective client's objectives from the projects.
Funding difficulties	Use financial advice from stakeholders and potential investors to design feasible projects. Renewable energy has shown to be a big market for investments based on the output of the projects therefor, the search for investors will continue.
Non-renewable electricity continues to lead the market	Prospective Wind Farms developed by Juracan Energy will compete with the price of Fossil Fuel Derived Energy. Electricity generated will be sold to PREPA which means cost of energy has to be lower than the typical kW/hr sold to the public to gain a profit. The cost will be invisible to the users since they will be paying the same rate. Supply power to third parties as part of micro grids or Power Purchase Agreements.

Wind farms often endure opposition from local communities debating they disrupt sights	Becoming ambassadors of renewable energy by proving that alternative ways of generating electricity are viable and should be pursued. Provide educational talks to raise awareness about the benefits and aids proposed by renewable energy. Convincing them that renewable energy is a clean alternative to generate energy will also support the claims.

2.5.8 Social Impact

Juracan Energy developed a survey oriented to the general population with some questions that are for wind farm sited communities here on the island. The survey is formulated to find how the people feel about wind farms and if they have any knowledge in renewable energy applications for their homes. This test was shared in the various social networks of the team members and some were asked in wind farm specific sites like Naguabo. The survey answered some of the team questions, which led us to the final assumptions for our target investors shown in figure 4.

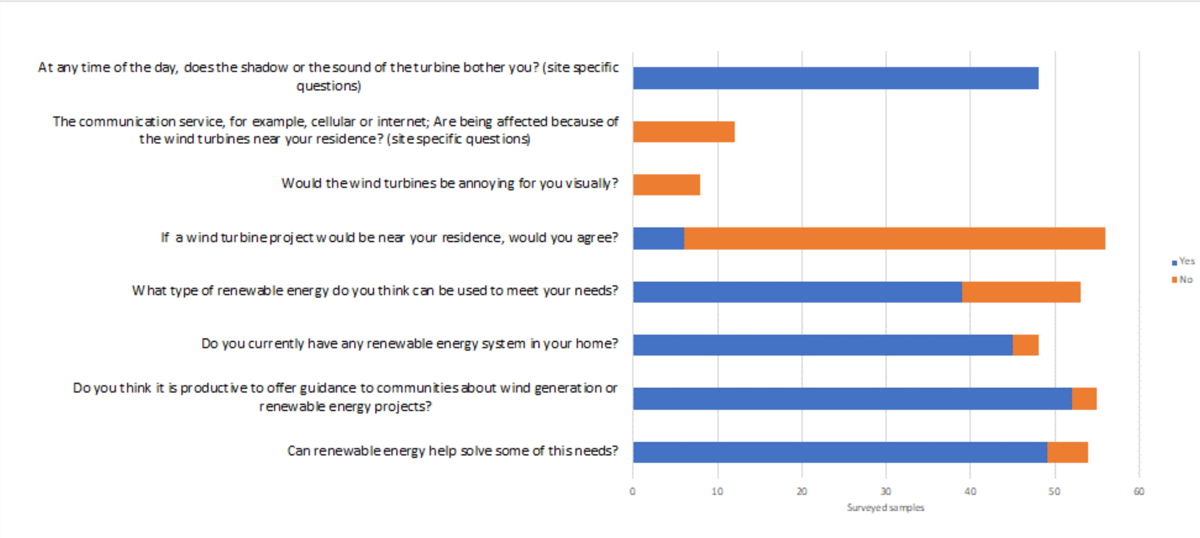


Figure 4: JE survey answers

2.6 MANAGEMENT TEAM

To contribute to the relief of Puerto Rico after hurricane Maria, JE took the initiative of developing a business that would provide a solution to the existing energy crisis. The official Juracan Energy management team is composed by:

- Chief Executive Officer (CEO) – Alvaro D. Garcia Baéz (Administrator) is in charge of the decision making, management and executing existing and future project to ensure policies and company guidelines are followed.
- Chief of Operations Officer (COO) – Andrea Del Mar Valenzuela Garcia (sales) is in charge of the daily operations while reporting directly to the CEO. She is responsible for the quality and marketing departments.
- Chief Technological Officer – (Juan M. Medina Vazquez is in charge of the research and development departments for the needs of the technical design aspects of the company and the product.

2.7 DEVELOPMENT AND OPERATIONS

Juracan Energy purpose is bringing the knowledge to Puerto Ricans who unknow the alternative of energy generation without using the fossil fuel. JE will web marketing, direct sales, industry events, green – energy events, educational talks to the communities, univerties, high-schools and energy forums and customer referrals as marketing channels. Prospective buyers will be able to visits the products website, visit the main offices or go to the customer directly in order to buy the product. Additionally, the product will be manufactured through third-party resources. The product deliverable and installation will be made through external subcontractors under the JE supervision and the maintenance of the product will be handled by Juracán Energy.

2.8 FINANCIAL ANALYSIS

The section focuses on the production and sales performance of Juracan Energy as a business. Moreover, Live Plan Business Plan software was used to develop the pro-forma financial statements shown in this report. Nonetheless, to have a realistic and conservative assumption, JE established to develop a wind farm in Yabucoa, P.R. The objective of JE is to generate renewable energy to sell it to the principal electric distributor in the island Puerto Rico Energy Power Authority.

2.9 START-UP SUMMARY

The principal objective of Juracan Energy its provider clean alternative energy solutions. Since JE its entrepreneur company in the renewable energy market in Puerto Rico. Nowadays, as an initiative to impulse the renewable generation and achieve the prognosticated percentage to the year 2020 in the island, there are Start-ups programs that help small business to start this projects with the goal or create jobs and develop the island economic with renewable alternative. Juracan Energy assume that the 25% of the capital cost of the project will obtain with the start-up programs and the 75% will be people interesting to invest in Juracan Energy project.

2.10 PERSONNEL PLAN

Juracan Energy will initially consist of 10 personnel, which three of them are part of the management team, five (5) field technicians, accountant, human resources and legal. Assuming fixed salaries for the first years of operation. The personnel wages are shown in table 3, the annual salary expenses for JE is an annual $236,160.00.

Table 3: annual salary expenses for JE

	Year 1	Year 2	Year 3	Year 4	Year 5
Manager Officer (CEO)	$ 38,400.00	$ 38,400.00	$ 38,400.00	$ 38,400.00	$ 38,400.00
Operation Officer (COO)	$ 38,400.00	$ 38,400.00	$ 38,400.00	$ 38,400.00	$ 38,400.00
Technical Officer (CTO)	$ 38,400.00	$ 38,400.00	$ 38,400.00	$ 38,400.00	$ 38,400.00
Technician	$ 19,200.00	$ 19,200.00	$ 19,200.00	$ 19,200.00	$ 19,200.00
Human Resources and Legal	$ 34,560.00	$ 34,560.00	$ 34,560.00	$ 34,560.00	$ 34,560.00
Financial Especialist	$ 34,560.00	$ 34,560.00	$ 34,560.00	$ 34,560.00	$ 34,560.00
Logistics and Supply Chain	$ 32,640.00	$ 32,640.00	$ 32,640.00	$ 32,640.00	$ 32,640.00
Payroll Total	**$ 236,160.00**	**$ 236,160.00**	**$ 236,160.00**	**$ 236,160.00**	**$ 236,160.00**

2.11 INITIAL CASE STUDY

Juracan Energy conducted an initial case study to calculate the cost of wind energy in Puerto Rico, according to the energetic market in the island and assuming the wind farm would have located in Yabucoa, P.R. Table 4 show a summarize analysis of the cost of energy from the wind resource, before and after applying the government incentives. Taking in consideration the following assumptions:

1. 2000 kW Wind Turbine
2. 24 – hour daily operation.
3. Yabucoa capacity factor 16.8%

Table 4: Summarize analysis of the cost of energy from the wind resource

	Unit	Values	
Annual Energy Production	kWh	147168000	147168000
Capital Cost	$	$165,000,000	$82,500,000
Capacity Factor	%	16.80%	16.80%
Rated Power	kW	2000	2000
Operation Hours	hrs	8760	8760
O&M Costs	$	$8,250,000	$4,125,000
COE	**$/kWh**	**$0.20**	**$0.10**

3 TECHNICAL DESIGN

Given the multi-disciplinary aspects of this enterprise, a systems engineering (SE) approach was used for the execution of the technical design of the project. The SE is widely used in multi-disciplinary project, it involves a structure approach for the design, realization, technical management, operations, and retirement of a system. SE is a way of looking at the "big picture" when making technical decisions, achieving the stakeholder functional, physical and performance requirements. A modified seven phases of NASA's SE process shown in Figure 5 was used were the first three phases involve the formulation of the system and the last four phases deal with the implementation and deployment of the system.

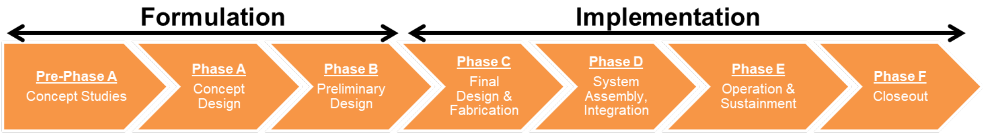


Figure 5: System Engineering Design Process

3.1 PRE-PHASE A: CONCEPT STUDIES

The Pre-Phase A includes preliminary design concepts, sitting ideas, market and problem assessments, and product breakdown structure.

3.1.1 Project Objectives

Juracan Energy proposes the implementation of hurricane-resilient horizontal axis wind turbine that compete in its respective renewable energy field. An island like Puerto Rico, exposed to every kind of natural disasters, a few months ago a hurricane hit the island wiping it from the entire electricity grid and everything on his path. Essential resources like water systems was massive damaged, establishing difficulties in the supply of clean drinking water and segregate hazardous debris. Our team's wind turbine design will be able to withstand hurricane severe winds and operate in emergency situation such as supplying energy to water system.

3.1.2 Measures of Effectiveness (MOEs)

The Measures of Effectiveness (MOEs) define operational requirements from the stakeholder. For the intended application, the MOEs were obtained from government officials and prospective customers from the private sector. These MOEs include a product that:

- Should be cost-effective design
- Should be optimal in Puerto Rico wind resource
- Shall resist high wind speeds
- Should last a long time
- Should have a good performance
- Should comply with laws and regulations
- Shall be capable of self-start
- Must minimize turbine components to improve reliability

3.1.3 Concept of Operations (Current State)

Puerto Rico Aqueducts and Sewers Authority (PRASA) has the highest power consumption at the island, consuming approximately 60 mega-watts (MW) for operation [Ing. David Degre]. Currently PRASA is powered by Puerto Rico Energy Power Authority (PREPA), is the main supplier using diesel generators for back-up operation. Juracan Energy is proposing a wind farm of efficient and resilient wind turbines that will operate connected to the main grid, for back-up generation, it can be disconnected from the main grid to supply the necessary power to battery back-up system which will powered water systems for water distribution.

3.2 PHASE A: CONCEPT DEVELOPMENT

3.2.1 System-Level Technology Assessment

Most of our design considerations are based in government and engineering standards. First of all, the IEC 61400-2 document requires design load considerations for both normal operation and fatigue loads (International Electrotechnical Commission, 2006). Also, equivalent stresses shall be calculated on all important load carrying components, whereas partial safety factors for materials are 1.35 and 10 for fully characterized and minimally characterized materials, respectively. Moreover, for performance an overall of a turbine rated power should be at wind speed of 11 m/s (IEC 61400-12-1). Additionally, design considerations for extreme wind conditions must be established as part of the American Society of Civil Engineers, (2005). In this case, the method of partial safety factors is suggested for the load estimates of the components. Finally, the turbine must be able to resist turbulent and extreme conditions, regardless of how infrequent they occur within the operating environment (Paraschivoiu I. , 2002). In other words, the turbine must be able to withstand category 4 hurricane force wind conditions.

A minimum coefficient of power (Cp) of approximately 0.4 should be achieved for optimum performance. The Cp determines the amount of power generated from the wind, in function of the wind velocity third powered cubed (V3). This parameter is influenced by the turbine dimensions and aerodynamic design. An optimum design shall be obtained to ensure a self-starting turbine, without compromising integrity or the performance of the turbine. Also, a control system should be used to avoid any electrical overloads or failure, and maintain steady operating speeds for the turbine according to the IEEE 1547, establishing that all electrical components must be safe and insulated (Institute of Electrical and Electronics Engineers)

3.2.1.1 Measures of Performance (MOPs)

The actual performance of a supplier's particular design solution is covered on the Measures of Performance (MOPs), which relates the stakeholder expectations and concerns with functional, performance and safety requirements. The engineering requirements were defined with the Quality Function Deployment method, which provided a quantities approach to evaluate if the MOPs complied with the MOEs.

Functional MOPs:

- The turbine should have the correct solidity to accomplish self-start
- The wind turbine main shaft characteristics should be optimized for performance rated speed
- Nacelle and rotor should have optimized for a better yaw motion
- Turbine yaw mechanism should consume the least amount of energy

Performance MOPs:

- The turbine C_p for the design should not be less than 0.4.
- The structural design of the turbine shall resist wind pressures of 0.3 MPA
- The generator should have efficiency more than 90%
- The turbine shall start operating 4 m/s
- The rated power must be generated at wind speeds of 11 m/s
- The generator should have a self-excitation control (black-start)

Safety MOPs:

- The safety factor should be 1.35 for fatigue and ultimate loads.
- The material safety factors shall be 1.1.
- The generator must have a high overload capacity.
- The turbine should have a start-up and emergency shut down procedure

3.2.1.2 System-Level Trade Studies
At first, three (3) different configurations of wind turbine, two HAWT and one VAWT, were studied as proposed ideas. See Figure 6. In order to comply with the customer's MOEs and select the optimal configuration, requirements were evaluated in a Pugh's Decision Matrix. As result of the matrix, the downwind HAWT was the best option, reducing the stiffness and having lighten blade mass in comparison to upwind HAWT and being more efficient that the VAWT.

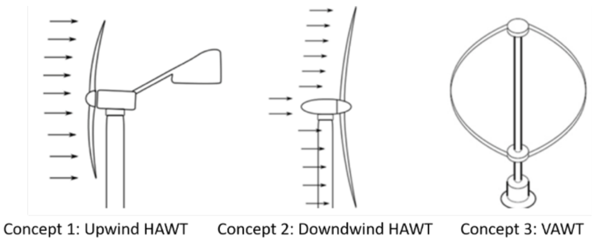


Figure 6: VAWT and HAWT concepts for Pugh's Decision Matrix

3.2.1.3 Project Architecture
The wind turbine design process was divided into five main sub-systems shown in Figure 7. These sub-systems included the Aerodynamic, Mechanical, Structural, Electrical and Control components and the Yaw Mechanism. Further all sub-system will interact by connecting our sub-system together.

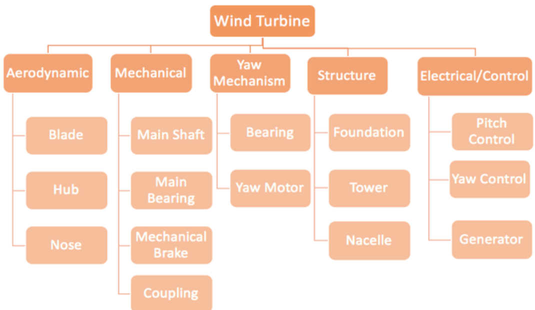


Figure 7: Wind Turbine Product Breakdown Structure diagram

3.3 PHASE B: PRELIMINARY DESIGN

The initial design calculation and modeling are included in this section. This calculation was done by hand or through spread sheets in order to have a preliminary design of the subsystems requirements. These results were later validated to compare with computational fluid dynamics (CFD) and computer aided design (CAD) model for Phase C.

3.3.1 Aerodynamic Sub-System

3.3.1.1 Technology Assessment: Aerodynamics Sub-System
In order to exploit wind energy, optimal blades performance needs to be developed and choosing an appropriate blade design process with accurate results is critical for the wind energy industry. The aerodynamic design was iterated using Blade Element Momentum Theory (BEM) found in Q-Blade. This relatively simple method takes in consideration the combination of the blade element and momentum theory. To design a wind turbine using the BEM theory, initial assumptions are needed such as number of blades, blade radius, pitch and twist angles, rotor rotational speed and wind speed [Wind Energy Explained]. National Renewable Energy Laboratory (NREL) airfoil family was used to design HAWT because of the performance characteristics at lower Reynolds number.

3.3.1.2 Trade Studies: Aerodynamics Sub-System

The XFOIL was used to determine airfoil characteristics at 1,000,000 Reynolds numbers and Montgomerie model was use in the 360-degree polar. For the initial iteration, a dimension (shown in Table 5) was used to compare twelve rotor configurations using 50-meter NREL families airfoils shown in Table #. The performance requirements such as power coefficient (CP) and the capability of producing power at low-wind speed were evaluated. Based on the performance, three configurations reached at least more than 40% of power coefficient.

Table 5: Airfoil family

NREL's Airfoil Families for 50m HAWT Rotor		
Root (15% - 40% r/R)	**Primary (40% - 75% r/R)**	**Tip (75% - 100% r/R)**
S818	S816	S817
S818	S830	S831
S818	S830	S832
S818	S827	S828

Table 6: Baseline wind turbine parameters

Baseline Wind Turbine Design					
Parameters	**Value**	**Units**	**Calculations**	**Value**	**Units**
Power	2000000	W	**A**	613318.00	
$V_{Cut-Off}$	33		**Radius**	44.18	m
V_{rated}	11	m/s	**W_{Cut-in}**	0.79	rad/s
V_{cut-in}	5			7.56	rpm
C_p	0.4		**W_{rated}**	1.74	rad/s
ρ "Air density"	1.225	Kg/m^3		16.64	rpm
Kinematic Viscosity	0.0000156	m^2/s	**Tip Speed Ratio**	7	

These three configurations were then analyzed with key parameter used for optimizing the blade geometry. The rotor blade parameters varied such as tip speed ratio (TSR) for chord distribution and angle of attack considering high L/D ratio for angle of twist distribution. Finally, the airfoil selected for the root the S818, mid-span the S827 and tip S828.

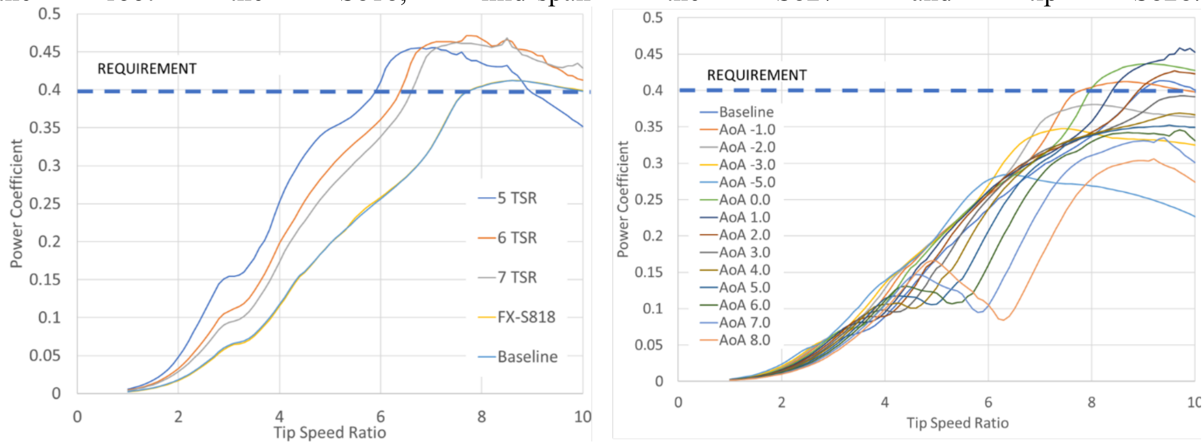
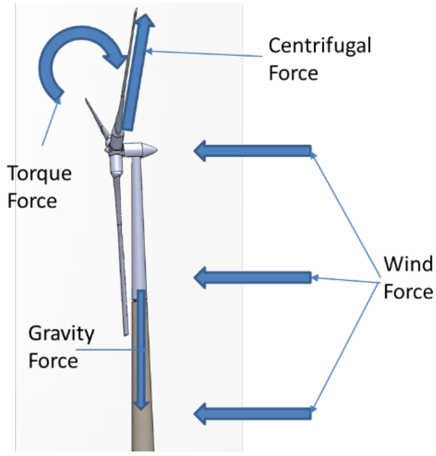


Figure 8: Chord Optimization with TSR variation (left) and Angel of Attack Optimization (right)

3.3.1.3 Trade Studies for the Blade Structure

The wind turbine blades were designed using the basic International Electrotechnical Comission's (IEC) design load cases for hurricane environmental conditions. The load types considered include gravitational (i.e., weight), aerodynamic and centrifugal loads shown in Figure 3. For the preliminary design, the blades were assumed to be built from carbon fiber reinforced polymer. For turbine blade structural analysis, it was assumed as a cantilevered beam and it was validated with the structural Euler-Bernoulli beam module (QFEM) found in Q-Blade. IEC design load cases specify the factor of safety should be 1.35, because of the destruction of the Naguabo's wind farm a factor of safety of 2.5 was reconsidered.



3.3.2 Mechanical Sub-System

3.3.2.1 Trade Studies: Mechanical Sub-System

The two alternative that were evaluated for the mechanical design are shown in Figure 9 with and without gearbox. One of the advantages of a direct drive is the low maintenance and low drivetrain cost compared to gearbox configuration, gearbox have a tendency to have complex design [ref]. Based on the Pugh's Decision Matrix, the direct-drive is best concept that would comply with cost, maintenance, weight and stresses. For the structural design of the turbine blade the safety factor was reconsidered because of the damage but drivetrain and other components did withstand severe wind speed and IEC standards.

Figure 9: Mechanical Design Alternative, With Gearbox and Without Gearbox [ref]

3.3.2.2 Trade Studies for the Main Shaft Design and Bearing Selection

The direct-drive shaft analysis was studied for three scenarios i) fatigue failure ii) hurricane loads (ultimate load) and iii) shaft deflection. The shaft and bearing were load calculation, and design was completed according to IEC standards. The best option for the shaft material was determined as AISI 1080, according to a Decision Matrix Tool shown in Table 3. For the bearing selection process, the reacting forces from the shafts calculations where used to determine the loads that the selected bearing would need to withstand. Another bearing design consideration was a 20-year life cycle. A Pugh's Decision Matrix tool was used to evaluate different options for both bearings. This selection process resulted in choosing a spherical ball bearing.

Table 7: Decision Making Tool for Direct-Drive Design

Decision Statement

Evaluation Criteria		Alt #1		Alt #2		Alt #3	
		AISI 1020 Steel		Carbon steel 1080		ColdDrawn 1026	
Shalls/Musts MOPs(Go/No Go)	Unit	Value	Decision	Value	Decision	Value	Decision
Safety Factor of 1.25 for fatigue	N/A	1.25	Go	1.25	Go	1.3	Go
Safety Factor of 1.35 ultimate loads	N/A	1.35	Go	1.35	Go	1.35	Go

MOPs	Unit	Wt.	Score				Score				Score			
			Comments	Raw	Norm.Raw	Raw*Wt	Comments	Raw	Norm.Raw	Raw*Wt	Comments	Raw	Norm.Raw	Raw*Wt
Cost	$	30		7942	6.9	208		9770	1.0	30		7000.00	10.0	300
Weight	lb	35		166283.66	1.0	35		165861.08	10.0	350		166030.11	6.4	224
Strength	Pa	35		4.20E+08	1.0	35		9.65E+08	10.0	350		5.50E+08	3.1	110
		100												
Total Score						278.18				730.00				634.14

3.3.3 Electrical & Controls Sub-System

The controls team developed a first-order mathematical model of the shaft in Simulink that relates the aerodynamic torque and shaft rotational speed. The aerodynamic torque was calculated using empirical data from the TSR and CP which depends on turbine rotational speed in rad/s and wind speed. Turbine torque can be calculated using aerodynamic formula, the mechanical system was composed by a Permanent Magnet Synchronous Generators (PMSG), *J*, turbine inertia and, *B*, friction coefficient. The proposed model was evaluated for rated speed and maximum power point tracking (MPPT). Torque control was used to achieve this control scheme both electromagnetic torque and brake system were proposed.

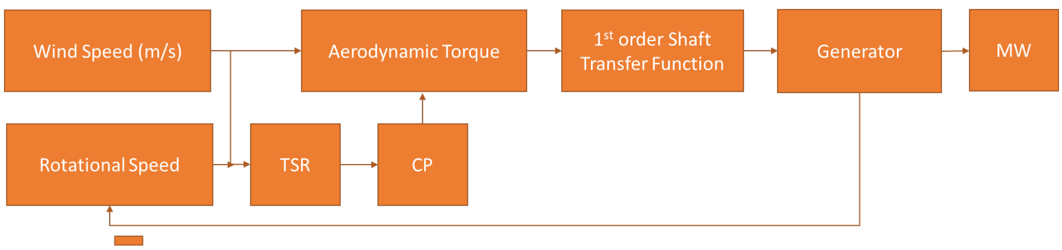


Figure 10: Control Block diagram

The team evaluated the configuration of three electric 3-phase generator i) squirrel-cage induction generator (SCIG), ii) double fed induction generator (DFIG) and iii) PMSG. Based on the MOEs and previous decision taken in consideration for the mechanical subsystem the PMSG generator comply with the requirement. This generator has the advantages of high power density, no need for excitation or gearbox, lower rotor losses and high efficiency. Even though the high cost of the permanent magnet is a major disadvantage the ability to generated energy after an emergency is important for Puerto Rico after hurricane Maria.

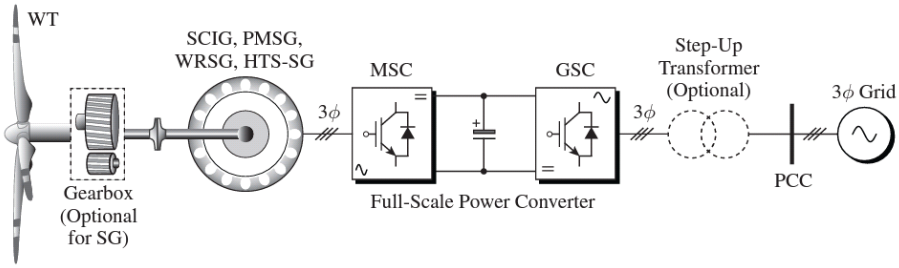


Figure 11: Turbine model

3.3.4 Trade Studies: Structural Sub-System

The two alternative that were evaluated for the structural design are shown in Figure 12. The first alternative is the hybrid tower that consist of concrete and steel, this alternative gives you the possibility of higher design with a lower cost. The second alternative is the all steel tower.

Figure 12: Structural Design Tower, Structural Design Tower, Hybrid Tower and Steel Tower

Once again, a Pugh's Decision Matrix was used to decide which concept was best. The criteria used to evaluate the concepts included the cost, weight, stresses, capacity factor and wind farm parameter. As a result, for the 2MW turbine the hybrid tower concept was choose.

3.4 PHASE C: FINAL DESIGN & OPTIMIZATION

This section focuses on the final design components of the wind turbine, including CFD and CAD analyses. Additionally, detailed analyses for each of the wind turbine's subsystems are also shown in this section.

3.4.1 Aerodynamic Sub-System

The aerodynamic blade design of model turbine is as regular as any other Horizontal Axis Wind Turbine (HAWT). The airfoil used for the rotor differ from the prototype wind turbine. The airfoils are AH-W-93-300, AH-W-93-215, and MH 102. These airfoils were selected taking into consideration the thickness percent require on each section on a blade design, Table 8. The blades sections are divided in three: the root, the mid-span, and the tip. The root is where the mayor stresses are and will provide support to the blade. The mid-span and the tip will provide the highest lift/drag (L/D) for a best efficiency in the aerodynamics. However, the model turbine does not possess a pitch control mechanism to provide an angle of pitch to optimize the efficiency at every rotation, but according to Manwell et. al (2009) to provide a stall regime in the blades, the lift coefficient (C_l) should be at its maximum. Generally, at angles of attack (AoA) of 10 to 16 degrees depending on the Reynolds number. Table 8 will show the AoA and their respective design Cl_{max}.

Stall occurs when the airfoil exceeds the angle of attack and the fluid starts to separate from the airfoil and creating vortex that increases the drag force.

Table 8: Airfoil design properties

Section	Airfoil	Thickness %	AoA	Cl design	Cd at Cl_{max}
Root	AH-93-W-300	29.98	14.5	1.437	0.058
Mid-span	AH-93-W-215	21.22	14	1.423	0.034
Tip	MH 102	16.98	14	1.515	0.029

Another parameter that is different from the prototype turbine is the Tip Speed Ratio (TSR). This adimensional coefficient is the ratio between the velocity of the rotor and the velocity of the wind. Since, JE had difficulties in the manufactured process of the blade, a TSR of 5 was used to provide better stability, support and thickness on the blades. Having a TSR of 5> will make the blade thinner taking in consideration that it has better aerodynamic efficiency, but due to 3-D printers constraints, JE decided to make the blade bigger by decreasing the TSR. Figures 13 and 14 will show the difference in performance based on the power coefficient (Cp) and the TSR.

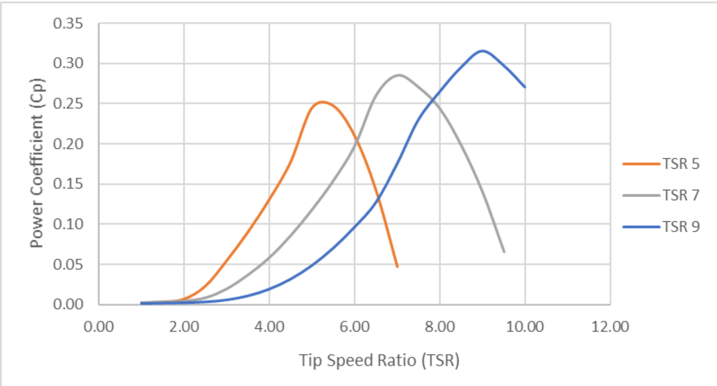


Figure 13: Cp vs TSR

The following figure (Figure 14) will show the behavior of the rotor after applying the initial conditions (Table 9) for the stall regime.

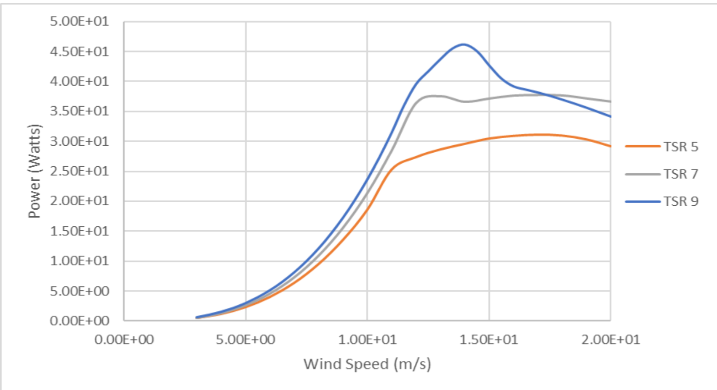


Figure 14: Power vs Wind Speed

As shown in Figure 14 the rotor will stall at 12 m/s, but the power keeps increasing until it gets to approximately 17 m/s were the decreasing of power starts to happen. All simulations and results were taken from the open source program Q-Blade.

Table 9: Rotor parameters

Turbine Rotor Parameters		
$V_{cut\text{-}in}$	3	m/s
$V_{cut\text{-}out}$	20	m/s
$\Omega_{cut\text{-}in}$	724.9	RPM
Ω_{rated}	2658	RPM
TSR	5	N/A
Fixed Pitch	0	
Variable Losses	0.1	

3.4.2 Mechanical Sub-System

The scope for the mechanical system includes the main shaft, which transmits the rotational energy from the rotor to the gearbox and then to the generator, the main bearing support, that will give stability to the main shaft, the gearbox which purpose is to reduce the angular velocity of the rotor and increase the torque in the generator shaft, and the mechanical brake to stop the turbine at any time. The design of the main shaft was analyzed for stress, moment and deflection in Finite Elements Analysis (FEA), following IEC standards. The main bearing support was analyzed and designed to support a thrust force at and over speed of (20 m/s). The gear ratio was determined with the main shaft velocity and the generator shaft velocity, then the gear teeth for each spur gear was calculated. For the mechanical brake, the force needs to apply in the rotor disk was calculated to reduce or stop the shaft rotation. For conciseness, the Mechanical sub-system results are not included in the report.

Figure 15 and 16 below, shows the stress and displacement analysis that acts on the shaft due to the torsion and the weight applied by the rotor. In figure 16, displacement test was also performed on the bearing support with thrust force at high speeds (20 m/s). For conciseness, the Mechanical sub-system results are not included in the report.

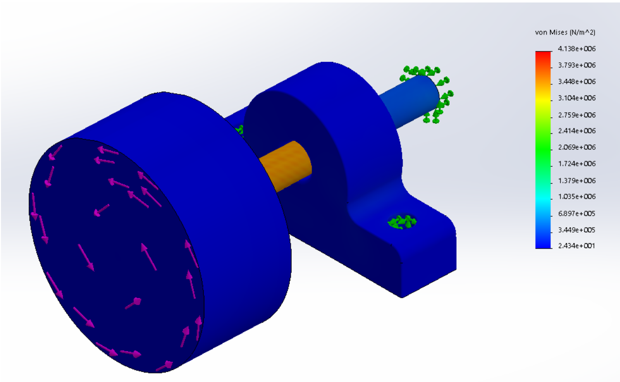


Figure 15: Stress Analysis results in SolidWorks

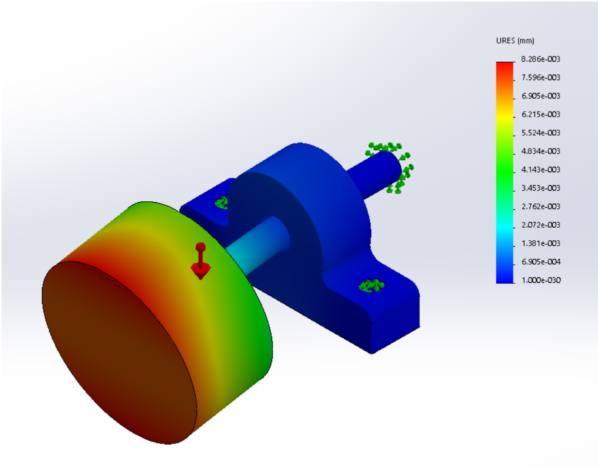


Figure 16: Displacement Analysis results in SolidWorks

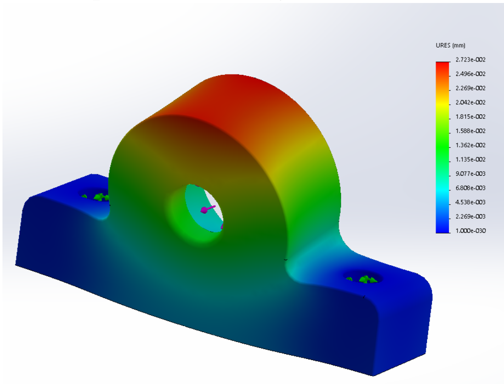


Figure 17: Displacement Analysis in the bearing support using SolidWorks

3.4.3 Electrical & Control Sub-System

The electric circuit design starts with the generator, then gets rectified by a three-phase module, as seen in figure 18. The first and second switch are part of the electrical brake, the second one with the capacitor is used for braking only not for storage. It has connected four voltage sensors to update the MCU and keep the control system going. An ammeter sensor was put to alert the system when the load is removed. Also, a buck boost converter was added to maintain the output voltage. The storage element in the middle will be used for the durability test only. The final electrical design is shown in figure 19 For the mechanical brake the diagram shows the servo motor that will be used to move the caliper from the disk brake. The simulation done in Simulink is showing dynamic controls of the system using a linear mathematical model as shown in figure 20.

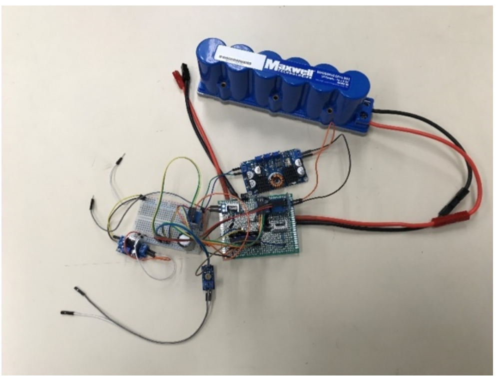


Figure 18: Wind turbine electrical circuit

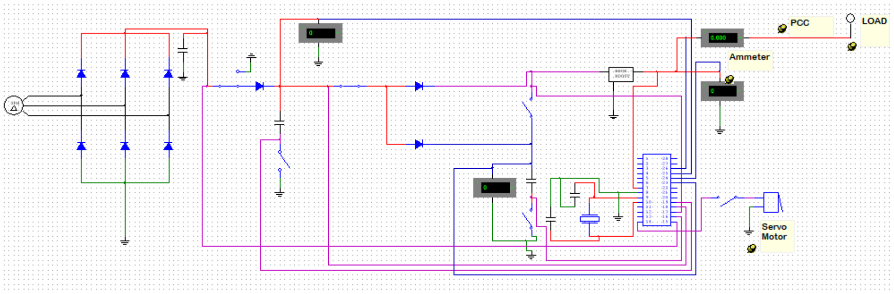


Figure 19: Electrical diagram of the turbine model

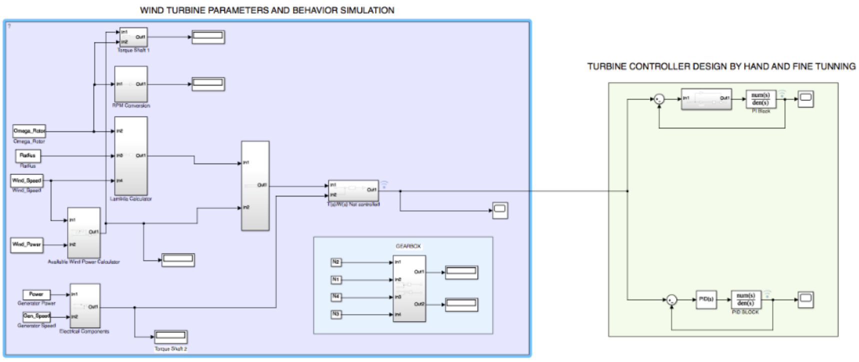


Figure 20: Linear mathematical model in Simulink

3.4.4 Structural Sub-System

The material for the tower selected to support the mechanical components and the rotor is 4130 Alloy Steel. The tower is welded to a disc to provide support and to simplify the assembly process. Using SolidWorks as a Finite Element Analysis program, the tower was analyzed for the stresses applied due to thrust force, drag force, and the weight of the components on top of the tower. The simulations were performed for the extreme condition (20m/s). To ensure that the tower will tolerate all loads at extreme condition, the Safety Factor (SOF) was calculated, which is 22. The maximum deflection was analyzed with a simulation, which gave 0.234 mm. Figure 21 will show the results.

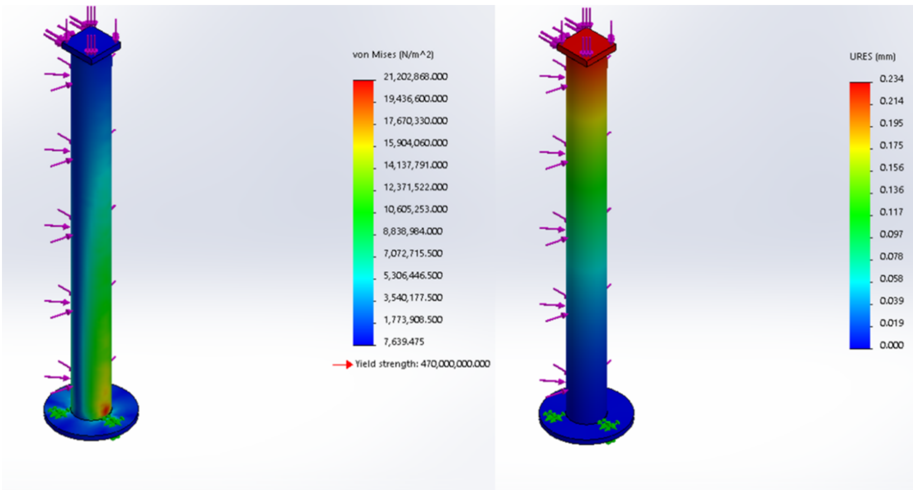


Figure 21: Stresses on the tower due to forces and weight

3.4.5 Yaw Mechanism Sub-System

For a horizontal axis wind turbine (HAWT) a yaw system is required to orientate the turbine with the wind and increase its efficiency. This can be done with an active yaw which needs a controls system, or a passive yaw which only needs a tail vane and a bearing [].

For the orientation with the wind, the turbine operates with a passive yaw system. The selection of this system was done primarily because of the configuration of the turbine being downwind. This also helps simplify the mechanical design and controls, because the system doesn't require power to function. For this turbine, the setup consists of a 6009-2RS bearing which is pressed into a housing and a bushing, to connect the upper part of the turbine with the tower. The connection of the housing and the nacelle base plate is achieved with four bolts and nuts, as seen in Figure 22.

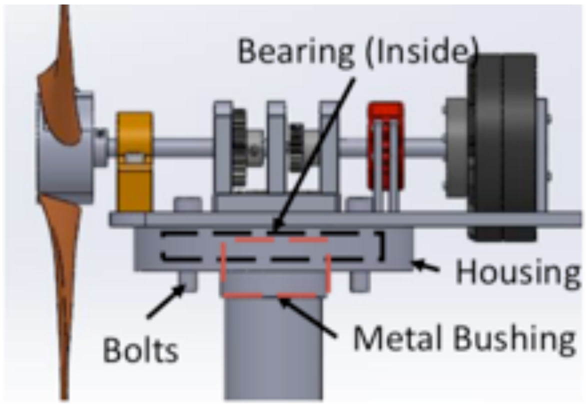


Figure 22. Yaw mechanism

3.5 PHASE D: SYSTEM ASSEMBLY & INTEGRATION

Table10: Assembly Names and Description

Item No.	Part Names	Description	Quantity
1	Nacelle Baseplate	Aluminum – Machined	1
2	Shaft generator	Aluminum – Machined	1
3	Generator	Turnigy 5208	1
4	Blades	PLA Material	3
5	Yaw bearing Housing	Aluminum – Machined	1
6	Main shaft	Aluminum – Machined	1
7	Rotor Hub	PLA Material	1
8	Tower	Chromoly – machined	1
9	Screws	Alloy Steel	31
10	Brake disk	Fiber glass Material	1
11	Brake caliper	Aluminum Material	1
12	Gearbox baseplate	Aluminum – Machined	1
13	Gearbox plate #1	Aluminum – Machined	1
14	Gearbox plate #2	Aluminum – Machined	1
15	Gearbox plate #3	Aluminum – Machined	1
16	Gears	Stainless Steel material	4
17	Bearings	Alloy steel	6
18	Gearbox shaft	Aluminum – Machined	1
19	Bearing support	PLA Material	1

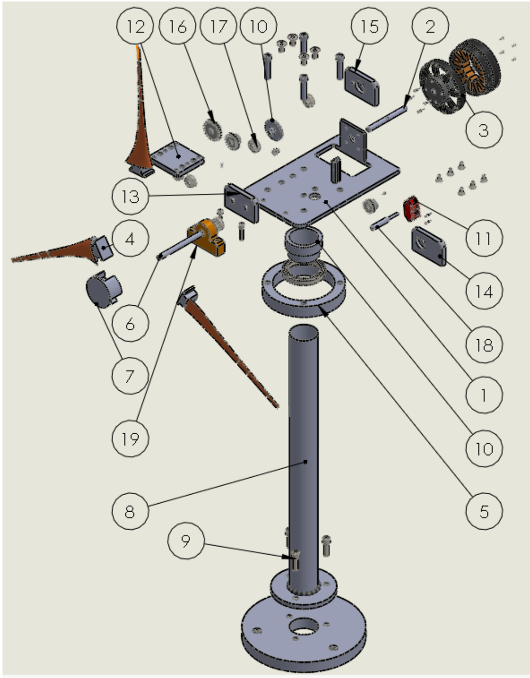


Figure 23: Final System Assembly

3.6 PHASE E: PROTOTYPE DEVELOPMENT

For the purposes of the CWC 2018, a small-scale version of the intended product was designed. This section includes the design and technical aspects of the small-scale wind turbine model presented for the CWC 2018. In essence, four main prototype subsections are outlined here: aerodynamics & structural, mechanical components, electrical & controls components and yaw mechanism testing and validation.

3.6.1 Prototype Testing and Validation

Control sub-system

The electric circuit was tested on two forms: one without the capacitor and the other with the capacitor. During the testing, we used both a 12v to 5w led and a 12V to 3W led as loads except for the durability in which we use power resistors to simulate a worst-case scenario. On both tests, the primarily objective was to power up the microchip, allowing the system to make decisions given the situation. For the first tasks, a buck-boost was used to maintain a constant output voltage of 12V, and we added a voltage regulator to maintain an input of 5V to protect the microchip.

Table 11: Circuit testing with variable loads

Volume Sweep to 5W Load			Volume Sweep 12V to 3W Load			Volume Sweep 5.1 ohms		
Input Voltage	**Input Current**	**Voltage**	**Input Voltage**	**Input Current**	**Voltage**	**Input Voltage**	**Input Current**	**Voltage**
8V	332 mA	12.4V	**8V**	440mA	12.4V	**8V**	440mA	12.4V
9V	287mA	12.4V	**9V**	376mA	12.4V	**9V**	376mA	12.4V
10V	253mA	12.4V	**10V**	330mA	12.4V	**10V**	330mA	12.4V
11V	227mA	12.4V	**11V**	294mA	12.4V	**11V**	294mA	12.4V
12V	206mA	12.4V	**12V**	265mA	12.4V	**12V**	265mA	12.4V
13V	193mA	12.4V	**13V**	246mA	12.4V	**13V**	246mA	12.4V
14V	177mA	12.4V	**14V**	226mA	12.4V	**14V**	226mA	12.4V
15V	163mA	12.4V	**15V**	209mA	12.4V	**15V**	209mA	12.4V
16V	154mA	12.4V	**16V**	196mA	12.4V	**16V**	196mA	12.4V
17V	146mA	12.4V	**17V**	185mA	12.4V	**17V**	185mA	12.4V
18V	139mA	12.4V	**18V**	175mA	12.4V	**18V**	175mA	12.4V
19V	139mA	12.4V	**19V**	167mA	12.4V	**19V**	167mA	12.4V
20V	128mA	12.4V	**20V**	160mA	12.4V	**20V**	160mA	12.4V
21V	123mA	12.4V	**21V**	154mA	12.4V	**21V**	154mA	12.4V
22V	119mA	12.4V	**22V**	148mA	12.4V	**22V**	148mA	12.4V
23V	115mA	12.4V	**23V**	142mA	12.4V	**23V**	142mA	12.4V
24V	111mA	12.4V	**24V**	137mA	12.4V	**24V**	137mA	12.4V

As for the durability task, the circuit remain the same with some slight changes in the code. In addition, the voltage regulator was remove and the MCU was connected directly to the buck boost. Because in this task the output voltage is set to a constant 5V and the capacitor is added to be charged in the first minute. Depending on how much the capacitor was charged, the system will change the flow of current between the capacitor and generator. Also, during this test it was determined the operation voltage of the system.

3.7 PHASE F: CONCLUSION AND RECOMMENDATIONS

Juracan Energy has created an innovative and reliable design that could operate even after severe hurricane wind speed. The market turbine was scaled down to validate the most important and critical characteristic. We concluded that aerodynamic design should be iterate if airfoil characteristic is change. Although the mechanical properties and structure a different from the market turbine the same design techniques. These was also validated in the scaled turbine as well as control strategy.

The team research and development consisted in designing a wind turbine from a technical design, business plan and site project. A scale down model was used to simulate different scenario in real life. Comprehending the behavior of the variation of the wind and complexity of the control system. Optimized the aerodynamic technology to further increase power generated and performance. Have a design that can sustain hurricane wind speeds and try to reduce cost.

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