COLLEGIATE WIND COMPETITION
U.S. DEPARTMENT OF ENERGY

JURACÁN ENERGY TEAM
UNIVERSIDAD DEL TURABO

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EXECUTIVE SUMMARY

Puerto Rico (PR) has been experiencing an energy crisis since the past decade. The cost of energy has not only been a direct burden on individuals, but also a barrier on economic development in the Island. The high cost of energy in PR is largely due to its full dependence on foreign fossil fuels. According to the Puerto Rico Electric Power Authority (PREPA), oil-burning plants currently produce 61% of the electricity in PR. Natural gas and coal represent 24% and 14%, respectively, and only 1% of the electricity is generated by renewable sources [1]. One of the key contributors to energy consumption in PR is public illumination. Public illumination includes street and highway lighting, traffic lights, public parks, and recreational facilities, among others.

According to the PREPA, the total cost for public illumination was $109.1M in 2014 [1]. Public illumination is provided to municipalities as part of an agreement with PREPA. According to this agreement, PREPA provides free electricity to municipal entities in lieu of paying municipal taxes. However, PREPA recovers the municipalities' electricity expenses through an 11% markup on the oil and other fuels that are later imposed to its regular customers [2].

A significant portion of electricity consumption in public illumination comes from light poles. There are about 550,000 light poles illuminating public roads and streets in Puerto Rico [3]. The overwhelming majority of the light poles (i.e., approximately 95%) belong to the government and municipalities on the Island. Unfortunately, PREPA's consumers and customers ultimately pay the incentives that municipalities receive in terms of public illumination.

Recognizing the elevated cost of electricity and the high level of energy consumption, Juracán Energy Team (JET) identified an excellent opportunity for an off-the-grid wind energy system for public illumination in Puerto Rico. Since a significant portion of electricity consumption comes from light poles, the initial focus in product development will be to provide a solution in product development that addresses street and highway illumination.

In order to provide a reliable solution, the proposed wind energy system must work at any site and adaptable to existing light poles. Furthermore, to provide a cost-effective solution, the wind turbine must not require wind-speed measurements before its installation. Due to the intrinsic variability in wind energy throughout the day and the relative low wind speeds that are usually found in Puerto Rico, the wind turbine must effectively work at relatively low wind speeds (i.e., around 3 to 5 m/s). Therefore, the wind turbine's aerodynamic design must allow the electricity generating process to start at very low wind speeds. The low wind speed requirement also imposes a limitation in the maximum available electric power, which implies the need to combine the development of the wind turbine system with efficient luminaries such as LED bulbs.

JET's design consists of original technology that integrates various aerodynamic concepts (e.g., drag and lift based components) to maximize low-wind performance. It also integrates a novel whale-blade design to help reduce the turbulence caused by the wakes generated by the turbine's blades during operation. As shown in the report, JET's wind turbine is capable of powering a completely grid-independent light pole for low wind speed applications. This new design will provide an effective solution to the fossil fuels dependence for public illumination in PR.

1 BUSINESS PLAN

This section outlines the development of Juracán Energy Team as a start-up company. Details regarding the Business Overview, Market Opportunity, Management Team, Development and Operations, and the Financial Analysis are outlined here.

1.1 BUSINESS OVERVIEW

Juracán Energy Team is a new company located in Gurabo, Puerto Rico that focuses in the design, manufacturing, and sales of small-scale wind turbines. JET is composed of a multidisciplinary group of students from engineering, business, and design at Universidad del Turabo (UT). The company was born to provide an alternative to mitigate the high cost of electricity in Puerto Rico. JET's 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 wind". The origin of the name came from the Taíno words "jura" (i.e., wind) and "cán" (i.e., center). JET's main product is a vertical-axis wind turbine (VAWT) for public lighting applications. The innovative wind turbine design is particularly suited for extra low wind speed applications. This particular feature gives a distinctive value and competitiveness versus other existing wind energy alternatives for Puerto Rico.

1.1.1 JET Company Mission

We provide cost-effective and off-the-grid wind energy solutions. Our clients are the reason for our existence; we seek to reduce electricity costs while contributing to environmental preservation.

1.1.2 JET Company Vision

To illuminate the world with a clean energy source.

1.1.3 JET Company Values

- Passion for renewable energy and environmental protection.
- Commitment to preserving the environment.
- Innovation in our products and path to market.
- Promote ethics to achieve excellence.
- Confidence in our products and services.
- Sustainability in order to improve the quality of life for present and future generations.

1.2 MARKET OPPORTUNITY

1.2.1 Problem Definition

Puerto Rico (PR) has been experiencing an energy crisis since the past decade. The cost of energy has not only been a direct burden on individuals, but also a barrier on economic development in the Island. One of the key contributors is the energy consumption in public illumination. According to the information provided by government officials, public illumination has become a significant contributor to the energy problem in Puerto Rico [3]. Public illumination includes street and highway lighting, traffic lights, public parks, and recreational facilities, among others. Figure 1 shows a qualitative view of the utilization of public illumination in Puerto Rico. As shown in the figure, there is a significant difference in the level of public illumination when compared to adjacent Islands in the Caribbean.

According to the Puerto Rico Electric Power Authority (PREPA), which is the sole provider of grid-connected electricity in Puerto Rico, the total cost for public illumination totaled $109.1M in 2014 [1]. This is particularly relevant to municipal entities and represents near 44% of their total electricity consumption. The public illumination in municipalities is part of an agreement with PREPA called Contributions in Lieu of Taxes (CILT) [4]. According to this agreement, PREPA provides free electricity to municipal entities in lieu of paying municipal taxes. However, PREPA recovers the municipalities'

Figure 1. Night view of Puerto Rico (Image from the International Space Station)

electricity expenses through an 11% markup on the oil and other fuels that are later imposed to its regular customers [2]. Unfortunately, PREPA's consumers and customers ultimately pay the incentives that municipalities receive in terms of public illumination.

Figure 2 shows the monthly cost of electricity (i.e., cents per kWh) for public illumination since 1999 to the present in Puerto Rico. As shown in the figure, the cost of electricity peaked at 43 cents per kWh in 2011. Although the cost of electricity has diminished since the beginning of 2013 due to the reduction in oil prices, the cost of electricity for public lighting is still relatively expensive. The cost in January 2016 was still nearly 30 cents per kWh. This is about 1.75 the cost of electricity for domestic customers in Puerto Rico during the same month.

Figure 3 shows the monthly energy consumption (in millions of kWh) for public illumination in the Island since 1999 to the present. Although not as high as the consumption by domestic, commercial, and industrial consumers, the electricity consumption in public illumination is the fourth largest segment in Puerto Rico. It can be observed in that same figure that the electrical consumption reached around 27.3 MkWh in January of 2016. Despite the high level of variation in the data, the positive slope in the trend line (i.e., red line in the figure) shows an increase in consumption throughout the years. Although the data includes various sources of public illumination, a significant portion of electricity consumption comes from lighting poles. There are about 550,000 light poles illuminating public roads and streets in Puerto Rico [3]. The overwhelming majority of the light poles (i.e., approximately 95%) belong to the government and municipalities on the Island.

In addition to the relatively high cost and consumption, the generation of electricity in Puerto Rico has two other relevant aspects. First, electricity generation in Puerto Rico is a monopoly. As a government-owned corporation, PREPA is the sole provider of electricity. Lack of competition may contribute to high electricity costs. Second, there is a high dependence on foreign fossil fuels to produce electricity. According to PREPA, oil-burning plants currently produce 61% of the electricity in the Island. Natural gas and coal represent 24% and 14%, respectively, and only 1% of the electricity is due to renewable sources [5]. It is important to note that PR does not produce any fossil fuels and therefore, needs to import all fuels utilized in electricity generation.

Minimizing the dependence on fossil fuels will also reduce its contribution to environmental pollution and greenhouse effects. In fact, a 2010 law in PR established a goal that 12% of the energy produced must be through renewable sources or alternative sources by 2015 [6]. As also established in the law, this percentage shall increase to 15% by 2020 and 20% by 2035. With only 1% of electricity currently produced by renewable sources, meeting these requirements has become a relevant challenge to the Island.

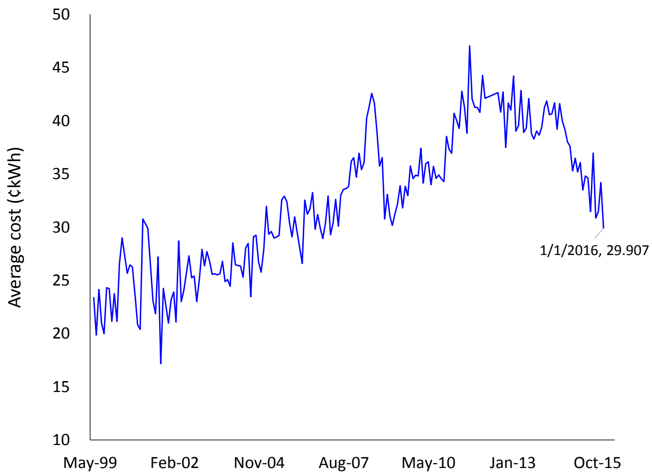

Figure 2. Monthly cost of electricity for public illumination in PR [7]

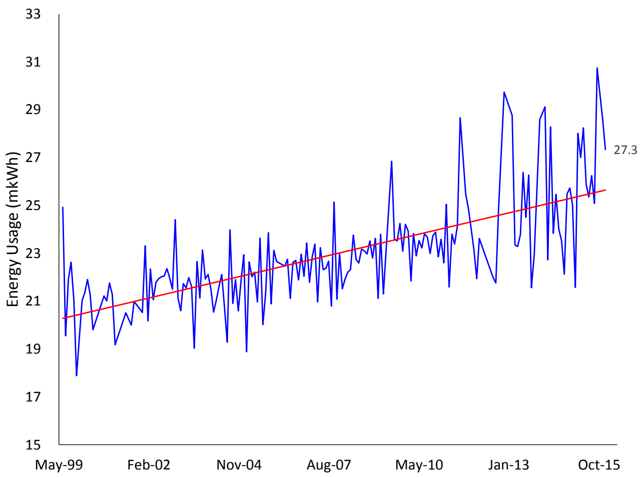

Figure 3. Monthly energy consumption for public illumination in PR [7]

1.2.2 Proposed Solution

Recognizing the elevated cost of electricity, the high level of energy consumption, the PREPA monopoly, and the law requirement to lower the dependence to fossil fuel in the Island, JET identified an excellent opportunity for an off-the-grid renewable energy system for public illumination in Puerto Rico. JET seeks to provide off-the-grid wind turbine systems for public illumination. Since a significant portion of electricity consumption comes from light poles (i.e., estimated at 550,000), the initial focus in product development will be to provide a solution in product development that addresses street and highway illumination (i.e., light-pole applications).

In order to provide a reliable solution for street and highway illumination applications, the proposed solution must work at any site and needs to be adaptable to existing light poles. Furthermore, to provide a cost-effective solution, the wind turbine must not require wind-speed measurements before its installation. Due to the intrinsic variability in wind energy throughout the day and the relative low wind speeds that are usually found inland in Puerto Rico [8] the proposed solution must effectively work at relatively low wind speeds (i.e., around 3 to 5 m/s). Therefore, the wind turbine's aerodynamic design must allow the electricity generating process to start at very low wind speeds. The low wind speed requirement also imposes a limitation in the maximum available electric power, which implies the need to combine the development of the wind turbine system with efficient luminaries such as LED bulbs. LED bulbs could consume up to 83% less energy than conventional light bulbs [9].

1.2.3 Target Client

JET's goal is to provide a cost-effective solution for the generation of electric energy in public illumination while reducing the use of fossil fuel sources. JET's primary target market is the local area of Puerto Rico. The high electrical consumption of public illumination and high cost of energy in Puerto Rico provide an excellent opportunity to market and sell the product in the Island. In particular, JET focuses in the municipalities of Puerto Rico. There are 78 municipalities in the Island with a total population of about 3.5 million. Figure 4 shows the overall electricity consumption by municipalities in the Island. As shown in the figure, the metropolitan area, which includes San Juan (capitol city), has the highest level of electricity consumption. To date, the municipalities are not paying for the public lighting services provided by PREPA. However, recent economic pressures at PREPA, and the fact that residential and industrial customers are subsidizing these cost, modifications to the CILT are being promoted. JET's goal is to provide a win-win alternative for both PREPA and the municipalities, by creating an alternative for the municipalities to generate their own electricity for public lighting without incurring in an additional debt to PREPA.

1.2.4 Market Size

Although public illumination includes various sources such as street and highway lighting, traffic lights, public parks and recreational facilities, among others, a significant portion of electricity consumption comes from lighting poles. The initial product development focus will be to address a light pole application. There are about 550,000 light poles illuminating public roads and streets in Puerto Rico [10]. The great majority of the light poles (i.e., approximately 95%) belong to the government and municipalities on the Island. Even a small percentage of implementation in existing light poles of JET's proposed solution (e.g., 1%) will provide a feasible business alternative (i.e., 5,500 turbines).

Although the primary target is Puerto Rico, the successful implementation of wind turbines for public illumination could be expanded to other jurisdictions outside the Island. In particular, this solution could be implemented in other areas that have a high dependence on fossil fuels, such as Hawaii.

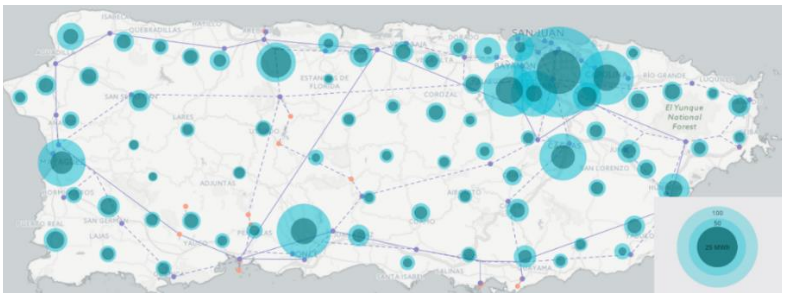

Figure 4. Geographical distribution of electrical energy consumption in PR [10]

1.2.5 Competition

Although there are no known current wind energy systems for public illumination in Puerto Rico to date, there are existing wind energy systems for similar applications elsewhere. Table 1 shows the preliminary findings of the direct competitors for JET's proposed solution. JET will address the potential direct competition from these available products by focusing on a design that will operate at the extreme low wind speed conditions.

Table 1. Existing wind energy systems for light pole applications

Product	Price
UGE HoYi 200W Vertical Axis Wind Turbine	$2,470
Maglev Vertical Axis 300W/24V	$2,826
Vertical Wind Turbine with Street Light	$3,528

1.2.6 SWOT Analysis

JET performed a SWOT (i.e., Strengths, Weaknesses, Opportunities and Threats) assessment to understand its competitive positioning in the intended market. Table 2 shows the results of the SWOT analysis.

Table 2. JET SWOT Analysis

Strengths	Weakness
Unique and innovative product in Puerto Rico.	No first-party manufacturing capability
First to use wind power integrated directly into a light pole in Puerto Rico	Lack of funds to start the company
We have prior wind studies to support that our product will work	Previous failure of wind energy projects on the Island
Strong design team	Lack of business experience
Opportunities	**Threats**
High-energy costs and consumption are making people look for alternative ways of generating electricity. (removable energy)	Puerto Rico's tropical weather. (Weather and winds speed vary a lot per sector)
Market size of over 550,000 light poles plus other possible applications	Bad perceptions people may have about wind turbines or wind energy
The local government in Puerto Rico has established a Law which says that Puerto Rico has to reach 15% of renewable energy by the year 2020	Complexity on behalf of Puerto Rico Government laws and regulations on the design, certification and implementation of wind turbine systems [11] & [12]
Potential to lower energy costs in Puerto Rico by substituting current grid-connected public lighting poles with off-grid micro-wind turbines	Puerto Rico's economic crisis restrains the development of new projects
Only product designed based on Puerto Rico weather	Less expensive technologies are being developed

1.2.7 Business Risk Management

Following the SWOT analysis, the following risk items and corresponding mitigation strategies were identified in Table 3.

Table 3. Risk Recognition and Management

Risk	Mitigation Strategy
Lack of business experience by the management team	Obtain external advice from available government initiatives for new businesses
Inability to raise capital funds to start operations	Seek further financial advice in order to demonstrate feasibility of proposed project
Negative public perception towards wind energy	Promote education about the benefits of wind energy
Lack of economic incentives for wind energy	Seek further cost reductions in design to eliminate need for external economic incentives for buyers
Emergence of direct competitors in PR	Continue developing the technology to demonstrate the leadership in the industry
Failure to launch projects on time and on budget	Ensure dedicated project management
Significant reduction in oil prices can make the wind turbine un attractive	Seek further cost reductions in design and manufacturing to further lower the cost of the product

1.2.8 Marketing, Pricing and Sales Plan

The product pricing was determined through a mark-up value strategy. A mark-up was added to the product after calculating initial start-up costs and other fixed expenses, in order to obtain enough revenues to obtain solvency (see Section 1.5). This contribution margin was chosen as a function of the assumptions used to develop the financial analysis for JET's business start-up and operation.

Moreover, after an initial survey was conducted with representatives from all the municipalities, it was found that at least ten of them were interested in JET's proposition (see Section 3). However, JET made a conservative assumption that at only five municipalities decided to buy 50 turbines each, for a total of 250 units sold during the first year. The financial analysis for the first year was based on this assumption, and it was determined that JET could operate satisfactorily. In other words, with only a minimum of the municipalities serving as initial clients for JET, they will still be able to operate under normal conditions, while expanding and generating more sales throughout their start-up years. Specific details regarding profit and losses, balance sheets, and other pro-forma statements are referenced in Section 1.5 and Appendix B: Full Pro-Forma Statements.

1.3 MANAGEMENT TEAM

To align with existing energy challenges, the JET took the initiative of developing a business that would provide a solution to the existing energy crisis. The official JET management team is composed by:

- Chief Executive Officer (CEO) - Harry Bonilla (Administrator) is in charge of decision making, management, and executing existing and future projects to ensure policies and company guidelines are followed.
- Chief Operations Officer (COO) - Miguel A. Díaz (Sales) is in charge of the day to day operations while reporting directly to the CEO. He is responsible for the quality and marketing departments.
- Chief Technological Officer (CTO) - Anthony Rivera (Design Engineer) is in charge of the research and development departments for the needs of the technical design aspects of the company and products.

1.4 DEVELOPMENT AND OPERATIONS

JET intends to raise the public's awareness of this product's existence through a series of different channels. JET will use web marketing, direct sales, industry events, green-energy events and customer referrals as marketing channels. JET will display their product in these events by doing test runs, as well as selling them to potential clients. Prospective buyers will be able to visit the product's website or visit the main offices in order to buy the product. Additionally, the product will be manufactured through third-party resources. The product distribution and delivery will be made through external subcontractors whereas the installment and maintenance of the product will be directly handled by JET.

1.4.1 Technology

JET's product's official name is *Balæna*. The etymology of *Balæna* derives from the latin word for whale. We chose to name our product *Balæna* given our inspiration and innovation on the aerodynamic effect that whale fins have while decreasing turbulence effects and drag resistance during motion. This whale-blade concept was implemented in our design to make it more aerodynamically feasible and more esthetically appealing to our customers. The details of the design are included in Section 2 of this report. A summary of the innovative features that *Balæna* possesses are listed as follows:

Innovative turbine features

- The turbine's "ribs" have a scoop design, allowing for more aerodynamic advantages during start-up at low wind speeds operation.
- The blades have a whale fin design that provides less turbulence and drag, consequently making the rotor self-start at lower wind speeds more easily.

Product Uniqueness

- Its design allows starting generating energy at extremely low wind speeds.
- It works with both lift and drag forces. The scoop design allows for harvesting the benefits of drag forces, whereas the blades provide additional lift forces to increase rotational power.

1.5 FINANCIAL ANALYSIS

This section focuses on the marketing and sales performance of JET as a business. Moreover, the Business Plan Pro Premier software was used to create and develop all the pro-forma statements shown in this report. A break-even analysis was performed to determine the variable costs, revenues and break-even point for JET's product. Moreover, a projection (i.e., Cash-Flow Analysis) for the first five years of business operation was modeled to determine the company's feasibility. Balance sheets, income statements and other pro-forma documents are highlighted in this section. On the other hand, pricing was established in order to complete an initial case study for JET's product as a function of cost per kWh in comparison to conventional public lighting poles. These analyses were performed for two distinct cases: one where no economic government incentives were considered and one where current government incentives were applied.

1.5.1 Start-up Summary

The start-up costs sum up to $47,707, half of which are mostly administrative, rent, insurance, transportation, and salary costs associated with initiating our business. On the other hand, assets for initial cash and inventory requirements compose the rest of the start-up costs. These assumptions are shown in Table 4.

Table 4. Start-up requirement costs

Start-up Requirements	
Startup Expenses	
Administrative Costs	$2,000
Insurance	$4,480
Rent	$1,000
Transportation	$1,000
Salaries	$15,227
Total Startup Expenses	**$23,707**
Startup Assets	
Cash Required	$1,000
Startup Inventory	$23,000
Other Current Assets	$0
Long-term Assets	$0
Total Assets	**$24,000**
Total Requirements	**$47,707**

1.5.2 Sales Forecast

After consulting with representatives from the 78 municipalities through a survey, it was determined that at least 10 of them were interested in JET's proposal. Nonetheless, to maintain a realistic and conservative assumption, JET established that only half of those municipalities would actually purchase their product. Consequently, the Sales Forecast was based upon the assumption that each of these five municipalities bought at least 50 turbines during the first year, for a total of 250 units being sold during the end of the fiscal year. This yielded a total revenue of $550,000, with a total direct cost of sales of $339,250, for a contribution margin of $210,750 during the first year of operations. Further details regarding the Sales Forecast are shown in Appendix B: Full Pro-Forma Statementsof this report.

1.5.3 Personnel Plan

JET will initially consist of six personnel, three of which are also part of the Management Team. The personnel salaries are outlined in Table 2. Assuming fixed salaries for the first five years of operation, the yearly amount of salary expenses for JET would total $167,112.

Table 5. Personnel Plan for JET's start-up and first five years of operation.

Personnel Plan					
	FY 1	FY 2	FY 3	FY 4	FY 5
Administrator/Manager	$48,000	$48,000	$48,000	$48,000	$48,000
Administrative Assistant	$13,920	$13,920	$13,920	$13,920	$13,920
Sales Specialist	$24,000	$24,000	$24,000	$24,000	$24,000
Design Engineer	$39,600	$39,600	$39,600	$39,600	$39,600
Technician	$20,796	$20,796	$20,796	$20,796	$20,796
Technician	$20,796	$20,796	$20,796	$20,796	$20,796
Total Payroll	$167,112	$167,112	$167,112	$167,112	$167,112

1.5.4 Break-Even Analysis

A Break-Even Analysis was performed by JET in order to analyze whether the business venture would succeed. The Business Plan Pro Premier software was used to determine this break-even point. Average variable costs per-unit were established as $1,357, whereas average revenue per-unit was established with a mark-up value of $2,200 (see Table 6). According to the software, JET would need to sell at least 25 units per-month in order to achieve break-even (see Figure 7).

Table 6. Break-Even Analysis

Break-Even Analysis	
Monthly Units Break-even	25
Monthly Revenue Break-even	$54,777
Assumptions:	
Average Per-Unit Revenue	$2,200.00
Average Per-Unit Variable Cost	$1,357.00
Estimated Monthly Fixed Cost	$20,990

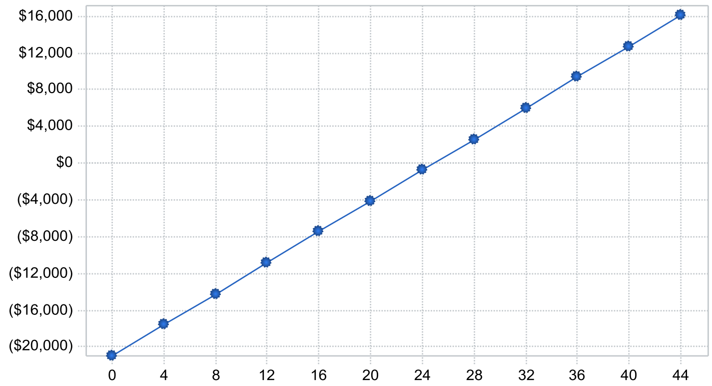

Figure 5. Break-even chart

1.5.5 Profit and Loss Analysis

An income analysis was performed in order to determine the net profit for JET during the first five years of operation. Sales revenues for the first year totaled $550,000, while direct cost of sales totalled $339,250, for a gross margin of 38.32% or $210,750. Additionally, operating expenses such as the payroll, administrative costs, rent, transportation, and insurance & payroll taxes are were included, for a total of $251,877 during the first year. After interests and income taxes were applied, the net loss for the first year totalled a value of $44,879 (see *Table 6*Table 7). Further information for the first five years of operation may be found in in the Appendix B: Full Pro-Forma Statements of this report.

Table 7. Profit and Loss table for the first year of operations.

Pro Forma Profit and Loss	**Fiscal Year 1**
Sales	$550,000
Direct Cost of Sales	$339,250
Total Cost of Sales	$339,250
Gross Margin	$210,750
Gross Margin %	38.32%
Expenses	
Payroll	$167,112
Administrative Costs	$24,000
Rent	$12,000
Transportation	$12,000
Insurance & Payroll Taxes	$36,765
Total Operating Expenses	$251,877
Profit Before Interest and Taxes	($41,127)
EBITDA	($41,127)
Interest Expense	$3,752
Taxes Incurred	$0
Net Profit	($44,879)

1.5.6 Cash Flow Analysis

JET performed a Cash Flow Analysis in order to track the number of units sold to identify what could affect the revenues, expenses and profits. For the first year, JET assumed a total revenue of $550,000 a total expenditure of $561,190, and a total value added tax collection of $63,250. Moreover, in order to avoid a negative cash balance, JET would solicit a $50,000 loan for the initial startup costs. Additional information for the first five years of operation is shown in Appendix B: Full Pro-Forma Statements of this report.

Table 8. Cash-Flow Analysis for the first year of operations.

Pro Forma Cash Flow	***Fiscal Year 1***
Cash Received	
Cash from Operations	
Cash Sales	$550,000
Subtotal Cash from Operations	$550,000
Additional Cash Received	
Sales Tax, VAT, HST/GST Received	$63,250
New Current Borrowing	$50,000
Subtotal Cash Received	$663,250
Expenditures	
Expenditures from Operations	
Cash Spending	$167,112
Bill Payments	$394,078
Subtotal Spent on Operations	$561,190
Additional Cash Spent	
Sales Tax, VAT, HST/GST Paid Out	$63,250
Principal Repayment of Current Borrowing	$9,163
Subtotal Cash Spent	$633,603
Net Cash Flow	$29,647
Cash Balance	$30,647

1.5.7 Pricing

JET revenue sources are wind turbines for light pole application. The Break-Even Analysis determined that a monthly production of 25 turbines would yield a production cost per-unit of $1,357 (including turbine components and assembly costs). Moreover, a market price per-unit of $2,200 was established to provide a large enough contribution margin to obtain solvency within the first five years of operation.

1.5.8 Initial Case Study

JET conducted an initial case study in order to calculate the cost of wind energy in Puerto Rico, according to the conditions set by the market. The following assumptions were taken into consideration when making the initial case study:

1. 200 W wind turbine
2. 24-hour daily operation
3. An average Capacity Factor of approximately 13.5% (see Section 3.1)

4. Fixed Charge Rate of 4.40% [13]
5. $20/kW O&M costs for the product [14]

Table 9 summarizes the results from the initial case study. It can be observed that if the system had a capacity factor of 13.5%, it would generate an annual energy production of 262.8 kWh, incurring in a Cost of Energy (COE) of approximately $0.43/kWh per unit before incentives, and approximately $0.22/kWh after incentives.

Table 9. Initial Case Study Cost of Energy (COE) per unit

JET Turbine Cost of Energy (CoE)			
Parameter	**Unit**	**Value**	
Rated Power	kW	0.2	0.2
Hours/Day	hr	8760	8760
Capacity Factor (CF)	%	13.50%	13.50%
Yearly Energy	kWh/yr	236.52	236.52
Cost per Unit	$	$2,200.00	$1,100.00
Fixed Charge Rate	$/yr	4.40%	4.40%
O&M Costs	$	$4.00	$4.00
COE	**$/kWh**	**0.43**	**0.22**

2 TECHNICAL DESIGN

Due to the multi-disciplinary aspects of this initiative, a systems engineering (SE) approach is adopted as the core methodology for the execution of the technical aspects of the project. The SE methodology is widely used by NASA and involves a disciplined approach for the design, realization, technical management, operations, and retirement of a system. The main goal of the SE approach is to design, build, and operate the system in the most cost-effective way by simultaneously considering performance, cost, schedule, and risk [15]. The SE methodology divides a complex system into manageable phases throughout its entire life cycle. The robustness of NASA's SE methodology is based in the consistent implementation of core technical development processes throughout all the project phases.

A modified version of NASA's SE process is depicted in Figure 6 and it involves seven phases: a preliminary phase (i.e., Pre-Phase A) and six subsequent phases (i.e., Phases A-F). As shown in the figure, the first three phases (i.e., Pre-Phase A, Phase A, and Phase B) involve the formulation aspects of the project (i.e., from definition of requirements to preliminary design) and the last four phases (i.e., Phases C-F) deal with implementation aspects of the project (i.e., from final design to conclusions and recommendations).

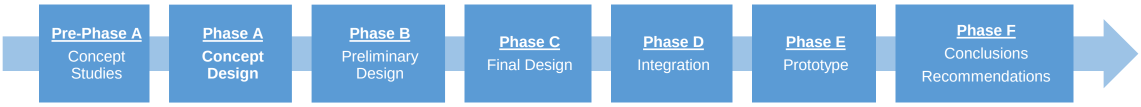

Figure 6. Systems Engineering Cycle (modified from *[15]*)

2.1 PRE-PHASE A: CONCEPT STUDIES

This section includes trade studies, preliminary design concepts, application ideas, market and problem assessments, and product breakdown structure for JET's wind turbine design.

2.1.1 Project Objectives

Our team proposes the implementation of grid independent wind turbines. The idea is to develop new and adaptable wind turbines to existing light poles. Due to the intrinsic variability in available wind energy, the solution will include a battery bank to store enough energy for an estimated 12-hr daily operation. The solution will also include the utilization of LED bulbs to provide an energy efficient system. LED bulbs generally consume up to 83% less energy than conventional light bulbs [9]. Our team's wind turbine's aerodynamic design will allow starting generating electricity at very low wind speeds. This wind turbine will also meet OSHA regulations as well as existing regulations regarding the installation of wind energy sources in PR.

2.1.2 Measures of Effectiveness (MOEs)

The Measures of Effectiveness (MOEs) define operational requirements from the customer/stakeholder viewpoint [15]. For the intended application, the MOEs were obtained from interviews with government officials and prospective customers from the private sector. These MOEs include a product that:

- Should be flexible to attach to any type of light pole
- Should be maintained without much effort
- Should last a long time
- Must have good aesthetics
- Should comply with laws and regulations (Environmental and Safety Regulations)
- Shall be low cost compared to available renewable technologies for light poles
- Should operate without much effort
- Should be reliable and work under a variety of wind conditions

2.1.3 Concept of Operations (Current State)

Currently, light poles are connected to PREPA's power grid. Except for very few isolated poles with small solar panels installed, there is no other method for energizing these poles. Thus, the majority of the public street lighting system is grid-dependent (see Figure 7).

Figure 7. Current Concept of Operation for Public Street Lighting in PR

2.2 PHASE A: CONCEPT DEVELOPMENT

This section includes the refinement of the preliminary trade studies performed for Pre-Phase A in order to establish engineering and design guidelines to develop an effective product. Technical design information including government regulations, engineering design codes along with other pertinent literature may be found here.

2.2.1 System-Level Technology Assessment

Most of our design considerations are based on government and engineering standards. First of all, the IEC 61400-2 document requires design load considerations for both normal operation and fatigue loads [16], which are part of the safety standards used in the U.S. and Puerto Rico. Also, equivalent stresses shall be calculated on all important load carrying components, whereas partial safety factors for materials are 1.25 and 10 for fully characterized and minimally characterized materials, respectively. Furthermore, no mechanical interference between the blade and the tower (light pole) can occur.

Additionally, design considerations for extreme wind conditions must be established [17]. In this case, the application of 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 [18]. In other words, the turbine must be able to withstand category 4 hurricane force wind conditions, even if these events are rare or unlikely to happen in PR.

Furthermore, resonance shall be avoided for normal operating conditions, and the design shall be reliable enough to resist resonance during turbulence [19]. On the other hand, a minimum coefficient of power (C_P) of approximately 0.45 should be achieved for optimum performance. The C_P determines the amount of power available from the wind, and is a function of the cube of the velocity of the wind (v^3). Since this parameter is influenced by the turbine geometry and aerodynamics, an optimum design must be obtained to ensure a self-starting turbine, without compromising integrity or the performance of the turbine. Also, a control system needs to be used to avoid any electrical overloads or failures, and to maintain steady operating speeds for the turbine.

2.2.1.1 Measures of Performance (MOPs)

While the MOEs represent stakeholder's expectations, which are critical to the success of the product, the Measures of Performance (MOPs) are a measure of actual performance of a supplier's particular design solution. These are indirectly related to the customer/stakeholder's concerns [15]. MOPs were defined as functional, performance, and safety MOPs, and described as follows:

Functional MOPs:

- The turbine shall generate power at wind speeds of less than 2.5 m/s.
- The rotor should have an optimum solidity to accomplish self-start.
- The turbine design should not exceed 2 x 2 meters in height nor length.
- The structural design of the turbine must be designed in two parts: rotor and attachment.
- The turbine must have a lifetime of over 100,000 hours.
- The system must have a battery bank to store energy during daytime hours.

Performance MOPs:

- The turbine should generate up to 3x the power needed by the load at the rated wind speed.
- The turbine C_p for the design should not be less than 0.45.
- The structural design of the turbine shall resist wind pressures of 6.9kPa (145 lb/ft^2).
- The turbine shall avoid resonance with the operational and the blade passing frequencies.
- The rotor should resist a maximum torque of approximately 3.13 N-m (2.31 lb-ft).
- The turbine shall start operating at 2.5 m/s.
- The generator should produce a rated power of 200 W (i.e., 2x the required load).
- The generator shall produce power for rotational speeds in the range of 25 rpm to 205 rpm (cut-in and rated speeds), assuming no gearbox.
- The power electronics, such as charge controller and rectifier, should comply with the wind turbine required performance.
- The power quality characteristics for the turbine shall meet IEC 61400-21 standards [16].

Safety MOPs:

- The safety factors shall be 1.35 for fatigue and ultimate loads [16].
- The material safety factors shall be 1.1 and 1.25 for ultimate and fatigue strengths, respectively.
- The generator must have a high overload capacity.
- The control system must be able to regulate operating velocity to avoid speeds over 300 rpm.

In order to develop the engineering specifications, the Quality Function Deployment (QFD) method was applied [20]. The QFD provided quantitative results to evaluate if the MOPs complied with the MOEs.

2.2.1.2 System-Level Trade Studies

Initially, three concepts for wind turbine were evaluated. These concepts included two Vertical Axis Wind Turbines (VAWTs) and one Horizontal Axis Wind Turbine (HAWT). The VAWTs were a Darrieus and a Savonius concept, whereas the HAWT was a traditional style turbine (see Figure 8).

Figure 8. VAWT and HAWT concepts for Pugh's Decision Matrix

Moreover, these concepts were evaluated using the redefined MOEs provided by the prospective customers and weighed by a qualitative engineering analysis. A Pugh's Decision Matrix was used for the turbine selection. As result of the matrix, the Darrieus VAWT was the best fit for the requirements.

2.2.1.3 Project Architecture

The wind turbine design process was divided into three main sub-systems. These sub-systems included the Aerodynamic & Structural components, the Mechanical components, and the Electrical & Controls components (see Figure 9). Each one of these is further divided into individual components that comprise intrinsic items within each system.

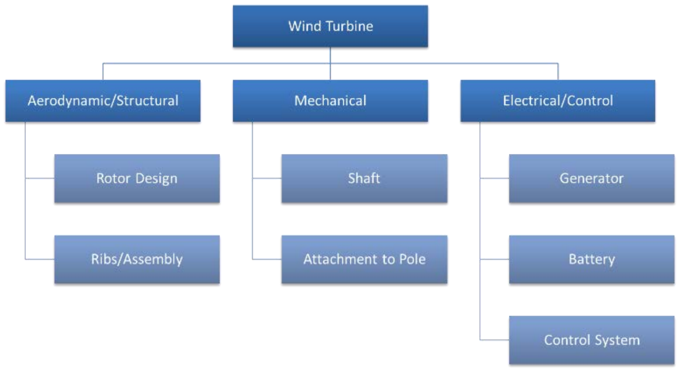

Figure 9. Wind Turbine Product Breakdown Structure diagram

2.3 PHASE B: PRELIMINARY DESIGN

This section includes initial design calculations and modeling. Most of these calculations were done by hand or through spreadsheets in order to have a preliminary idea of the component requirements and performance. These results were later used to compare CFD and CAD model analyses and results performed for Section 3.5 (Phase C).

2.3.1 Aerodynamics & Structural Sub-System

2.3.1.1 Technology Assessment: Aerodynamics & Structural Sub-System

The turbine dimensions were iterated using the Double Stream-Tube Model (DMS) found in Q-Blade [21] . This method is specifically used for the development of VAWTs given that it considers energy losses for upstream and downstream winds for the blade position in the rotor. This DMS model assumes two disks where the blade or rotor assembly will be interacting. Each disk represents a semi-circle of the turbine position, consequently modelling the blade location and operation. The DMS accounts for the energy losses due to the vertical assembly of the turbine, which is done by calculating an induction factor.

2.3.1.2 Trade Studies: Aerodynamics & Structural Sub-System

Three airfoils were evaluated for performance. The airfoils chosen are commonly used for VAWTs and can be seen in Figure 10. Their performance was weighed as a function of their C_P and self-start capability, along with the capability of producing the required power at low wind speeds. For normalization purposes, the same rotor dimension and parameters were used for all three airfoils. This was done to obtain the highest C_P within a feasible rotor size. The criteria used for this decision was independent from the original sub-system MOPs, since the primary focus was obtaining a specific blade for the rotor itself. By using a Pugh's Decision, the selection process determined the NACA 0018 as the most promising option.

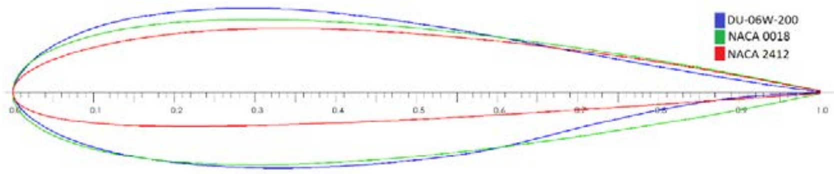

Figure 10. Evaluated Airfoil Options

2.3.1.3 Trade Studies for the Rotor Design

This sub-system requires many key considerations in order to obtain the optimum performance. The main factors that affect aerodynamic performance involve having the correct turbine solidity and aspect ratio (AR) for the rotor. Parameters shown in Table 7 were evaluated in Q-Blade. The considered concepts varied the AR, while maintaining a constant projection area and solidity range for each analysis. The highest power curves for each aspect ratio are shown in Figure 11.

Table 10. Design Parameter Varied for desired rotor dimension

Parameter	Value
Number of blade	3
Aspect Ratio	0.5<AR<3.0
Area (m^2)	2.0371
Power Coefficient	0.5
Solidity	0.1<S<1.0
Wind Speed (m/s)	5
Density (kg/m^3)	1.225
Generator Operation	100-600 RPM

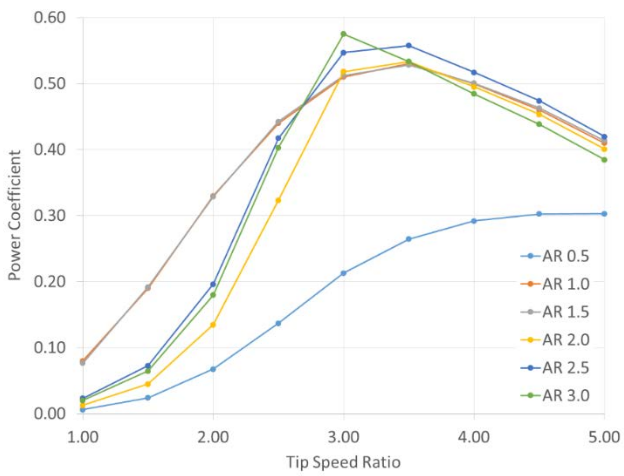

Figure 11. CP and TSR curves comparison for all six VAWT concepts

Power curves were plotted for each concept and the amount of potential monthly energy production for each turbine was calculated. Each of the turbines complied with the minimum energy required for the selected load. Thus, a Decision Matrix Tool was used to evaluate all the turbine alternatives as a function of C_P, aerodynamics, and energy production. The AR 3 turbine resulted as the best option.

2.3.1.4 Trade Studies for the Blade Structure

The wind turbine blades will encounter several load conditions. The load types considered include gravitational loads (i.e., weight) and centrifugal loads. Additionally, aerodynamic loads such as lift and drag forces need to be considered as well as tangential and normal forces, which act on the blade during operation. The blades were also studied both under normal as well as extreme operating conditions [16]. For the preliminary design, the blades were assumed to be built from aluminum.

2.3.2 Mechanical Sub-System

2.3.2.1 Trade Studies: Mechanical Sub-System

The three alternatives that were evaluated for the structural design of the rotor assembly are shown in Figure 12. The first alternative provides a main shaft with two supports for the rib attachment. It also provides bearing support for axial loads and rotation. The housing for the generator is located bellow the blades and has a pinion-gear setup. The second alternative provides a single hub as the main support point for the ribs, along with a small shaft to transmit the torque and power to the generator. Moreover, the housing for the generator and turbine support is placed bellow the blades, and it also contains a pinion-gear setup, similar to the first alternative. Lastly, the third alternative provides a single hub as the main support for the ribs and blades, similar to the second alternative. Also, it possesses an integrated shaft in the hub to transmit the torque to the transmission. Note that this alternative's generator housing is located in the center of the rotor, whereas the drivetrain has a pinion-gear setup.

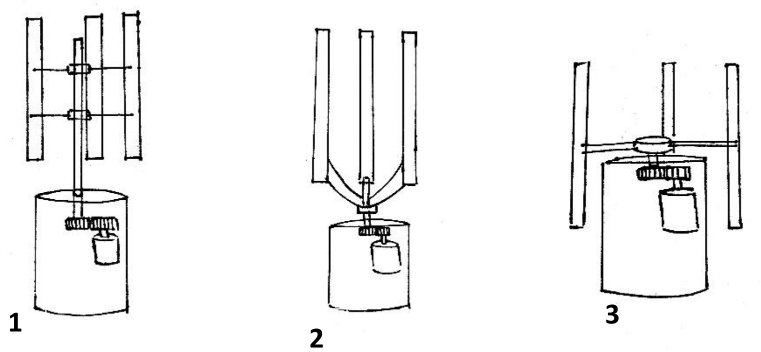

Figure 12. From left to right, rotor assembly configuration alternatives 1, 2 & 3

Once again, a Pugh's Decision Matrix was used to decide which concept was best. The criteria used to evaluate the concepts included the rotor attachment to the pole, maintenance, installation feasibility, aesthetics, manufacturability, cost, operation, and reliability. The best option was alternative number 2, according to the matrix evaluation.

2.3.2.2 Trade Studies for the Main Shaft Design and Bearings Selection

The main shaft analysis was done with two different scenarios: fatigue failure and extreme loads from hurricanes [17]. The best option for the shaft material was determined as Aluminum 6061, according to a Decision Matrix Tool.

For the bearing selection process, the reacting forces from the shafts calculations where used to determine the loads that would need to be withstood by the selected bearing, besides radial loads. Another bearing design consideration was a 10-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 tapered roller bearing and a regular ball bearing for the top bearing and the bottom one, respectively.

2.3.2.3 Trade Studies for the Wind Turbine Attachment

The system shall be able to withstand all wind forces, including the weight of the rotor and generator systems. The whole assembly will be placed on top of a light pole. This design is similar to a cylinder where the rotor will be attached on the top, whereas the light pole will be attached at the bottom. Moreover, since the attachment is similar to a cylinder, the bending moments were readily obtained by using the moment of inertia equation for a cylinder, along with the bending stress equation **[23]**.

2.3.3 Electrical & Controls Sub-System

2.3.3.1 Trade Studies: Electrical & Controls Sub-System

The main interface for the electrical & control sub-system requirements are shown in Figure 13.

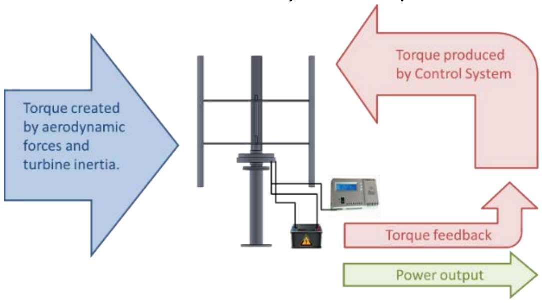

Figure 13. Interface Requirements for the Electrical & Controls Sub-System

Two main alternatives were evaluated for this sub-system. These alternatives included an open-loop and closed-loop controls system. A decision matrix evaluation led to choosing the open-loop controls system as the best option (see Figure 14). The open-loop control system is an optimal alternative due to the size and design of the turbine. This simple yet stable design helps the turbine operate more efficiently.

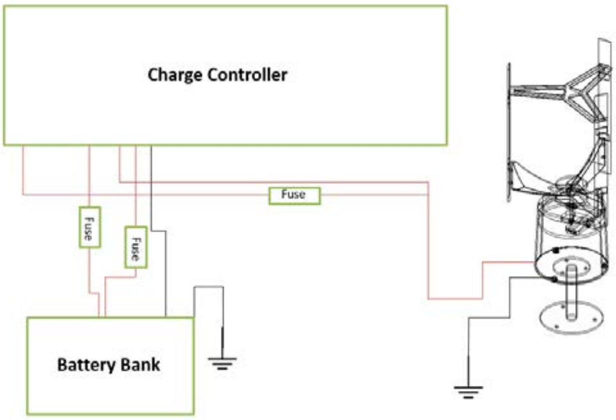

Figure 14. Open-loop Control System

2.3.3.2 Architecture and Interfaces: Electrical & Controls Sub-System

The sub-system is mainly composed of two items, the control system and the power generation system. The control system is one of the most important parts of the turbine given that it maximizes the service life of the turbine and helps it operate safely and efficiently. This system includes the charge controller and the battery bank. The electrical system defines the power generation of the turbine by containing the generator and the rectifier.

2.3.3.3 Trade Studies for the Generator

The power curves of the aerodynamics design were obtained using Q-Blade simulations and were compares to the manufacturer power curves for the generator as shown in Figure 15. Factors such as torque, RPMs and power determined the selection of the turbine by taking the generator power curve that mostly resembled the wind turbine power curve. Local wind studies were used to approximate the wind availability, and consequently, the power generation for the turbine.

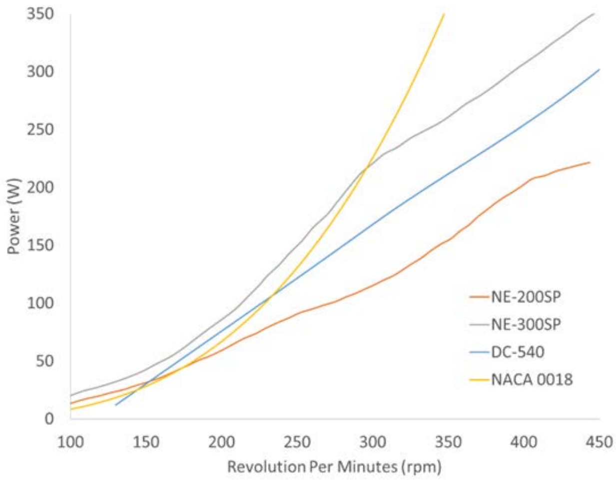

Figure 15. Power Curves for the generator comparison

A decision matrix was used to compare the advantages between three different generators using the MOE's and MOP's defined in Phase A. The best option turned out to be the NE-300SP generator from Jiangsu Naier Wind Power Technology Development Company.

2.3.3.4 Trade Studies for the Battery

Due to the charging and discharging cycles of the battery, a deep cycle acid battery was evaluated. By using a Pugh's Decision Matrix, the best option resulted in a battery bank from two Sealed Lead Acid 12V/100Ah battery in parallel connection. In addition, these batteries should store three times the power consumed by the LED bulb in a day, mitigating lack of wind availability during certain periods.

2.3.3.5 Trade Studies for the Charge Controller

To protect the battery bank, the component interface requirements included having a control system that could handle the electricity produced by the generator, and that was capable of storing it in a battery bank. For this action, a WindBlue Power 12V-25A charge controller for wind generators was chosen. The charge controller distributes the electricity between the load and the battery efficiently and effectively and allows braking the turbine in over-speed or full battery charged conditions.

2.4 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.

2.4.1 Aerodynamics sub-system.

JET's aerodynamic system possesses unique and innovative design configurations to maximize its performance during low-wind availability. In the optimization process, whale tubercle blade designs were considered due to the intrinsic properties whale fins have for aerodynamic performance. These tubercles disrupt the line of pressure against the leading edge. In other words, they sheer the flow of water and direct it into the scalloped valley between each tubercle, causing swirling vortices that roll up and over the flipper to actually enhance lift properties [24]. Moreover, a flow separation at the top occurs and relieves pressure, whereas the pressure underneath is greater, hence creating better lift characteristics (see Figure 17 and Figure 18). This effect amplifies with pitch angle, which is beneficial for VAWTs since it is characterized for having higher angles of attack when compared to HAWTs. To facilitate self-startup in low wind speed conditions, the rotor's ribs adapted a drag-based feature to maximize wind utilization. Figure 19 shows the final CAD model of the wind turbine. The final design was determined with tunnel testing of the scale-model, reference at section 3.7.5. Double-chord whale blade turbine configuration was determined as the final design for manufacturing. The C_p vs lambda curve (see Figure.22) was determined with new double chord and whale design.

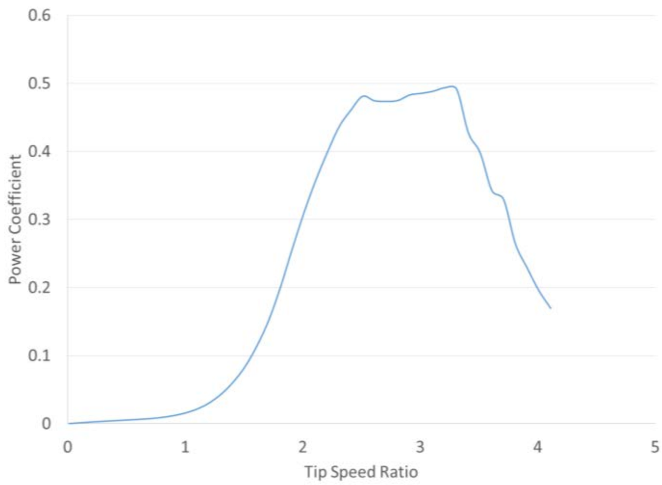

Figure 16. C_p vs. TSR for optimize turbine rotor

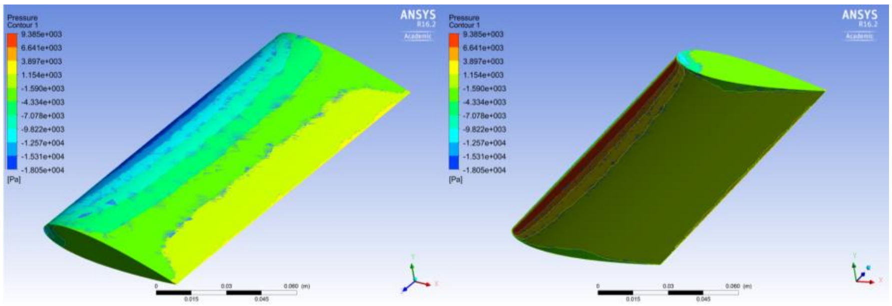

Figure 17. Aerodynamic Pressure NACA 0018 Blade

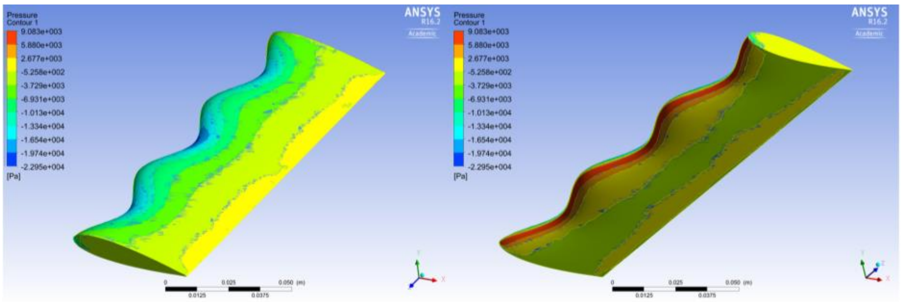

Figure 18. Aerodynamic Pressure NACA 0018 Whale Blade

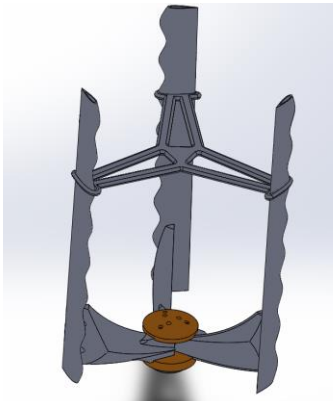

Figure 19. Final design for the rotor

2.4.2 Structural sub-system.

A Finite Element Analysis (FEAs) was performed on the blades to determine if they were capable of withstanding wind load requirements determined by the MOPs shown in Phase B. The analysis consisted on stress concentration evaluation against material mechanical properties while implementing a method of Partial Safety Factors (PSF). This PSF method was used assuming a fully characterized material and a limit evaluation against ultimate strength [25]. Rotational loads were generated by assigning the rotational velocity. Additional loads were added as determined in Phase B. Boundary conditions were applied as a fixed support and a pinned support at the upper and lower blade sections (see Figure 26). This figure shows a simulation performed with the ANSYS software, in which high stress areas were evaluated to comply with the PSF method.

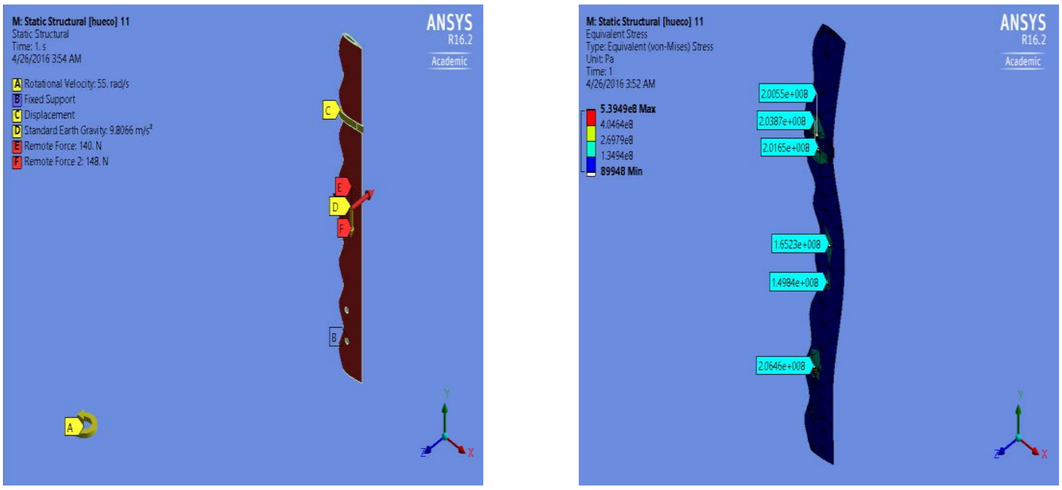

Figure 20. Stress analysis performed on the blade

2.4.3 Mechanical Sub-system.

The focus of the mechanical system includes the main shaft, which transmits the rotational energy from the rotor to the generator, the inner structure that will support the entire system and the attachment of the wind turbine onto the light pole. Additionally, the design and analyses of the remaining components were completed through CAD. The stress analyses performed for the blade structure and mechanical systems followed IEC standards. In addition to the stress analyses, a modal analysis was conducted to determine the systems natural frequency and to identify the possibilities of operating during resonance conditions. The results were interpreted with a Campbell Diagram, which allows to verify possible resonance points due to the operating frequency and the blade passing frequency [19]. For conciseness, the Mechanical sub-system results are not included in the report.

2.4.4 Controls Sub-System

A control circuit was designed to regulate the power from the generator, in order to avoid any malfunctioning or damage to the turbine. An NC25A-12 Open-Loop controller was selected as part of JET's design. This controller works in conjunction with a battery bank that provides the necessary energy storage for when the turbine is generating energy during daylight hours. For over-speed conditions, a load resistor will be connected to the diversion terminal. Figure 21 shows a sketch for turbine's control system and battery configuration. The finalized power curve with generator integration is shown in Figure 22.

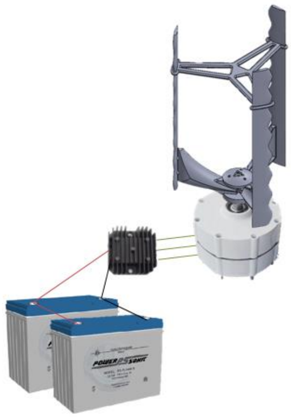

Figure 21. Turbine's controls system configuration diagram

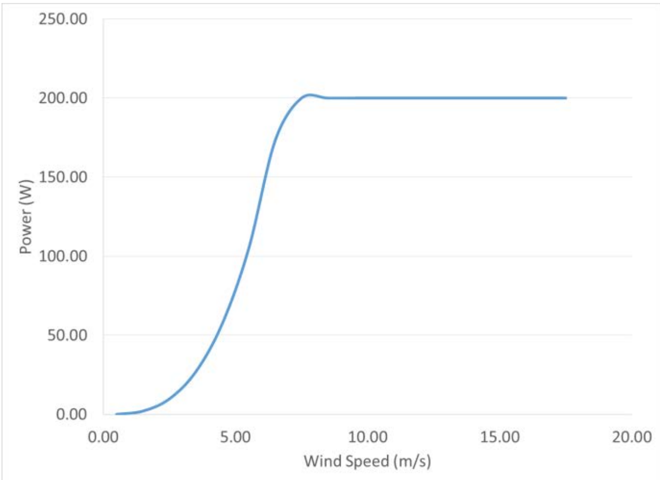

Figure 22: Power Curve of modified Whale Turbine

2.4.5 Wind Energy Production

The energy production from a wind turbine is determined from the product of instantaneous power and time. Depending on the available wind speed, information the expected energy production can be estimated using direct or statistical methods. Wind data is typically gathered over a long-period of time (e.g., a year) and averaged over time intervals Δt. In the presence of wind data, the energy estimate is obtained as [19]

$$E = \sum_{i=1}^{N} P_o(U_i)\Delta t \,, \quad (1)$$

where $P_0(U_i)$ is the instantaneous power at a given wind speed form Figure 22, N is the total number of wind speed observations each averaged over a time interval Δt. Figure 23 shows the histogram for a 10-min time averaged wind data for the year 2015 at a NOAA weather station in the municipality of

Fajardo [26]. The data from the weather station was extrapolated from an anemometer height of 6.4-m to a typical height of 30-m for a light post. The histogram shows the percentage available wind speed for a percentage of the considered time for the energy calculation (i.e., 8,760 hrs. in a year). Using the data in Figure 22 and Figure 23, the estimated yearly energy production at a site in Fajardo will be 510 kWh per year.

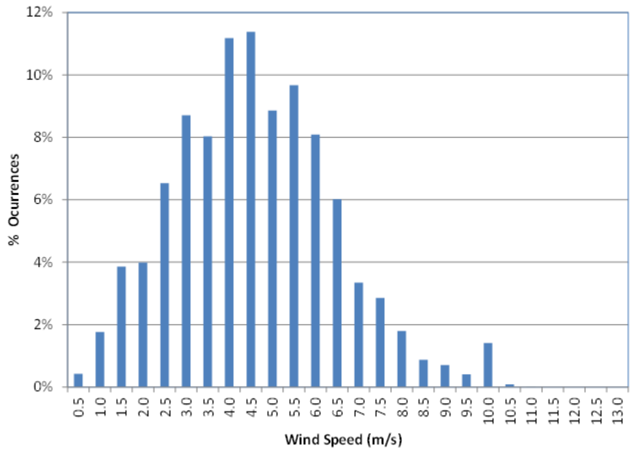

Figure 23. Histogram for wind data at Fajardo, PR [26]

2.5 PHASE D: SYSTEM ASSEMBLY & INTEGRATION

This section represents the integration phase of the turbine. The final assembly along with detailed specifications for each of the sub-system interactions are shown here. A full CAD model was developed to show the interaction between the aerodynamics and mechanical components of the turbine. The system integration of these sub-systems is done through a two-piece hub, which will secure the scoops (ribs) from the top and bottom and will connect directly with the main shaft through a pin on top of the shaft.

2.5.1 Mechanical and Electrical/Controls Sub-Systems Interaction

Figure 24 shows the final design assembly in exploded view in a CAD drawing. Also, Table 11 shows the part buildup for the final assembly.

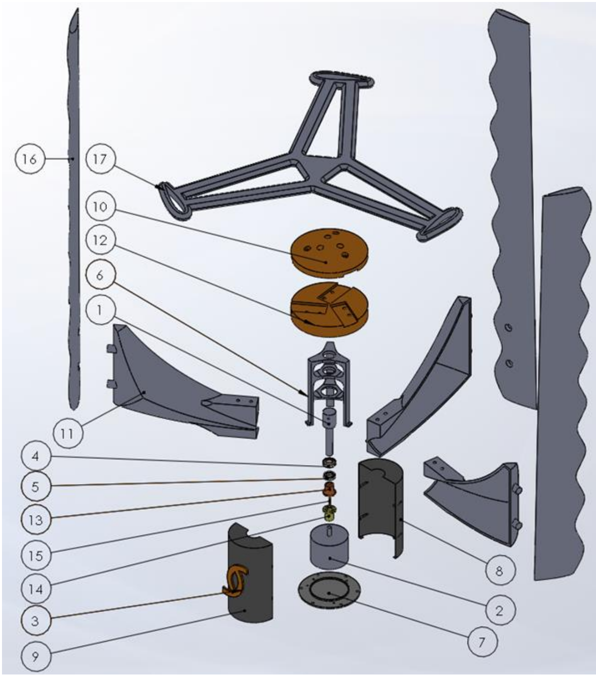

Figure 24. Final System Assembly

Table 11. Assembly part names

ITEM NO.	PART	DESCRIPTION	QTY.
1	Main Shaft	Aluminum - Machined	1
2	Generator	Off the Shelf	1
3	JET Logo	Aluminum - Machined	1
4	Top Bearing	Off the Shelf	1
5	Lower Bearing	Off the Shelf	1
6	Inner Structure	Steel - Machined	1
7	Base	Steel - Machined	1
8	Housing Cover Back	Aluminum - Formed Sheet Metal	1
9	Housing Cover Front	Aluminum - Formed Sheet Metal	1
10	Hub Up	Aluminum - Machined	1
11	Rib Scoop	Aluminum - Machined	3
12	Hub Below	Aluminum - Machined	1
13	Coupling Main Shaft	Aluminum - Machined	1
14	Coupling Generator Shaft	Aluminum - Machined	1
15	Key	Aluminum - Machined	1
16	Whale Blade Full Scale	Fiber Glass	3
17	Rib Up	Aluminum - Machined	1

2.6 PHASE E: PROTOTYPE DEVELOPMENT

For the purposes of the CWC 2016, 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 2016. In essence, four main prototype subsections are outlined here: aerodynamics & structural components, mechanical components, electrical & controls components and testing and validation.

2.6.1 Small-Scale (Prototype) Aerodynamics & Structural Components

2.6.1.1 Objectives

The main objective of this phase is to develop a scale model representative of the wind turbine. This scale model developed would have key features, which are distinctive of the turbine's design to validate their intended performance. Additionally, the scale model will consider the competition rules for design constraints and performance requirements. The development of such model followed similar structure applied SE to the main design. This section will provide a summary of this process highlighting important aspects of the prototype.

2.6.1.1 Design Requirements (MOPs)

For the development of the scale model wind turbine, the design parameters were established according to competition rules and constraints. Additionally, the distinctive features of the full size design were prioritized in the scale down decision-making process. The requirements of the design were divided by categories, such as functional (which focused on important aspects of the design that need to be maintained), performance (which are driven by competition testing goals), and safety requirements governed by standards applied to the main design.

Functional:

- The wind turbine shall be a vertical axis.
- The wind turbine shall contain whale blade design.
- The wind turbine shall use drag-based ribs/scoops.
- Rotor configuration should be keep the same as market turbine.
- Solidity and Aspect Ratio should be the same as market turbine.

Performance:

- The scale model turbine shall generate 10W continuous for at least one wind speed from 5m/s to 11m/s.
- The power reading should be stable for 5s for a 30s limit for every wind speed interval.
- Scale model rotor dimensions shall not exceed 45cm any dimension while still performing to competition standards.
- Turbine shall withstand variable speed from 6m/s to 18m/s for a continuous testing period of 5 minutes.
- Turbine should have a cut-in-wind speed of 2.5m/s.
- The turbine shall control rated speed after the 11m/s while still generating power.
- The voltage output shall be from 5 to 48 VDC.
- The center of the rotor shall be within 2.54 cm of the centerline of the wind tunnel.

Safety:

- The turbine shall be design for factor of safety 1.25 for fatigue strength and 1.1 ultimate strength.
- Wind tunnel mounting flange shall withstand the torque of approximately 10N-m.
- The structure components shall not weigh more than 11.34kg (25lb).
- The structural design of the turbine shall resist wind pressure of 89.5Pa (1.87 lb/ft2).
- The rotor should resist a maximum torque approx. 3.0N-m (2.21 lb.*ft).

2.6.2 Scale-model Aerodynamics Components

For aerodynamics analysis different charasteristics had to be taken from the full scale design to the prototype. The self start characteristic, power coefficient, and tip speed ratio are dependant of the solidity and aspect ratio. For this reason, the dimensions of the wind turbine were scale down by a 4:1 ratio. The turbine was then analyzed in Q-Blade to determine the power curve as shwon in Figure 25. The analytical power curve from Q-Blade provide the aerodynamic output necessary to select a generator that could meet the requirements. The cut-in-wind speed were achieved at 2m/s and 10W at 6.2m/s, effectively satisfying design requirements.

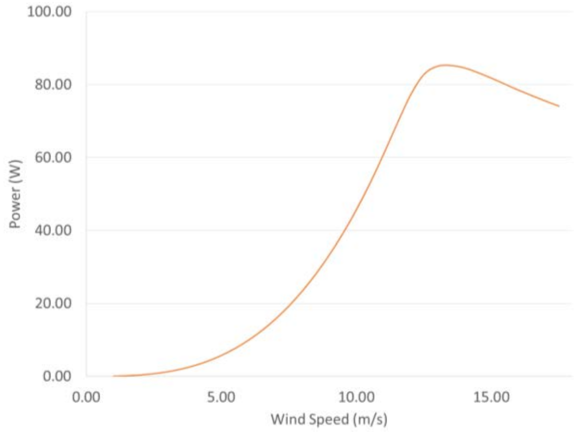

Figure 25. Power Curve for Scale Model without electrical system

Principal components such as blades, drag-scoop rib and hub were fabricated in ABS 3D printer plastic. In order to ensure the durability and performance of main components, these were analyzed using ANSYS Workbench for structural integrity and the results were validated with hand calculation. In order to meet the requirements, optimization was realized by adding whale-like leading edge and a self-starting cup. To validate these additions, preliminary tunnel testing was done. Information regarding this testing can be found in Section 3.7.5.

2.6.3 Small-Scale (Prototype) Mechanical Components

Similarly to the main design, the structural analysis of the blades where completed through FEA software. The aerodynamic loads as well as inertial loads where applied to the small-scale model. For manufacturability reasons and ease of rapid prototyping, the blades were develped with 3D printing technology. The material was characterized in a previus research conducted by a team member in which its mechanical properties were obtained. After analyses and optimization, the final design consists of the 3D printed ABS blade with the adition of an internal steel rod, as shown in *Figure 26*, to provide the required structural performance required at high rpms (see Figure 27).

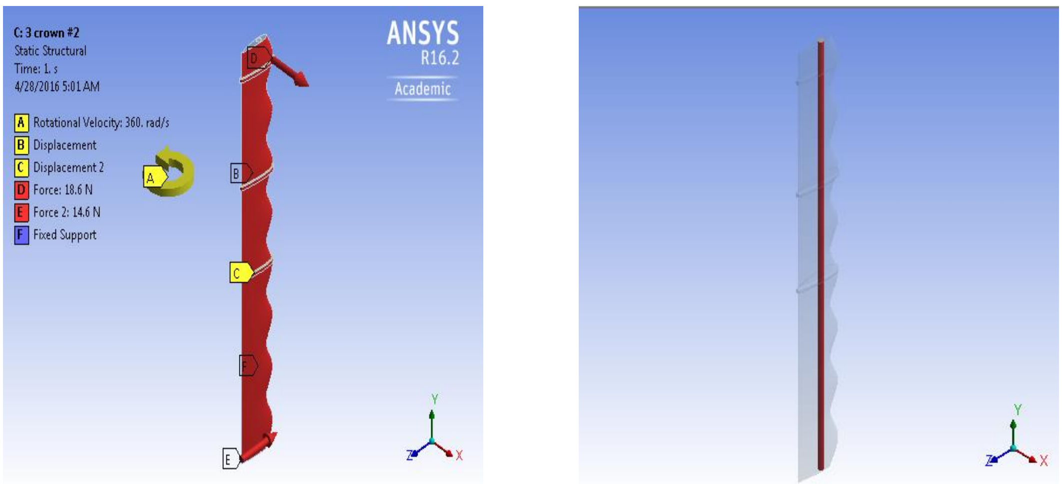

Figure 26. Blade with internal rod

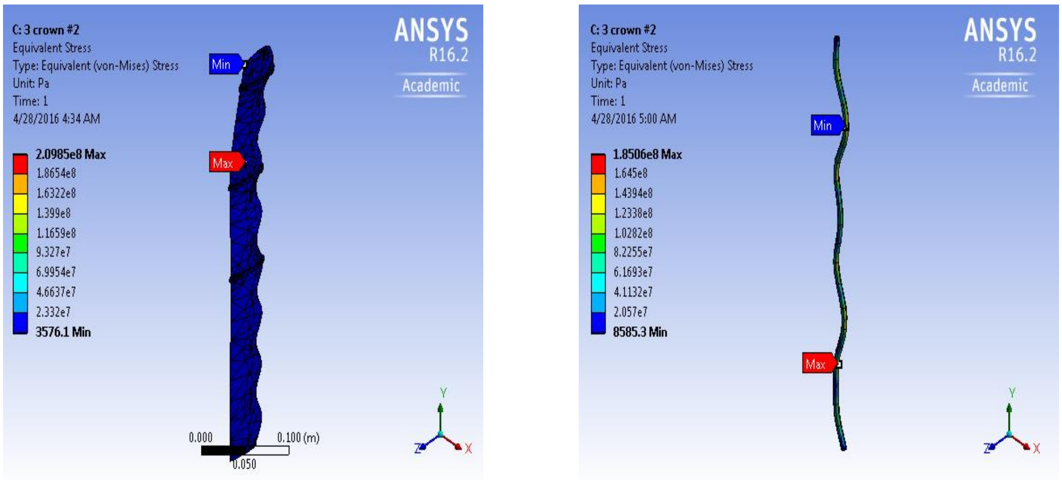

Figure 27. Scale blade structural analysis results

Vibrational analyses were also considered due to the wide range of operational speeds of the wind turbine. In this case, the model was found to experience possible resonace within the operational range. A central steel shaft was integrated in the design to increase the stiffnes of the system and consequently have a higher natural frequency. This component is an of-the-shelf shaft with given material and dimensions. In order to ensure the chosen product complied with the safety requirements, further structural analyses for the mechanical system with the main shaft included were conducted. The results for the analyses were satisfactory, as the selected shaft complied with the safety parameters required.

2.6.4 Small-Scale (Prototype) Electrical & Controls Components

For the competition, the generator must be the only source of power production in the system, with no additional power storage allowed to aid power production to the system. However, for communication purposes with controls, power storage units can be utilized. Rotor performance is critical for generator selection, as VAWTs tend to have low rotational speeds, which is the main reason why aspect ratio and solidity were taken into consideration when designing turbine with direct drive application. The generator taken into consideration needed to operate at low speeds; but the motor selected at first had high RPM/V, meaning that they needed to operate at high speeds to work for our application. Furthermore, the RPM/V ratio required was calculated to simplify generator selection, the estimated RPM/V ratio was approximately 50RPM/V. A commercial micro-turbine generator with 22RPM/V having a perfect fitting together with our rotor was identified. Physical characterization of the generator was performed using turbine drag-based cup and air pressure, and a preliminary circuit was used to determine generator power curve, as shown in Figure 28.

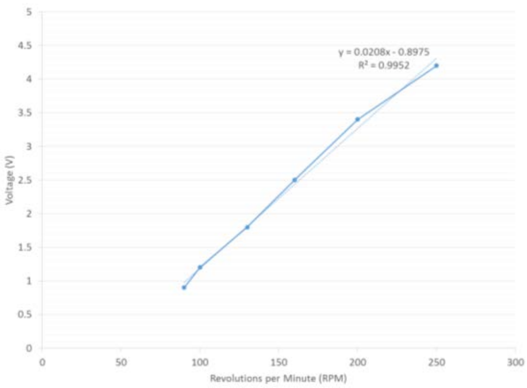

Figure 28. Voltage vs. RPM Micro-Wind Turbine Generator

The electrical system of the wind turbine includes a braking relay with dump load, a three-phase rectifier (AC/DC), a DC/DC converter, and microcontroller, show in Figure 29. *Electrical and Control System Diagram* The braking relay system consists of three mechanical relays that route generated power back to the generator, called dynamic braking. The dump load consists of a low-ohm resistor bank, which dissipates external heat to protect the generator from these high current levels. The AC power is then rectified using the three-phase bridge rectifier circuit shown in Figure 30. *Three phase rectifier circuit and DC/DC boost converter* This consist of six diode conducts for 120˚, which return six-pulse ripples on the output voltage to create a full wave DC output. The DC/DC boost converter uses switching techniques for input voltage augmentation. The converter consists of inductor, a power MOSFET, a diode, and a capacitor.

The switching of the ON/OFF states is determined by the change in the duty cycle of the PWM signal When the MOSFET turns on, the supply voltage flows across the series inductor. Under steady state conditions, when the MOSFET is turned on, current in the inductor will increase linearly in the forward direction. The diode will be reverse-biased and not conducting. Simultaneously, current will be flowing from the output capacitor into the load, discharging the capacitor. When the MOSFET turns off, the current in the inductor will continue to flow in the same direction, the diode will conduct, and the inductor current will be transferred to the output capacitor and load. Since the output voltage exceeds the supply voltage, inductor will now be reverse-biased, and the current in the inductor will decay linearly backwards towards its original value during the "off" period of the MOSFET.

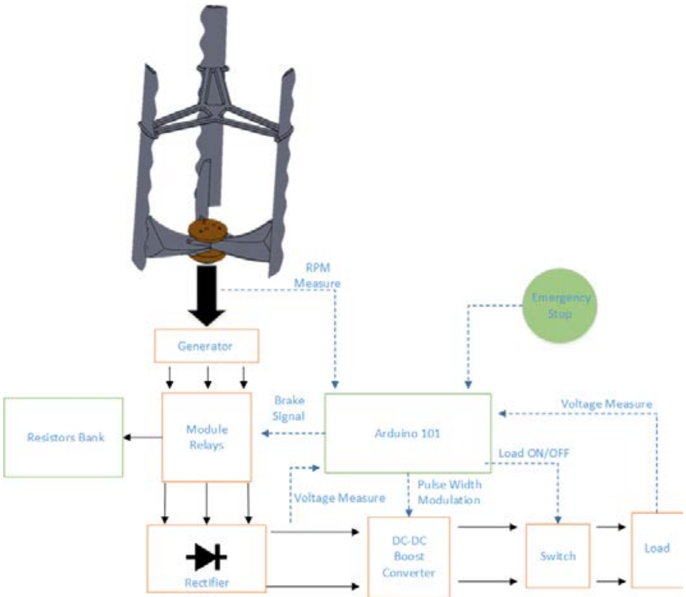

Figure 29. Electrical and Control System Diagram

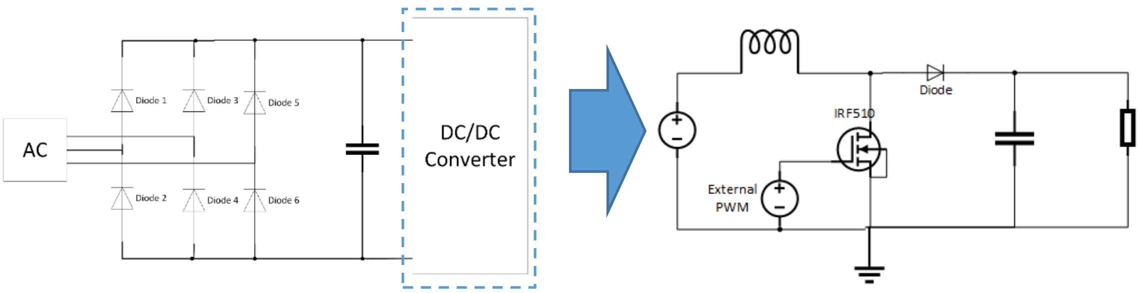

Figure 30. Three phase rectifier circuit and DC/DC boost converter

The switching duty cycles also change the speed of the turbine. This is due to the high-level currents during the ON state; the current is shorted to ground due to the very small resistance of the MOSFET and inductor, resulting in slowing down the rotational speed. During the OFF state, the generator sees more resistance, placing the turbine in a free-run state. By using the voltage as an input for this DC boost converter, the required load and rated speed for the turbine are determined. Inductance and capacitance of the components were determining for a continuous current mode operation. The last and most critical component of the electrical system is the microcontroller, which is constantly monitoring the values of turbine speed, voltage and load current, to send activation signals to relays and the MOSFET, for braking and control output power. The flow chart that details the microcontroller programming shown in Figure 31.

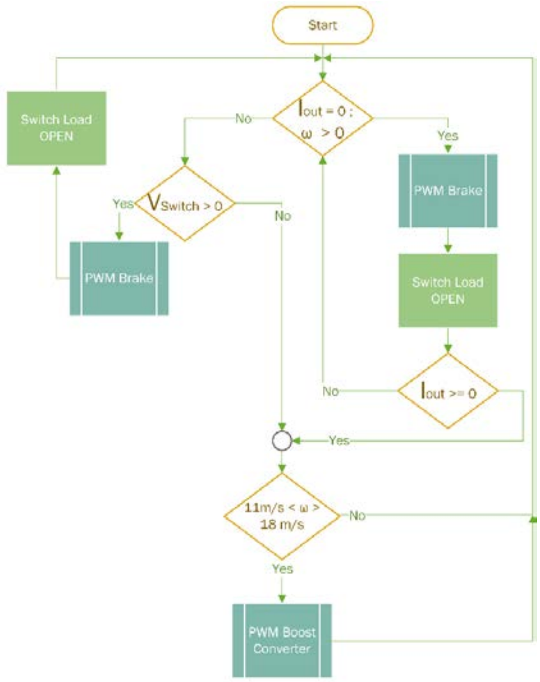

Figure 31. Flowchart for rated speed control and braking

2.6.5 Prototype Testing and Validation

Testing of the turbine first took place in a wind tunnel of 8-in by 8-in cross sectional area. Eight different turbine configurations with 1:2.4 ratio of the competition model turbine were designed, varying chord, self-start cup and whale leading edge. The reasoning behind this multiple testing was to enhance the design in a smaller model that could be 3D printed fast and easily before designing the selected testing turbine model. It was determined that the whale leading edge combined with self-starting cup turbine provide an advantage in self-starting and performance. The results are summarized in Figure 32.

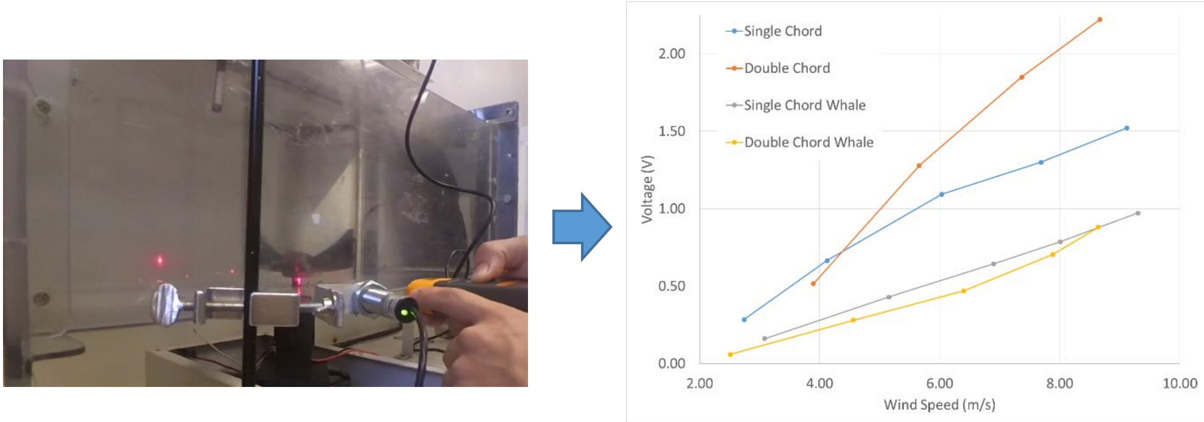

Figure 32. Voltage vs. Wind Speed data collected from preliminary tunnel testing of 2.4:1 model with scoop

Testing showed that the double whale turbine and single chord straight blades had low cut-in-wind speeds from 2.5m/s to 2.7m/s. In addition, the single chord had better power output, but due to structural requirements, the double chord ensured better structural integrity. Given this data, the double chord whale turbine was selected. The acquired knowledge from the experimental data facilitated generator selection and load analyses in the structural and mechanical sub-sections. This preliminary design was optimized during Phase C, when the double chord whale blade turbine was fabricated to specific competition requirement. The prototype was tested in a closed loop wind tunnel at University of Puerto Rico, Cayey Campus (see Figure 33).

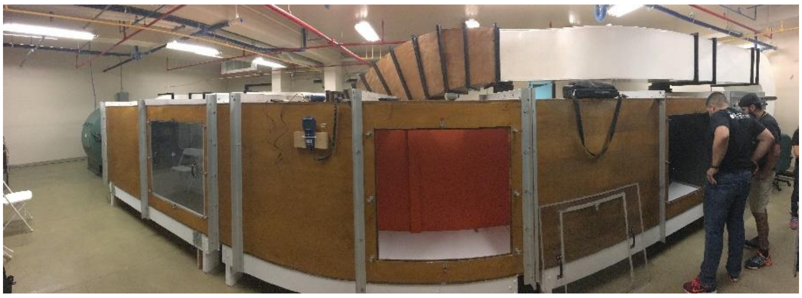

Figure 33. Close-Loop Wind Tunnel at the University of Puerto Rico, Cayey Campus

The close-loop wind tunnel had a wind capacity from 8m/s to 20m/s, where turbine performance and durability was observed. Data acquired during these tests was also utilized for developing the turbine's power curve (see Figure 34), needed to identify the correct load capacity needed for our application.

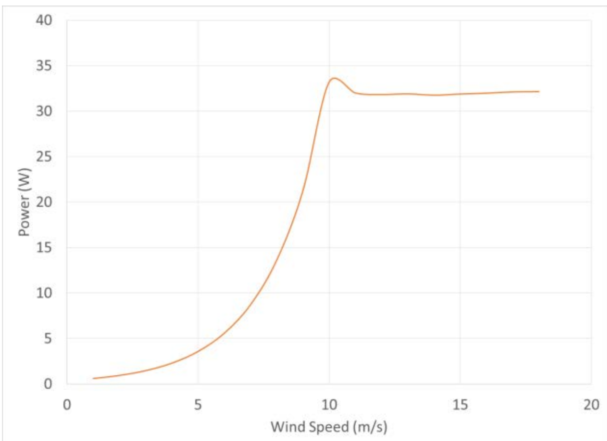

Figure 34. Wind speed vs Power output using 30W load

2.7 PHASE F: CONCLUSION AND RECOMMENDATIONS

The PR energy crisis and low wind speed availability motivated JET to create an innovative design that could operate almost anywhere it could be installed. Market turbine characteristics were scaled-down to the prototype turbine to validate that the turbine could solve the public illumination problem in PR. The scale down model validation was key to determine the performance of the market turbine. The integration of whale blade design and self-starting cup gave the turbine a distinct advantage by lowering the cut-in-wind speed and producing power at low wind speeds without affecting high wind speed operation.

Although the mechanical properties for the prototype turbine defer from the market turbine, the same design methods were applied. These practices included safety factors, stress analyses and vibrational analyses. By applying these procedures, the selected design process was validated to be used for the full size wind turbine. The scaled turbine completed testing satisfactorily, maintaining its structural integrity and preforming as predicted, thus, the designed structure will operate as expected without posing risks in a public environment. The electrical and controls system complied with the available aerodynamic torque required to generate the electrical power required for the light pole application.

3 DEPLOYMENT STRATEGY

3.1 PROJECT SITE EVALUATION AND SELECTION

This project seeks to install wind turbines in existing light poles that are currently connected to the grid. A critical aspect in the use of wind turbines is the availability of enough wind speeds to drive the wind turbine. Several sources were studied to investigate the available wind resource in PR. The most significant wind study in PR to date was performed by Elliot [27]. This study was part of a collaborative effort between the DOE/NREL Wind Powering America Program, AWS Truewind and the Commonwealth of Puerto Rico. The study considered a comprehensive modeling and validation process that led to the development of detailed wind resource maps with a special resolution of 200 m. The modeling component included the use of a numerical weather model with climatic data and a wind flow model to produce preliminary maps. The preliminary maps were validated to determine 30-m annual average wind resource maps using available high quality data as shown in Figure 35. Although typical light-poles are at 10-m height (i.e, instead of 30m), the data in the figure provides a qualitative assessment of the location with the best wind resources in PR. As shown in the figure, wind speed range is higher in the coasts of Puerto Rico, than in the center of the Island.

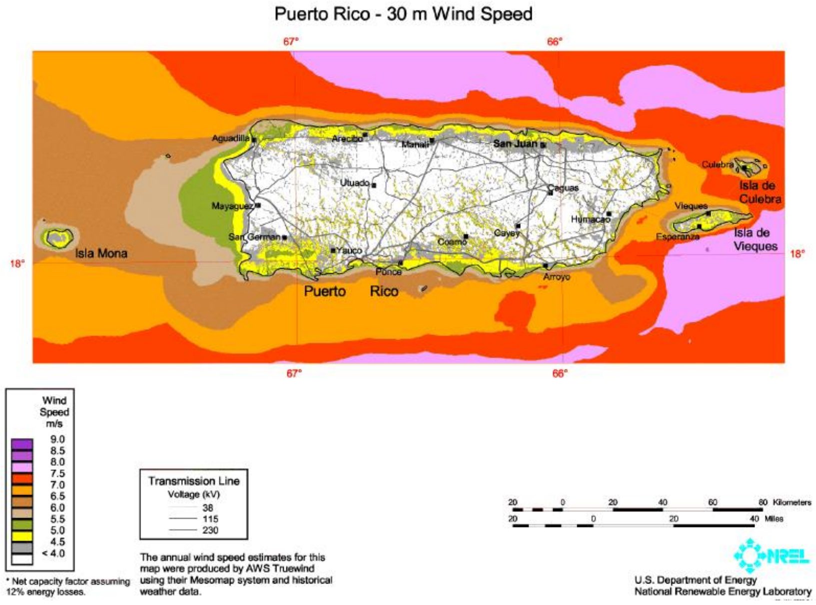

Figure 35. Wind speed map at 30m [27]

Although the proposed wind turbine is intended to successfully operate at very low wind speeds, a preliminary assessment of the wind resource in specific municipalities was performed using wind speed data available at NOAA stations around the Island [26]. Figure 36 shows municipalities were wind speed data is currently available. The wind speed data was used along the power curve in Figure 18 to calculate the capacity factor (i.e., the time during operation in which the turbine would produce energy at the rated power). According to results, the municipality of Peñuelas has the highest capacity factor of 30.2%, followed by Fajardo with 29.1%, Guanica with 25% and Santa Isabel with 21.9%. These four municipalities are highlighted with a star in Figure 36.

Figure 36. Municipalities with available weather stations

Table 12. Capacity factors at NOAA weather stations.

Municipality	Capacity Factor (%)
Aguadilla	5.0
Arecibo	10.6
Fajardo	29.1
Florida	2.0
Guánica	25.0
Guaynabo	16.6
Gurabo	3.1
Lajas	6.4

Mayagüez	6.7
Peñuelas	30.2
Rincón	4.8
San Juan	16.3
Santa Isabel	21.9
Vieques	8.0

3.2 STAKEHOLDER IDENTIFICATION AND COMMUNICATION

JET identified the main stakeholders as the 78 municipalities of Puerto Rico. As mentioned previously in this report, the total market size includes approximately 550,000 light poles distributed around the Island, which belong to the different municipalities. During their marketing assessment, JET contacted government officials from the 78 municipalities by phone, to survey their view about wind energy. The questions outlined in the survey are shown below:

1. How serious is the problem of public illumination costs in Puerto Rico?
2. Do you think that renewable energy may help solve this problem?
3. What kind of renewable energy could be used for this purpose?
4. Will you be willing to implement a solution based on wind energy?
5. How possible would you consider replacing existing light pole illumination systems with wind energy as their power source?
6. How much are you willing to pay for a wind turbine that will assess the problem of public illumination in Puerto Rico?

Thirteen responses were obtained (i.e., 17%) from the survey. Survey results indicated that 85% of the interviewed municipalities mentioned that they are concerned with the serious problem of cost of public illumination in PR. All of them (i.e., 100%) indicated that renewable energy could help to solve this problem. Eighty five percent of the interviewed municipalities were willing to implement a solution based on wind energy, and 77% of them considered replacing the current light pole illumination system with wind energy as its power source.

3.3 DEPLOYMENT TIMELINE AND PROJECT LIFE CYCLE

This section outlines the deployment timeline and project cycle for JET's wind turbine product. Figure 37 depicts how the project will move and how long it will take after stablishing a design, whereas Figure 38 shows the project life cycle for the product. Furthermore, details regarding the project magnitude, community, permits, manufacturing orders, assembly and maintenance are outlined below:

- Determining the Project Magnitude- Defines how many turbines the project requires and the area where the product is going to be installed.

- Informing the Community- Explaining how the project may affect the public, and answering any possible questions or concerns on behalf of the public.
- Permits- Making the adequate arrangements and paper work needed in order to ensure that the project is legally implemented.
- Place Manufacture Order- Producing the required number of turbines for the project.
- Assembly- Installing the turbines on the target light poles.
- Maintenance- Monitoring and replacing the components every two years, unless there are any major problems beforehand, or during the turbine lifespan.

Figure 37. Deployment timeline.

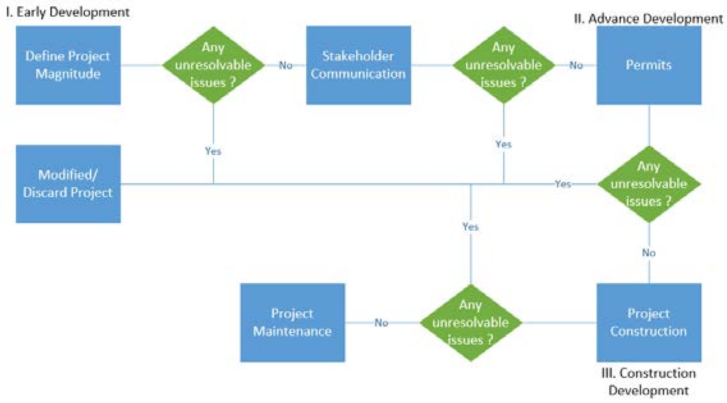

Figure 38. Project life cycle

3.4 INSTALLATION AND MAINTENANCE

Once the client places an order, the installation of the wind turbine will initiate as shown in Figure 39. The turbine system includes the housing and hub ready for installment, making it easy for a two-party installer team to mount the assembly on the light pole. In order to fulfill this installation, a cherry picker truck will be required to transport the wind turbine as well as the necessary equipment to install it on the light pole.

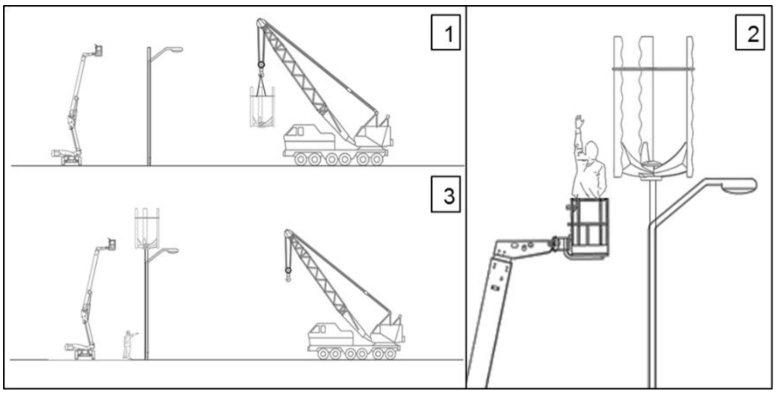

Figure 39. Process of installation to existing light pole

The maintenance of the wind turbine will require an inspection that will indicate the status of its components. Depending on this status, actions will be taken to prevent any deterioration or any other problem that may affect the wind turbine performance. A maintenance program will be available as a reference to establish the maintenance schedules and requirements for the turbine. This maintenance program will have certain quality control specifications that need to be followed to satisfy the design and engineering standards. Both installation and maintenance costs are included in the unit sales price.

3.5 RELIABILITY AND RISK MANAGEMENT

Risk management contemplates any potential events that may have a negative impact on the wind turbine development strategy. The risk matrix shown in Figure 40 was used to introduce the risk management concept for JET's wind turbine system. This tool helped recognize the probability and impact of the evaluated risks and classified them from low risk, to medium risk, to high risk with three colors (i.e., green, yellow and red). The risks that were evaluated are outlined below:

1. Technical failure – mechanical or electrical failure during operation due to lack-of or improper maintenance.
2. Not reaching rated power – wind availability does not allow the turbine to reach the required energy for the light pole application.
3. Public acceptance – people might neglect the project.
4. Factory malfunction – possible problem with a component due to manufacturing flaws.
5. Not resistant to natural disasters – Turbine structure does not resist storms or hurricanes.
6. Installation problems – Attachment of the turbine on the light pole might not be possible.
7. Design failure – Possible problems were not taken into consideration during the turbine design.

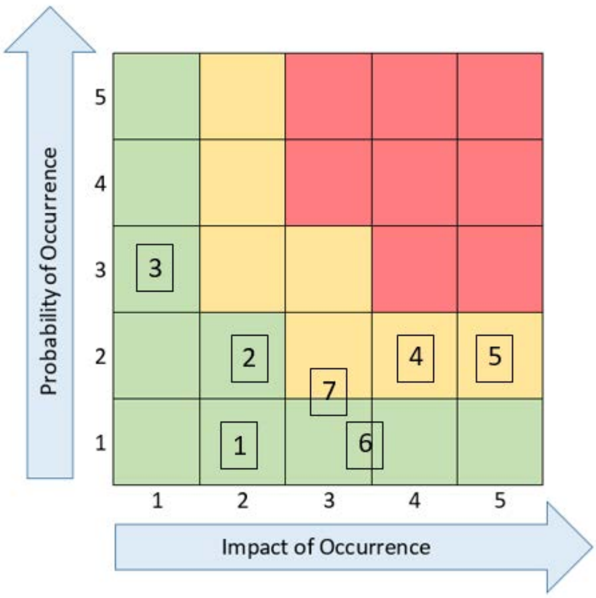

Figure 40. Risk assessment matrix used for the operations development

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APPENDIX B: FULL PRO-FORMA STATEMENTS

Table 13. Forecast analysis projection for the first five years of operation

Sales Forecast	FY 1	FY 2	FY 3	FY 4	FY 5
Total Unit Sales	250	300	350	400	500
Unit Prices	$2,200.00	$2,200.00	$2,200.00	$2,200.00	$2,200.00
Total Sales	$550,000	$660,000	$770,000	$880,000	$1,100,000
Direct Unit Costs	$1,357.00	$1,357.00	$1,357.00	$1,357.00	$1,357.00
Direct Cost of Sales	$339,250	$407,100	$474,950	$542,800	$678,500

Table 14. Cash flow statement for the first five years of operation

Pro Forma Cash Flow	FY 1	FY 2	FY 3	FY 4	FY 5
Cash Received					
Cash from Operations					
Cash Sales	$550,000	$660,000	$770,000	$880,000	$1,100,000
Subtotal Cash from Operations	$550,000	$660,000	$770,000	$880,000	$1,100,000
Additional Cash Received					
Sales Tax, VAT, HST/GST Received	$63,250	$75,900	$88,550	$101,200	$126,500
New Current Borrowing	$50,000		$0	$0	$0
Subtotal Cash Received	$663,250	$735,900	$858,550	$981,200	$1,226,500
Expenditures					
Expenditures from Operations					
Cash Spending	$167,112	$167,112	$167,112	$167,112	$167,112
Bill Payments	$394,078	$507,059	$562,950	$633,366	$778,833
Subtotal Spent on Operations	$561,190	$674,171	$730,062	$800,478	$945,945
Additional Cash Spent					
Sales Tax, VAT, HST/GST Paid Out	$63,250	$75,900	$88,550	$101,200	$126,500
Principal Repayment of Current Borrowing	$9,163	$9,163	$9,163	$9,163	$9,163
Subtotal Cash Spent	$633,603	$759,234	$827,775	$910,841	$1,081,608
Net Cash Flow	$29,647	($23,334)	$30,775	$70,359	$144,892
Cash Balance	$30,647	$7,313	$38,088	$108,447	$253,340

Table 15. Income Statement for first five years of operation

Pro Forma Profit and Loss	FY 1	FY 2	FY 3	FY 4	FY 5
Sales	$550,000	$660,000	$770,000	$880,000	$1,100,000
Direct Cost of Sales	$339,250	$407,100	$474,950	$542,800	$678,500
Other Costs of Sales	$0	$0	$0	$0	$0
Total Cost of Sales	$339,250	$407,100	$474,950	$542,800	$678,500
Gross Margin	$210,750	$252,900	$295,050	$337,200	$421,500
Gross Margin %	38.32%	38.32%	38.32%	38.32%	38.32%
Expenses					
Payroll	$167,112	$167,112	$167,112	$167,112	$167,112
Administrative Costs	$24,000	$24,000	$24,000	$24,000	$24,000
Depreciation	$0	$0	$0	$0	$0
Rent	$12,000	$12,000	$12,000	$12,000	$12,000
Transportation	$12,000	$12,000	$12,000	$12,000	$12,000
Insurance & Payroll Taxes	$36,765	$36,765	$36,765	$36,765	$36,765
Total Operating Expenses	$251,877	$251,877	$251,877	$251,877	$251,877
Profit Before Interest and Taxes	($41,127)	$1,023	$43,173	$85,323	$169,623
EBITDA	($41,127)	$1,023	$43,173	$85,323	$169,623
Interest Expense	$3,752	$3,372	$2,992	$2,612	$2,231
Taxes Incurred	$0	$0	$1,607	$3,308	$6,696
Net Profit	($44,879)	($2,349)	$38,574	$79,403	$160,696
Net Profit/Sales	-8.16%	-0.36%	5.01%	9.02%	14.61%

Table 16. Balance Sheet for first five years of operation

Pro Forma Balance Sheet	FY 1	FY 2	FY 3	FY 4	FY 5
Current Assets					
Cash	$30,647	$7,313	$38,088	$108,447	$253,340
Inventory	$50,209	$41,088	$46,604	$52,175	$71,333
Other Current Assets	$0	$0	$0	$0	$0
Total Current Assets	$80,856	$48,401	$84,692	$160,622	$324,672
Long-term Assets	$0	$0	$0	$0	$0
Total Assets	$80,856	$48,401	$84,692	$160,622	$324,672
Liabilities and Capital					
Current Liabilities					
Accounts Payable	$60,898	$39,955	$46,835	$52,525	$65,042
Current Borrowing	$85,837	$76,674	$67,511	$58,348	$49,185
Other Current Liabilities	$0	$0	$0	$0	$0
Subtotal Current Liabilities	$146,735	$116,629	$114,346	$110,873	$114,227
Total Liabilities	$146,735	$116,629	$114,346	$110,873	$114,227
Paid-in Capital	$2,707	$2,707	$2,707	$2,707	$2,707
Retained Earnings	($23,707)	($68,586)	($70,935)	($32,361)	$47,042
Earnings	($44,879)	($2,349)	$38,574	$79,403	$160,696
Total Capital	($65,879)	($68,228)	($29,654)	$49,749	$210,445
Total Liabilities and Capital	$80,856	$48,401	$84,692	$160,622	$324,672
Net Worth	($65,879)	($68,228)	($29,654)	$49,749	$210,445