WiscWind

U.S. Department of Energy
Collegiate Wind Competition

University of Wisconsin – Madison

First Name	Last Name	Email Address	Role	Team
Scott	Williams	spwilliams@wisc.edu	PI	Advisor
Benjamin	Kufahl	bkufahl@wisc.edu	Student Lead	Mechanical
Alex	Lebrun	atlebrun@wisc.edu	Student Lead	Mechanical
Austin	Renfert	arenfert@wisc.edu	Team Member	Business
Connor	Sawyers	sawyers2@wisc.edu	Team Member	Business
Srinidhi	Emkay	emkay@wisc.edu	Team Member	Business
Ian	Berg	imberg@wisc.edu	Team Member	Deployment
Wilson	Towne	wtowne@wisc.edu	Team Member	Deployment
Walker	Willis	mlwillis@wisc.edu	Team Member	Electrical
Joseph	Snodgrass	jsnodgrass@wisc.edu	Team Member	Electrical
Brent	Grimm	bwgrimm@wisc.edu	Team Member	Electrical
Ryan	Rodenkirch	rrodenkirch@wisc.edu	Team Member	Electrical
Mamyrkhan	Kassymov	kassymov@wisc.edu	Team Member	Electrical
Evan	Wolfenden	eswolfenden@wisc.edu	Team Member	Mechanical
Emily	Blase	blase@wisc.edu	Team Member	Mechanical

Table of Contents

Table of Figures

Executive Summary

WiscWind is a cross-functional team of engineering, business, economics, and environmental studies students formed at the University of Wisconsin - Madison. During research and development, WiscWind was organized into mechanical, electrical, business and deployment subteams. WiscWind LLC offers the Ventus 3k System; a customizable, integrated off-grid wind and solar solution designed to retrofit to existing structures, mobile telecommunications structures in particular. By utilizing 2 kW wind power and 1 kW solar, the Ventus 3k system capitalizes on the differing availability of solar and wind resources. Cell tower owners, able to afford the upfront cost of renewable energy systems, comprise WiscWind's target market. Because diesel generators are the industry standard, energy comprises an average of 25% of our target market's overall cost of operations. WiscWind will promote the spread of network access to developing rural areas at significant cost savings to our customers.

The Ventus 3k Series system is designed to last 20 years. To achieve this, WiscWind has employed a vertical axis wind turbine with a helical blade design and a direct drive generator. A generator has been chosen based on a low starting torque, and a high voltage at a low rotational velocity. To allow for time and cost-efficient product development, WiscWind utilizes 3D printing to generate our turbine blades. By doing so, several blade designs have been produced and tested. By reducing the turbine's diameter, rotational speed has been increased to boost efficiency significantly. WiscWind utilizes a robust electrical design to allow for simple, safe control and maintenance.

WiscWind has selected India as a base of production due to India's wind and solar resources overlapping the country's rural under-electrification. This overlapping resource and demand is concentrated in Southern India, and after considerable analysis, this region has been targeted for initial system deployment. An investment of $250,000 will be necessary to establish operations and begin production in India. Utilizing lean startup principles, WiscWind has proposed a trial pilot period in the United States prior to establishing operations in India to ensure the safety, efficiency, and durability of the turbine and system.

The WiscWind team and its members have already exhibited its product in several showcase opportunities and innovation competitions to test the viability of our business plan and technical design. The company is poised to showcase at the AWEA Conference to refine our plan and strengthen our design, based on feedback from industry professionals. WiscWind prides itself on our vision to solve large-scale energy problems using decentralized, elegant design.

Business Plan

Overview

WiscWind LLC has envisioned the Ventus 3k Series turbine system, a vertical axis wind turbine designed to attach directly to an existing cellular tower. Integrated with solar and battery storage capabilities, the Ventus 3k series can power off-grid cell towers or supplement towers with a limited grid power supply. Our product is a renewable-based solution for the existing power demand of the telecom tower industry at a superior value to other systems that are currently in use. At WiscWind our mission is to connect people through renewable energy to accelerate electrification of rural communities. Our vision is a world in which everyone is connected to the network; by harnessing the potential of off-grid wind and solar energy, WiscWind is working toward making this vision a reality.

Value Proposition

WiscWind LLC's mission is to provide safe, sustainable, vertical axis wind turbines designed to attach to cellular towers in rural areas, integrated with photovoltaic panels and battery storage. The system’s durable design minimizes maintenance, and produces no carbon emissions during operation. WiscWind LLC strives to power off-grid cell towers at a better value than diesel generators and grid expansion.

The Problem

Economic development in the world over the past century has been powered largely by fossil fuels. Large, centralized coal plants provided the opportunity for increased population density and job growth, resulting in improved manufacturing capacity and prosperity. Our increasing use of oil allowed us to travel farther, transport goods faster, and develop innovative supply chains. Following the invention of the integrated circuit, access to information began to decentralize, allowing more and more people to access the world’s greatest literary works, economic data in real time, and most importantly access to one another: spurring innovation and connecting entire communities of people. Today, anyone with an internet-enabled device has access to this wealth of information, and this flow of information drives economic development.

However, not every country followed this same development pattern. While the growth of the world’s urban areas was nourished by large, centralized energy production, 30 percent of the world’s rural population still lacks access to electricity according to The World Energy Outlook. This energy deficiency is present in many areas of rural India. According to Worldbook.org, India had a 2014 electrification rate of just 78.3% - leaving 269 million people without access to electricity. To put this into perspective, if Indians without electricity constituted the populace of a country, it would be the 4th largest in the world. Without electricity, a large number of people are denied many necessities and luxuries, one of these being access to the world’s wealth of information via the internet. Traditional grid expansion is expensive, however, and in many cases decentralized energy production is more cost effective. Increasing demand for information in these areas has created a market for off-grid cellular towers [1].

The WiscWind Solution

New innovations in sustainable energy have made off-grid renewable solutions cost-effective in rural areas compared to large, centralized power plants. WiscWind LLC has developed a solution to capture this opportunity with its premier system, the Ventus 3k Series turbine, a vertical axis wind turbine (VAWT) designed to attach to off-grid cellular towers. This Ventus 3k Series is capable of integration with solar and battery storage technology to reduce or eliminate the use of diesel generators and fuel in off-grid applications. WiscWind's turbine provides long-term value for cell tower companies looking to cater to developing rural areas not just by reducing carbon emissions, but also the fuel and maintenance costs created by using diesel.

Deployment in India

WiscWind LLC chose India to address the problem created by the gap in rural electrification. India has the necessary wind and solar resources for our system, making it a viable choice. With 1.24 billion people, India has the 2nd largest population of any country in the world. While there are many other countries with a greater proportion of the population living without access to electricity [2], India presents a large overall market size with rich manufacturing capabilities. There are around 250,000 grid-connected villages with frequent intermittent blackouts, many of these villages in rural areas lacking sophisticated power grids. With a growing market gap, the potential for off-grid systems in India is predicted to rise to over 1GW per year by 2016 [3].

Political Environment

The Telecom Regulatory Authority of India has proposed strict standards that would require 50% of rural telecom towers be powered by renewable energy by 2015 and 75% by 2020 [4]. While these regulations would create a favorable environment for market penetration, these standards have not been adhered to in practice. Because of the lack of independence of India's regulatory agencies, along with other factors creating a separation between regulatory goals and reality, these exact regulations cannot be relied on to require 210,000+ towers to switch to renewable energy sources as proposed. However, regulations such as these echo the Indian government's push towards sustainability, an example of which is the Partnership to Advance Clean Energy (PACE), an international commitment between the U.S. and India to set realistic targets and prioritize investments in clean energy [5]. The 2003 Energy Act removed the need for licenses to provide off-grid renewable energy in rural areas.

Market Data

Market Opportunity

The market opportunity for decentralized renewable energy presented by Indian telecom towers was $500 million in 2015. At the estimated rate of growth, the market opportunity will reach $950 million by 2018 [6].

Indian Wireless Telecommunication Services Industry

India's telecommunication services market is valued at $33,070 million, which represents a 14.3% growth rate from 2014. While the compound annual growth rate (CAGR) from 2011-2014 was only 0.1%, the industry has been growing at an increasing rate from 2013. Industry reports, estimate the market to grow at a CAGR of 6.9% from 2015-2020, with an industry valuation estimate of $64.2 billion by 2020 [7] (See Figure 1).

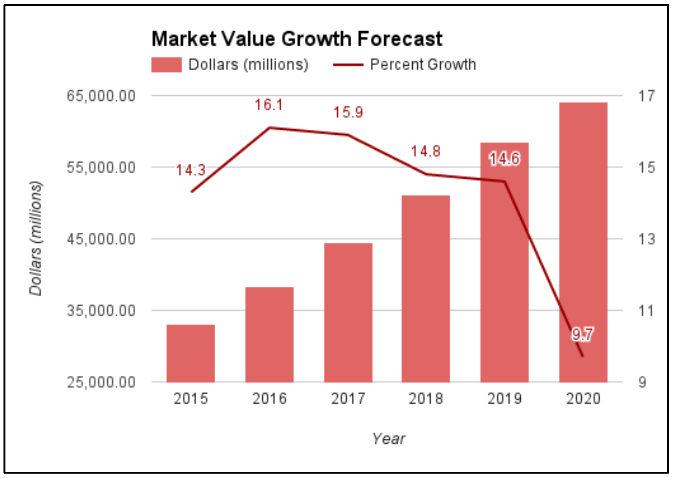


Figure 1: Forecast of market value growth for India telecom industry (Data courtesy Marketline).

Telecommunication Services Market Trends

The growth at a decreasing rate shows a maturing market, with an expected increase in competition in an already fiercely competitive market. India's cellular market is an oligopoly with four firms controlling 70.1% of the market. Low switching costs between carriers, high supplier power, and the high cost of operations drive market competition. Energy makes up 25% of these operating costs on average.

The Cost of Diesel to Fuel the Indian Telecommunications Industry

The telecom tower industry in India consumes an estimated 2.6 billion liters of diesel per year, which costs approximately 1.15 billion USD and produces an estimate of 6.6 million metric tons of CO2 emissions. For an individual off-grid cellular tower, the cost of a diesel generator, maintenance, and fuel can be found below, compared to the 20+ year estimated life of WiscWind's system. Diesel generators and batteries are used in 90% of the cell tower sites in India [8]. The EPA estimates the average lifetime of a 0-50 horsepower diesel generator to be 2,500 hours (6.8 years), so an average of 2.9 generators would need to be installed at a site over the life of a WiscWind hybrid system [9]. A summary of a cell tower owner's expenses for a diesel generation system and the WiscWind over 20 years is contained in Table 1 below.

Expense	**Diesel Generator + Battery**	**WiscWind: Turbines + Solar + Battery**
Capital Expenditure	$13,035	$60,000
Fuel Cost	$148,263	$0
Maintenance	$19,053	$10,000 / # towers serviced
Total	$180,351	≤ $70,000

Table 1: Expenses, traditional diesel vs. Average WiscWind LLC Market Price.

Market Penetration

Because of the high fuel cost and competitive market environment, WiscWind LLC will penetrate the market by directly targeting tower owners. The company plans to secure a partnership with an early adopter, providing our system and service at no cost in exchange for the opportunity to collect data on that system. Using that data, the company will secure subsequent customers seeking a cost advantage over their competitors.

Small Wind and Solar vs. Grid Expansion

Small wind technology can be a more cost-effective solution for communities as close as 2.99 km away from the existing power grid, and photovoltaic (PV) systems become cost competitive as near as 3.72 km to the grid. This system combines wind and solar energy to minimize the size of the battery, which is often the highest cost of an off-grid renewable system.

Target Market

Customer Segment

WiscWind LLC has modeled the Ventus 3k Series turbine based on the demand presented by our market, which has been segmented to target the telecommunication industry in India. We further segmented this market with our decision to target rural telecom towers that use diesel fuel generators. This decision was based on the high cost of diesel fuel, and the ability of telecom companies to afford the upfront cost of a VAWT, battery, and solar panels. Our system was designed based on a 3 kW average demand, wherein 2 kW are supplied by the wind system and 1 kW supplied by a solar system. This is an estimate based off the average demand for an Indian telecom tower [8].

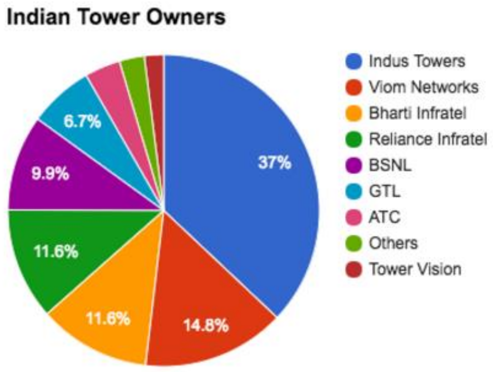


Figure 2: Ownership breakdown of Indian telecom industry.

Customer Relationship

The telecom tower market can be further segmented into 9 parts, with 8 key players making up 97.4% of the market. The telecom industry in India has become increasingly competitive, and several companies have found a market leasing towers to other telecom companies. Because of the large capital resources of our target market, and the durability and high capital cost of our system, there is a potential for high customer lifetime value (CLV). To maximize CLV, WiscWind LLC will use a trial offer for early adopters, provide site assessment and maintenance at a low cost, and provide system analytics and case studies to customers to foster future business.

Competitor Analysis

Several energy companies have identified the opportunity for decentralized energy production for Indian cell towers. Fuel cell storage is in place for thousands of grid-connected towers in India; however, no competitor has been able to capture a significant portion of the off-grid market. Information on competitors found to have been relevant is contained in the Table 2.

Purpose	Brand	Product	OPEX Cost Reduction / Year	Price (CAPEX)
Diesel / Grid Power Supply	Varies by tower	Diesel generator / Battery Storage / Grid Energy Supply	OPEX Price / year = $4673	$7,035
Off-Grid Diesel Power Supply	Varies by tower	Diesel generator / Battery Storage	OPEX Price / year = $7,409	$5,160
Diesel OPEX Reduction	Poweroasis	Diesel Generator / Solar PV / Lithium Ion Battery	80%	Customized to site
Diesel OPEX Elimination	Hydrogenics	Hydrogen Fuel Cell	100% diesel cost reduction, increased grid power cost	Information not available.

	Intelligent Energy	Hydrogen Fuel Cell	100% diesel cost reduction, increased grid power cost	Comparable to diesel
Grid Supply / Diesel OPEX Elimination	WiscWind	VAWT Turbines, PV Panels, Battery Storage	100% diesel cost reduction, up to 99% maintenance / operation cost CAPEX Cost / year over lifetime = $3,000	$60,000
	Panasonic	Solar PV, Battery	Plan to offset diesel and grid power completely, no data available	Information not available.
	OMC Power	Solar, wind, or biogas	Plan to offset diesel and grid power completely, no data available	Information not available.

Table 2: WiscWind LLC competitor analysis.

Management Team

Below is the management structure of the company. WiscWind is organized as a LLC to protect its stakeholders. Alex LeBrun and Benjamin Kufahl will transition from their R&D roles as Team Lead and Team Co-Lead to Director of Product Development and Director of Operations to facilitate cross-functional development. Austin Renfert is WiscWind's Director of Business Development, with Srinidhi Emkay as Head of Marketing to attract customers, and Ian Berg as Director of Customer Development to the site analysis and operations team. Connor Sawyers is our Director of Finance, securing the required funding for WiscWind's R&D and operations. The engineering department is separated into electrical and mechanical development, with Evan Wolfenden as Director of Engineering, Walker Willis as the Lead Electrical Engineer and Emily Blase as the Lead Mechanical Engineer.

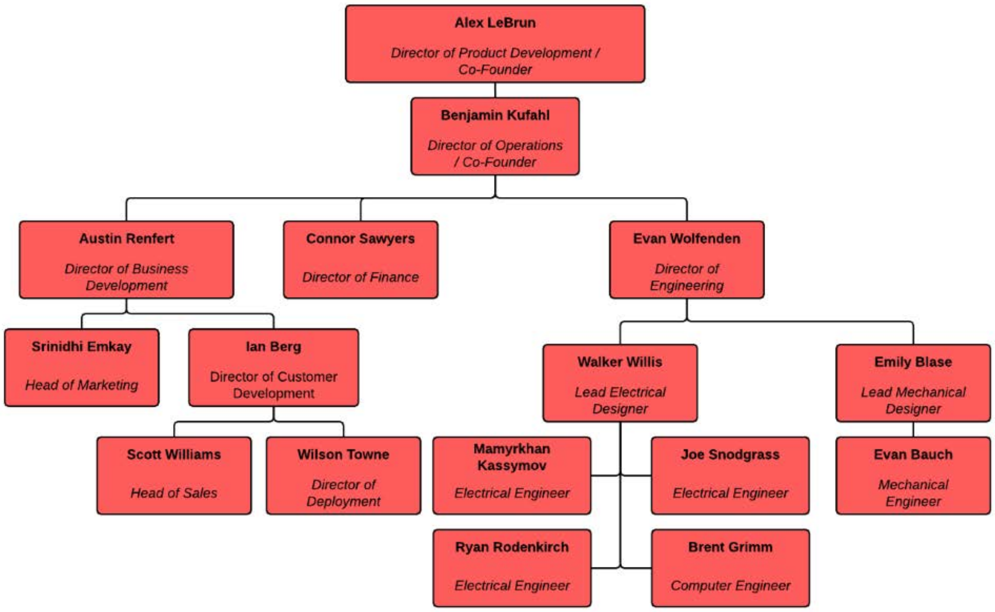


Figure 3: Management structure of WiscWind, LLC.

Development and Operations

Development

Currently located in the cradle of Lake Mendota and Lake Monona in Madison, Wisconsin, WiscWind LLC developed and manufactured the Ventus 3K Series, a vertical axis wind turbine well suited to meet the increasing demand of telecom tower companies attempting to convert from diesel engines to renewable energy technologies. WiscWind's business development operations include networking with local entrepreneurs, researchers, and professionals in the wind industry, as well as establishing contacts in the Indian power industry. WiscWind has gained support from local firms including Madison Gas and Electric, Milwaukee Tool, Midwest Prototyping, and Pedal Power Music, as well as the U.S. Department of Energy to alleviate initial R&D costs. Making a move overseas will allow WiscWind to establish business relations with major startup incubators and accelerators across India. Establishing these relationships with programs such as the Indian Angel Network Incubator and Veddis in Delhi, and GSF and Kyron in Bangalore, has allowed the company to begin establishing its presence around the country. Utilizing these programs in various cities lays the framework for future growth and development outside of the target market in Anantapur and the Southern Region. However, in this initial penetration of the Southern Region's market has some barriers. Table 3 contains the foreseen development barriers to market entry, and WiscWind's business development plan to overcome these barriers.

Barriers to Entry	**Business Development Plan to Address**
Operating Overseas in India	WiscWind plans on leasing a base of operations in India for sales, production, site assessment, and maintenance. The company will send engineering and operations managers to India, and hire engineering, sales, and site analysis/maintenance staff to work full time.
Lack of Long-Term Field Testing	The company has explored the option of a pilot program for field testing on a US cell tower. In order to attain field data and acquire early adopters, a partnership in the target market will be secured, initial services will be provided for a reduced rate to customers and system efficiency data will be gathered.
Oligopolistic Target Market	By targeting smaller, more flexible players in the cell tower industry WiscWind LLC can pursue companies seeking an innovative, competitive advantage over their larger competitors.
High Up-Front Cost of System	The Ventus 3k Series system can be provided at a significantly lower price than the cost of diesel power.

Table 3: Barriers and corresponding strategy to target market entry.

Operations

Establishing operations in India following our pilot period is WiscWind's largest anticipated use of funding. WiscWind has instilled a safety culture in our R&D Process, and plans to continue to do so during business operations. Two Production Engineers, two Research Engineers, and two Deployment Engineers will be hired and trained internally to provide safe operations. Our deployment engineers will handle all site assessment and maintenance, and will be trained in lock-out-tag-out procedures to safely conduct these activities. An in-depth manual will accompany safety training to ensure injury-free maintenance and installation. An engineering manager will oversee all site assessment, maintenance, production, and design activities. Also necessary for hire is an operations manager to oversee all activities, and two sales associates to acquire new customers and handle point of sale negotiations. WiscWind will handle production of our turbine, and storage of our system at our Indian facility. WiscWind plans to partner with a PV panel producer and a battery producer to outsource production of those system components. Our system full system cost uses industry standards in India to price those components. WiscWind will invest in a 3D printer, mill, and lathe for production, as well as a pulley system and two vehicles for deployment of our turbines on existing cellular towers. By keeping site assessment and deployment in house, WiscWind can provide our customers with the best possible system efficiency.

Financial Analysis

Financing

WiscWind's owners plan to invest $20,000 of working capital to fund the pilot period and related marketing and data acquisition activities. This will allow WiscWind LLC to gather necessary field efficiency data for our system, while remaining lean and agile. We are seeking a $250,000 equity investment from investors with expertise in the Indian cell tower industry. Based on our 3 year financial projections at a venture capital industry standard 25% required rate of return, the net present value of that investment is $402,849.6. A large portion of the sales revenue in the first three years will be reinvested into through customer acquisition and R&D, as noted in the attached Pro Forma in the

Appendix.

Revenue Streams

WiscWind's revenue model has two components and can be characterized by the following equation:

$$Revenue = \sum_{i=1}^{N} Fixed\ Price\ Service + \sum_{i=1}^{M} System_i$$

Where $Fixed\ Price\ Service = \$10{,}000/yr$ per customer and $System_i =$ CAPEX and installment cost of the system. Here, N represents the number of customers and M represents the number of systems. The fixed service price includes site assessment at any of a customer's cell tower sites to quote the viability and price of a WiscWind hybrid system. It also includes maintenance on the tower for the 20 year expected system life. By using a combination of a fixed service price and variable system price, WiscWind can extract more value from site assessment and maintenance activities while incentivizing existing customers to install subsequent systems.

Technical Design

Design Summary

In accordance with the business model and marketing strategy of the WiscWind system, the objective of the turbine technical design is to satisfy three major criteria:

1. Produce a reliable off-grid wind driven system, capable of being retrofitted to the structure of existing cellular towers.
2. Reduce the necessity of regular maintenance and/or replacement of wearable turbine components.
3. Provide a customizable platform that will allow the airfoil design to tailor to individual deployment locations.

As such, WiscWind selected to develop a vertical axis wind turbine (VAWT) to directly drive (i.e. no gear reduction) a three-phase permanent magnet generator. A helical blade structure was developed to both a) address the torque imbalance and consequent fatigue issues of more traditional VAWT designs [10] and b) take advantage of 3D printing for the fabrication of the turbine blades. Additionally, the vertical axis design reduces the need for several mechanical subsystems:

- *Gear Reduction* - because of the direct drive design, the WiscWind turbine negates the need for a gearbox that contains mechanical elements (gears, oil, bearings etc.) prone to failure, regular inspection and expensive maintenance.
- *Pitch and Yaw Control* - the helical VAWT design allows the turbine to generate electricity from omni-directional wind. As such, an electromechanical pitch and yaw control system is not necessary to reorient the turbine into oncoming winds.
- *Mechanical Braking* - the ability to employ dynamic braking via the turbine generator reduces the reliance on a mechanical braking system for light braking needs. However, a mechanical brake would still be implemented in a full-scale turbine as a safety precaution for extreme winds and periodic maintenance.

The turbine presented in the prototype stage utilizes a single tower support wherein the bearings are embedded in the generator housing. However, the WiscWind turbine will employ a two-arm system (see Figure 4) to secure the turbine to a cellular tower, to a) provide increased rigidity to the mounting configuration and b) remove the thrust (weight) component of the turbine from the generator bearings and onto the support structure. Because of variances in tower design, the mounting configuration will vary from tower to tower but will ultimately follow a template similar to as shown in Figure 4. Two structural arms will secure the top and bottom of the turbine chassis, with the bottom arm also providing a mounting platform for the thrust bearing, generator and electrical control box. The structural arms will mount to the uprights of the cellular tower via a coupling, the design of which will depend on the specific cross-section of the tower support.

The dimensions of the theoretical full-scale turbine differ from the prototype presented at the U.S. Department of Energy Collegiate Wind Competition. To satisfy the 2 kW load needed by the wind system in the business model, each full-scale turbine will be roughly 1.5m in diameter and 2.5m in height, mounted on each side of a cellular tower. A total of six wind turbines with an average (adjusted for capacity factor) output of 350 W each would be mounted to the tower vertical supports at a height of 25-35 meters (80-115 ft.) to provide the energy necessary for the wind component of the overall system.

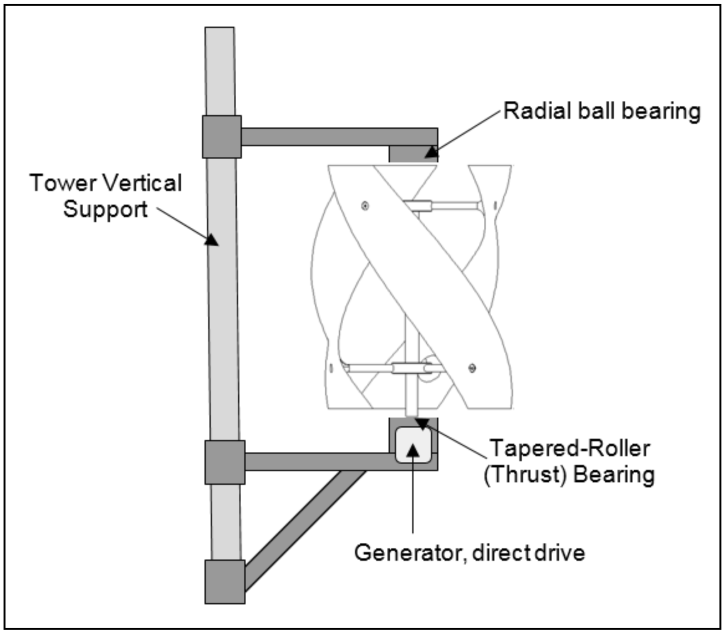


Figure 4: Sample mounting configuration of turbine**.**

Mechanical

Overall Design Objectives

The prototype was designed largely to reflect the objectives of the full-scale turbine required by the WiscWind's business objectives. That is, both the prototype and the theoretical full-scale model are helical blade VAWTs with a direct-driven three-phase AC generator. For both cases, a relatively low cut-in wind speed was desired, at or below 5 m/s. In the prototype stage, this is to satisfy the requirements of the Collegiate Wind Competition, whereas in the full-scale case this is necessary to tailor to the moderately low wind speeds in the target region (see *Deployment Strategy* for more detail). Control simplicity was another prime objective in both cases, and vertical axis was selected to address this goal; both to avoid complicated mechanical controls for the prototype (e.g. use of electrical dynamic braking to slow the turbine) and to produce a low-maintenance and thus more marketable product to satisfy the business objectives of WiscWind. Additionally, in accordance with the business plan and target market, vertical axis was chosen for simplicity of mounting to rural cellular towers. That is, vertical axis need not be reoriented to accommodate changing wind direction, and allows a more simplistic mounting configuration in terms of retrofitting an existing cellular tower.

Prototype

Objective

As mentioned above, the design objectives of the prototype were driven by the Rules and Regulations of the Collegiate Wind Competition. Three major criteria were addressed in accordance with these regulations:

1. **Size Constraints** - the turbine must fit within a 45cm x 45cm x 45cm cube area. The team explored different size configurations, first building a prototype with a 45cm height and 45cm diameter, but ultimately reduced the diameter to increase rotational velocity as well as adjust the aspect ratio in an effort to increase performance. Additionally, different tower mounting configurations were built and tested (discussed below).
2. **Power Production** - to provide the electrical system with enough voltage to produce sufficient power (min. 10 W), the mechanical team focused both on producing optimum torque via the shape of the airfoil, and producing the highest possible rotational velocity at a given wind speed. As such, several airfoils were tested, at various radii such that the effect of turbine radius and airfoil shape could be observed.
3. **Durability** - the turbine must withstand 18 m/s wind, including various wind-speed profiles. The chassis was designed to be lightweight and strong, and each blade and chassis configuration was tested to this maximum wind speed to assure compliance.

The design process of the prototype turbine is described below, beginning with preliminary airfoil selection and ending with prototype construction methods. Testing data is presented in the *Testing and Results* section.

Airfoil Selection and Blade Design

The team used QBlade[1], an open-source airfoil and blade analysis software for the preliminary design stages of the VAWT. Research indicated that symmetrical NACA[2] blades are the most commonly used for vertical axis turbines [12]. The NACA 0018 airfoil with a 10 cm chord length and 0° pitch was consequently selected as a baseline airfoil. From here, a research thesis on airfoils provided the team with recommendations for increasing starting torque by adjusting camber, pitch angle, chord length, and thickness [11]. The thesis also recommended several potential asymmetrical airfoils. In total, twelve airfoils were analyzed with QBlade. Figure 5 shows a coefficient of lift/drag analysis (C_L/C_D) of these airfoils.

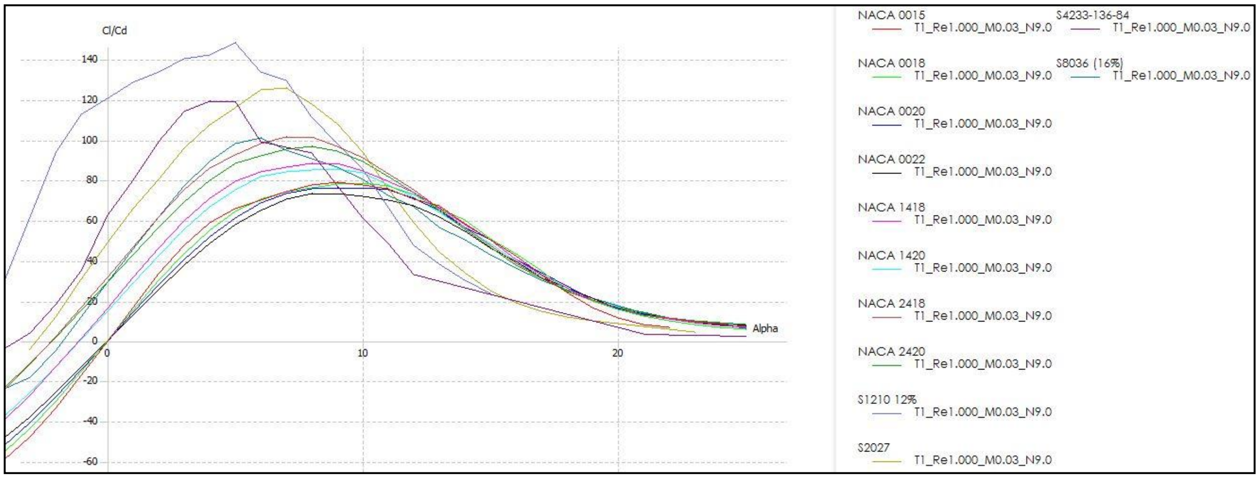


Figure 5: QBlade analysis of lift/drag coefficient ratio for various airfoils.

From the analysis, the team concluded that cambered airfoils may have an increased C_L/C_D ratio, and the airfoil thickness only marginally affects the performance of the blade system. Ultimately, test results and

---

[1] http://www.q-blade.org/

[2] National Advisory Committee for Aeronautics

engineering judgement guided the selection of airfoils and configuration of the rotor. This process is described in more detail in the *Testing and Results* section.

Analysis

Each blade is made from a Nylon 12 Polymer which has a relatively low yield strength (45.8 MPa) compared to more commonly used fiberglass composites (200 MPa) [12] [13]. To ensure our blades could handle the rotational forces endured from strong winds, Solidworks Finite Element Analysis was employed. Figure 6 shows that at 18 m/s winds (the maximum survival speed) and a rotational speed of 2000 rpm, the fastener joints of our blades will have a minimum factor of safety of 3.7, well within the design criteria. Figure 6 depicts the centrifugal forces on a blade at 2000 rpm, twice the prototype rated speed of 1000 rpm.

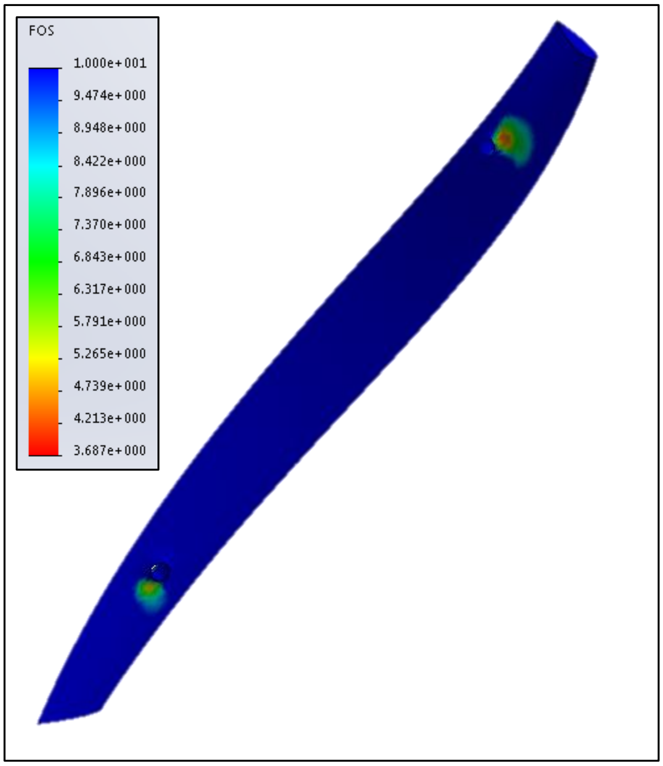


Figure 6: FEA of rotational forces on helical blade.

Manufacturing

Blades

All of the prototype turbine blades were manufactured by a local prototyping facility, Midwest Prototyping[3]. In addition, the team was invited to travel to the manufacturer to learn more about the manufacturing process. The Polyamide (Nylon 12) construction was achieved via Selective Laser Sintering (SLS) 3D printing. SLS printing is the ideal process for constructing turbine blades of this geometry because of the complex shape and necessity for dimensional accuracy. Unlike some more traditional 3D printing methods (like Fused Deposition Modeling), the SLS process results in a part of uniform material strength and mass characteristics. Nylon was chosen as the material based on its strength-to-weight ratio, low cost and availability in the SLS process. Additionally, Nylon plastic exhibits strong UV resistance among 3D printed plastics; which makes it an ideal material for harsh outdoor environments [14].

---

[3] https://www.midwestproto.com/

Structure

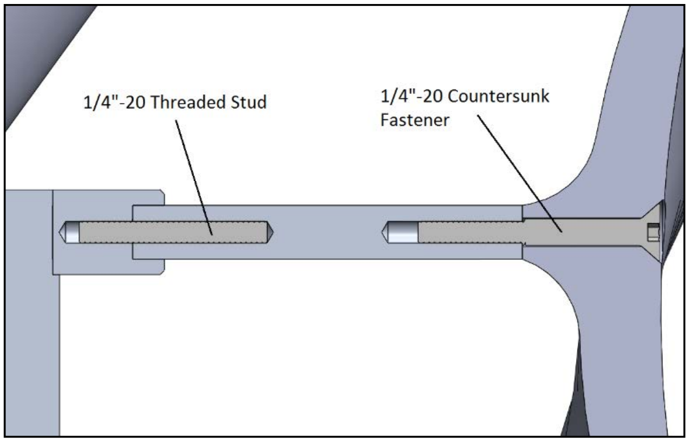


Figure 7: Cross sectional view of blade mounted to turbine chassis.

All other turbine components were designed by the WiscWind mechanical team and custom machined from 6061 Aluminum Alloy, selected for its high strength-to-weight ratio, good machinability, and low cost. An important aspect of the prototype turbine was modularity; this allowed the team to test several airfoil and diameter configurations while making use of a common chassis. Spokes attach to the central frame via ¼"-20 threaded studs, and each 3D printed blade was attached to the spoke via two ¼"-20 countersunk fasteners, as shown in Figure 7. In the case of the prototype frame, two iterations were explored. In an effort to emulate the design characteristics of the turbine mounted to a cellular tower, the first frame was welded steel and featured a top and bottom bearing housing, as seen in Figure 9. There were two major problems with this prototype iteration. Firstly, the steel frame experienced warpage during the welding process, which made it very challenging to align the other critical components (such as the gear driven motor) beneath the bottom bearing housing. Secondly, the cogging torque[4] from our first generator (donated by Milwaukee Electric Tool Corporation) was much too high to yield a cut-in wind speed competitive for competition. More details on the generator selection are discussed in the *Generator Selection* section below. The second iteration of the prototype featured several major design changes. Firstly, the original donated generator was abandoned because of it's high cogging torque, and costly custom gears that needed to be cut to

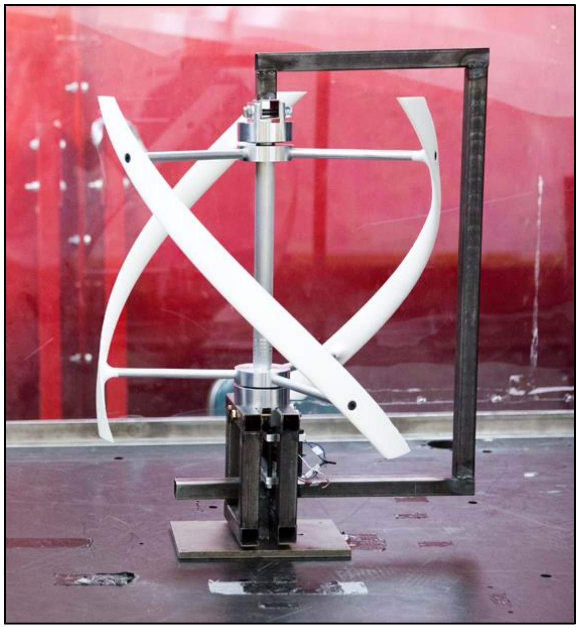


Figure 9: WiscWind 1st prototype iteration.

Figure 8: WiscWind 2nd prototype iteration.

---

[4] Torque caused by the discrete alignment of rotor magnets with stator windings; must be overcome to begin rotation.

mesh with the pinions on the provided rotors. Instead, a three-phase permanent magnet motor was acquired by the electrical team, exhibiting a cogging torque much lower than the predecessor. In addition, the top/bottom bearing tower configuration was replaced in favor of the embedded bearings in the generator casing of the new machine. This eliminated the need for the spur gear on the turbine shaft that had been previously used to increase the rotational speed of the Milwaukee Tool generator. A coupling was designed to directly mount the turbine to the shaft of the new generator. The result was a much simpler drive configuration, with a noticable decrease in cogging torque (and thus cut-in wind speed) of the turbine system. A picture of the second iteration of the WiscWind turbine is shown in Figure 8.

Full-Scale Turbine

Objective

To meet the power requirements proposed in the WiscWind business model, a few design changes would need to be to be implemented. The prototype serves as an illustration of concept, but to implement a full-scale solution to the WiscWind business model would require additional research and development, focusing on four major aspects:

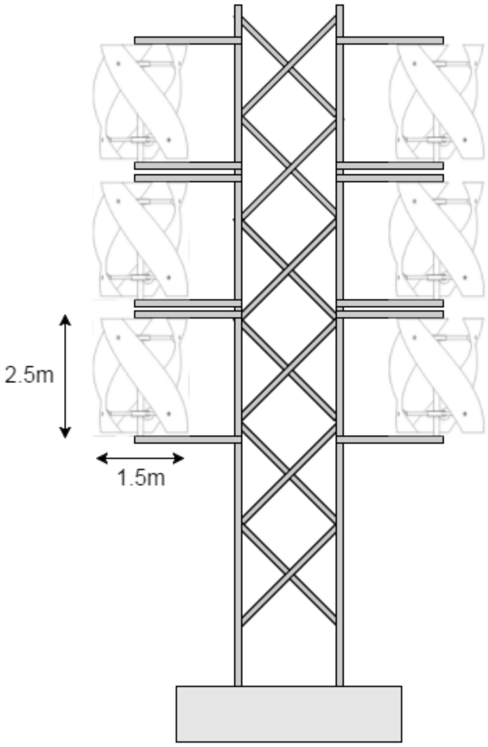


Figure 10: Sample WiscWind turbine mounting configuration.

1. **Reliability –** to remain competitive with traditional diesel generator systems, the full-scale turbine would need to have a lifetime of 20 years. Design aspects such as a directly driven generator and control system simplicity that were factored into the prototype will be extended into the full-scale stage to achieve this goal.
2. **Performance –** due to the relatively low wind speeds at the selected deployment zone, the full-scale turbine would be designed around achieving high performance at low wind speeds. Much of this aspect would be heavily dependent on generator design, but optimizing the shape and size of the helical blades would have a tangible effect on cut-in wind speed, as was seen during prototype testing.
3. **Lightweight –** to safely mount to existing cell towers, the full-scale turbine would need to be as lightweight and non-intrusive as possible. This would be addressed by utilization of Aluminum alloy for chassis components. Additionally, multiple blade manufacturing options are being considered to save weight, including 3D printing Nylon with reduced infill in non-critical sections, as well as composite blades such as fiberglass and carbon fiber. Ultimately more research and development will need to be dedicated to optimizing the full-scale blade production method.

Notable Differences

Several important differences exist between the prototype turbine and theoretical full-scale machine. To satisfy the 2 kW wind component of the WiscWind system, four turbines measuring roughly 1m in diameter by 2m tall would need to be mounted onto each side of the tower. Typically cell phone towers are of lattice structure with three or four sides [15]. In the case of a 4-side lattice structure, the 500 W turbines could be mounted on opposing sides, wherein two of the four are mounted roughly 10 ft. higher than the other two, such that all turbines receive adequate wind resources. In the case of a three sided structure, slightly smaller (~300 W) turbines could be employed on all sides, again with three of them mounted at a different height, similar to Figure 10. In any case, a site-by-site analysis of the structural configuration would be necessary to determine if the WiscWind system is viable. If not, on-site structural strengthening would be designed and implemented to ensure compliance with the structure.

Analysis

Because of the importance of mounting to existing cellular towers, it was important to consider the static loading effects of the full-scale turbine. A conservative mass estimate of 500 lbs. (226 kg) per turbine system was used to evaluate the structural effect of both the axial loading and bending moment induced in a sample tower structure. For the four sided tower shown in Figure 11, a static analysis can be performed:

Properties of Assumed Steel Structural Tubing

$D_o = 152.4\, mm\ (6")$

$D_i = 127\, mm\ (0.5"\ wall)$

$A = 5574\, mm^2$

$I_z = 1.37 \cdot 10^7\, mm^4$

Additionally,

$$w = mg = 3 \cdot 225[kg] \cdot 9.81 \left[\frac{m}{s^2}\right] = 6621.5\, N$$

Force and Moment Analysis

Reaction moments defined in counterclockwise direction. Additionally, each reaction force and moment is shared with the two additional structural supports not shown (i.e. into the page), which reduces the axial and bending stress induced. This is accounted for in the stress analysis below.

Stress Analysis

Stress in structural member is the sum of axial and bending stresses induced by load. As mentioned, each of the forces and moments are reduced by a factor of two here, because the loads are shared with another upright support.

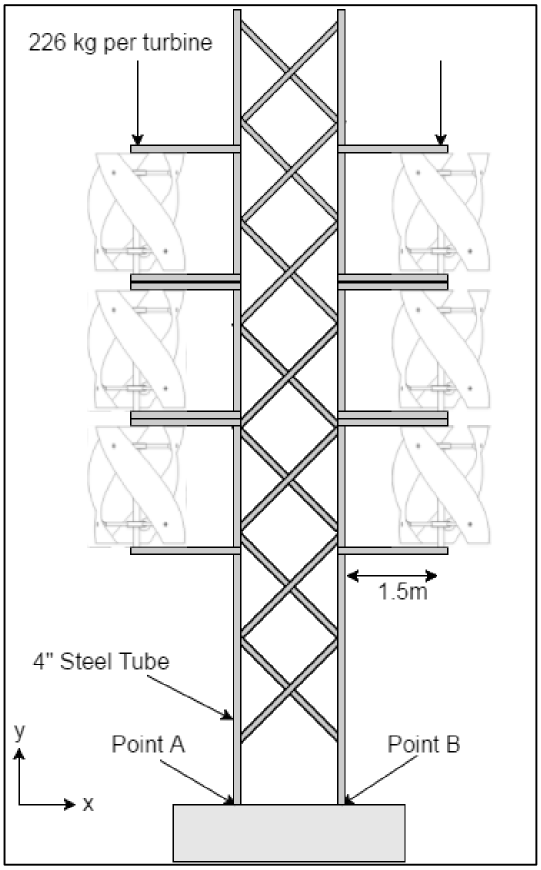


Figure 11: Sample tower free body diagram.

Balance	Results	Balance	Results
$\sum F_x = 0$	$F_{A,x} = F_{B,x} = 0$	$\sum M_A = 0$	$M_A = 9932.6\, Nm$
$\sum F_y = 0$	$F_{A,y} = F_{B,y} = 6621.75\, N$	$\sum M_B = 0$	$M_B = -9932.6\, Nm$

$$\sigma_{total} = \sigma_{axial} + \sigma_{bending} = \frac{F}{A} + \frac{My}{I} = \frac{3311\, N}{5574\, mm} + \frac{4966\, Nm \cdot 0.152m}{1.368 \cdot 10^{-5} m^4} = 0.6 + 55.2 = 55.8\, MPa$$

The yield strength of A653 Galvanized Steel like that used on a cellular tower is approximately 250 MPa [16], giving a factor of safety of 4.48. Note that this is also a very conservative estimate, as the 500 lb. turbine assumption is very high, and would likely be less than half of that weight in practice, depending on the blade construction and chassis configuration. Also as mentioned previously, each mounting configuration will vary depending on the specific cite needs, considering factors such as the type of tower, existing equipment weight, and lateral forces induced by the local wind resource. This means that more in depth structural analysis would be exhausted prior to deploying a WiscWind system. This analysis serves simply as a proof of concept of the WiscWind system.

Electrical

Overall Design Objectives

Four major aspects define the electrical design: the generator, the power electronics, the controls, and safety. Each aspect presented different design specifications that needed to be implemented to meet the requirements of the competition. The generator needed to work without any external power supply, have a very low starting torque, be reliable and efficient, and have a high voltage rating in low RPM situations. To satisfy these criteria, a three-phase, permanent magnet generator was determined to be the best choice, because the permanent magnets negate the need for externally excited magnetic fields. Additionally, PM machines can be optimized to reduce the cogging torque, which is essential for cut-in wind speed performance. The power electronics needed to be low cost, reliable and capable of operating in wide range of conditions. With this in mind, automotive grade components are used throughout and the design was kept simple to avoid costs and reliability issues. The control logic needed to be simple, reliable, and low cost while addressing a number of different operating conditions. To achieve this, an Arduino microcontroller (MC) was chosen to implement the controls. Safety is one of the most important aspects of any system. In an effort to address the hazards associated with electricity and rotating mechanisms, the electronics and controls are implemented to keep the turbine safe even in the most severe conditions and all electrically live components are properly insolated and isolated. The turbine is implemented with a manual shutdown capability and a load disconnect shutdown capability. The Canonical model in Figure 12 gives a high-level overview of the electrical side of the design.

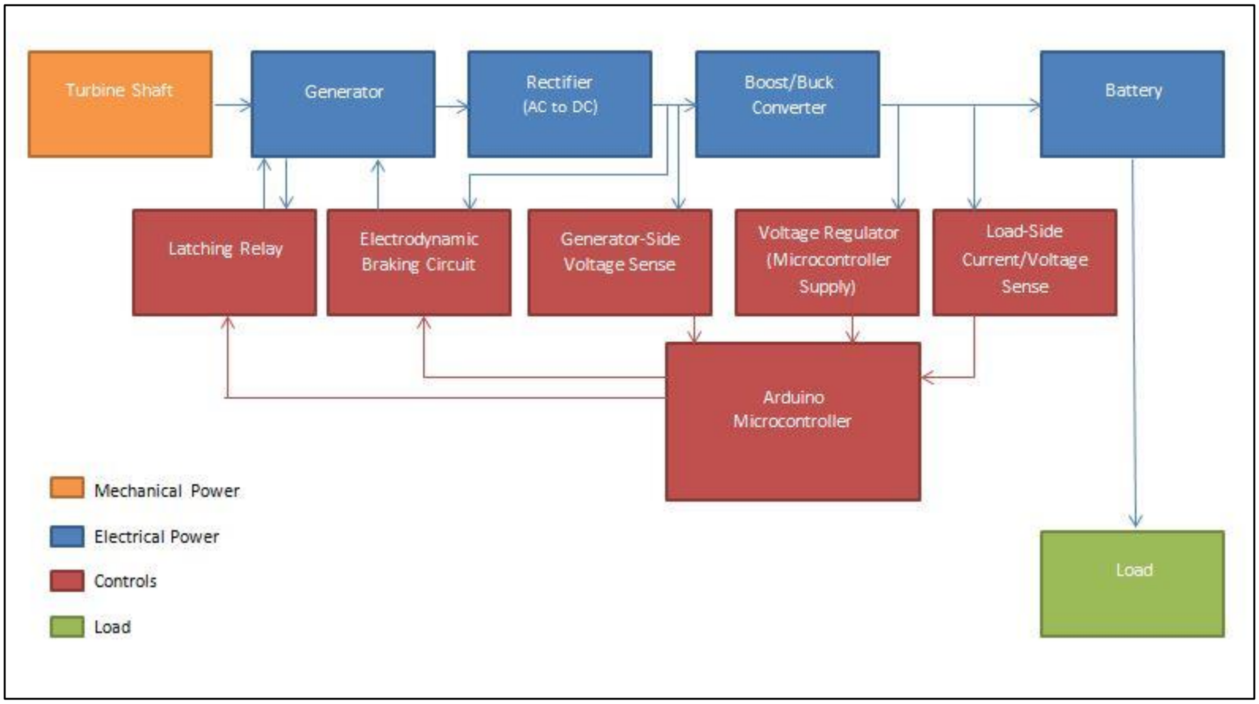


Figure 12: Canonical Model of Electrical Design.

Generator Selection

The most important design criteria for the generator was low cogging torque. Voltage produced by a generator is related to the motor velocity constant K_V (units RPM/Volt) by $K_V \cdot RPM$ = Voltage. The competition regulations dictate that the voltage range is up to 48 V with minimum output power of 10 W. The first generator came from Milwaukee Electric Tool Corporation, initially used as the motor in a cordless power drill. The team rewound the generator stator with a thinner gauge wire to get a higher voltage output. However, the cogging torque of the generator was far too high to cut in at a reasonable wind speed. To address this problem, the team employed a two-generator configuration skewed from each other, in which the cogging torque of one generator would be used to directly combat the cogging torque of the other via a common gear. However, after testing in the wind tunnel, it was discovered that the cogging torque was still high, which forced the team consider another generator.

The generator that was finally selected came from the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC); a 4 pole, 3-phase PM motor with minimal cogging torque and a much higher K_V value of 15 [RPM/V], which meant that it could be directly coupled to the turbine, augmenting the overall strategy of a robust and reliable wind turbine via reduction of complex mechanical components.

Power Electronics

The power electronics of the turbine serve several important purposes:

- Receive the 3-phase AC output of the generator and rectify it to DC.
- Control the amount of power being produced as well as the turbine speed.
- Regulate the voltage for purpose of battery charging.
- Function without storing any power (against competition Rules and Regulations)
- Force the turbine to shut down when the load was disconnected or the manual shutdown button was pushed.

A schematic of the power electronics circuit is shown in Figure 13. The ultimate circuit design was tested prior to interfacing with the full prototype and before the manufacturing of a printed circuit board (PCB).

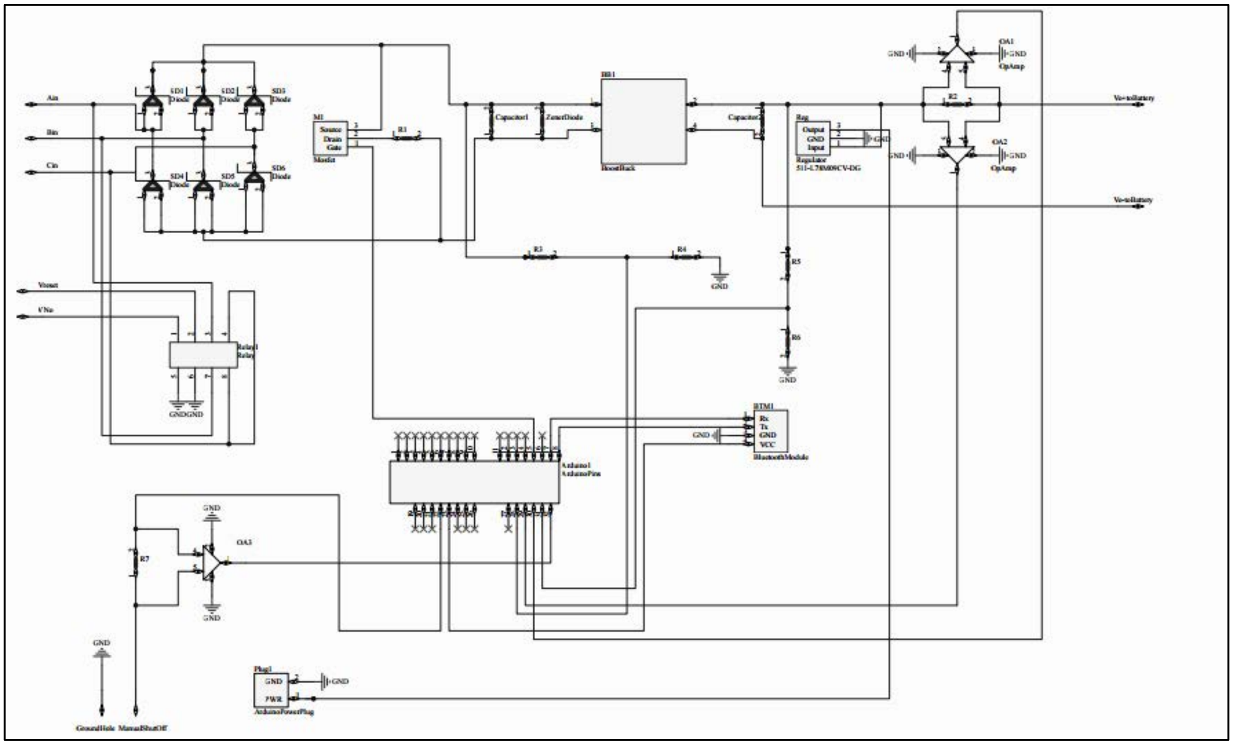


Figure 13: Schematic of turbine power electronics.

The 3-phase input from the generator was first rectified using six Schottky diodes, selected for the low voltage drop they exhibit. After rectification, a power MOSFET (essentially an electrically controlled switch) was used to control the power output and speed of our turbine. By adjusting the pulse width modulation (PWM) of the MOSFET, it is possible to alter the associated dump load. This “load dumping” is necessary for leveling off our characteristic curves at 11m/s and above per competition requirements.

A normally open (NO) latching relay powered by a microcontroller (MC) is used to control the electrodynamic braking of the turbine. Upon closing the relay, the three phases of the generator are short circuited, resulting in electrodynamic braking that brings the turbine to within 10% of its rotational speed. Additionally, a NO relay allows the turbine to brake and remain stopped even after the MC loses power. Upon restarting, the MC will apply another signal that will unlatch the NO relay.

To be able to implement the logic controls of the turbine, current and voltage sensing in the power electronics were implemented. The voltage sensor on the generator side of the circuit is used as a reference to the RPM of the turbine and is implemented by a voltage divider with two resistors, with the highest expected output voltage set to produce 5 volts at the input of the microcontroller. The current sensors include Maxim 9938 single-supply current sense amplifiers in conjunction with a .01 Ω resistor. These amplifiers provide an advantage for this current sensing application since the positive input is also used as the supply voltage, and the circuit results in very little power consumption. The voltage across the current sense resistor is amplified by 100 V/V and input to the microcontroller, where the power at the load side can be calculated using the fixed output voltage of the boost/buck converter. These controls allow the turbine to sense and adjust its power production in real-time.

Finally, the boost/buck converter adjusts the power electronics output voltage in accordance with the charging parameters of the battery load, in this case 13.7 Volts. Once the minimum voltage threshold is overcome (6 V), the converter begins applying power to the load. In order to protect the Buck/Boost converter from over voltage, a Zener diode is placed on the generator side of the circuit.

To most closely resemble the load specified in a market-scale system, a 12 V lead acid battery was chosen as the load for the prototype. Since a battery is to be float-charged at a constant voltage, the voltage on the load side of our circuit is fixed by the buck/boost converter. As mentioned previously, this particular battery requires a load-side voltage of 13.7 V. As a result, current is dependent on the power output of the generator. This can be modeled as a voltage-dependent current source on the load-side of the circuit, as shown below.

$$P = V_{Gen} * I_{Gen} = V_{Load} * I_{Load}$$

The resistance seen at the load side of this circuit, therefore, also varies by the output power according to:

$$R_{Load} = \frac{V_{Load}}{I_{Load}}$$

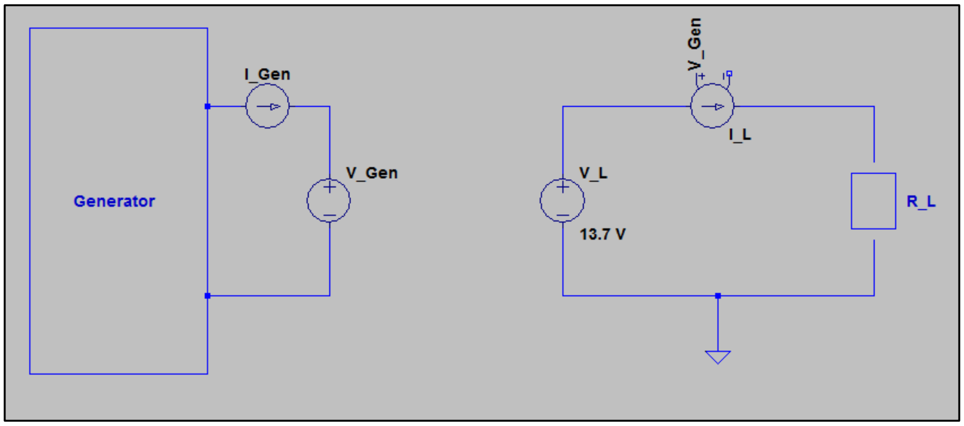


Figure 14: Equivalent circuit of a load model.

However, the load resistance seen by the generator is defined by the voltage and current on the generator side of the circuit:

$$R_{Gen} = \frac{V_{Gen}}{I_{Gen}}$$

This model can be applied to any battery that is charged at constant voltage, meaning we can easily project the output behavior of our circuit if a battery of different floating-charge voltage were attached and the buck/boost adjusted accordingly.

Control Logic

The control logic for the wind turbine was developed to meet a number of important competition rules. The most important aspect of the control logic was to maintain the power production and turbine speed between 11m/s and 13m/s. The logic also dictates the means of shutting down the wind turbine when the load is disconnected or when a manual shutdown button was pressed. Lastly, the logic then had to account for the fact that there are no power storage elements allowed on the turbine side of the wind tunnel.

The controls for shutting down the wind turbine went through a number of iterations prior to realizing the final design. Initially, the electrical team hoped to control the shutdown with only passive elements; however, after the testing of a number of designs it was determined that the circuitry could not be realized without a number of active elements. It was at this stage that the Arduino MC was introduced, with three current and two voltage sensors. The input from these sensors are what allow for the safe and reliable control of the turbine. A state machine diagram of the turbine behavior is shown in Figure 15, illustrating the startup, system ready, run and shutdown states of the turbine. During the run state of the program control, the Arduino will circulate between checking the output current sensors (CS1 and CS2), checking the voltage sense for the power control, and checking the manual shutdown current sensor. In the event that both of the output current sensors or the manual shutdown are outputting a zero will cause the relay to close and latch bringing the turbine safely to a stop.

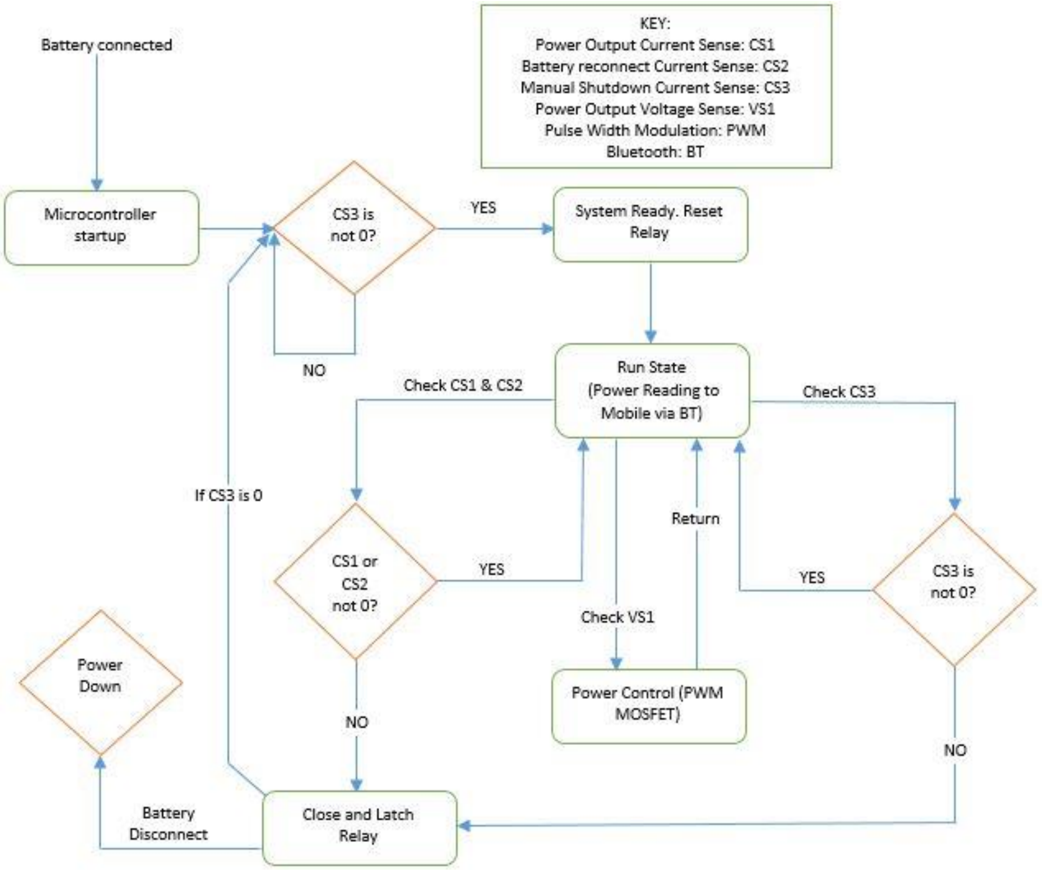


Figure 15: Control flow diagram.

Part of the competition requirements is to maintain the same output power and rotor rpm at wind speeds from 11m/s to 13m/s. The difference in power outputs at each wind speed with respect to the output at 11m/s is the amount to be dissipated with a dump load across the generator input terminals via an Arduino controlled MOSFET. To hold the speed constant, the duty cycle of the switch operating the braking circuit is informed by the voltage on the generator side of the circuit. By creating a lookup table of generator output voltages as they relate to rotor speeds, the braking can be engaged to bring the rotor back to the desired speed.

Finally, the competition rules dictate that no power storage elements existed on the turbine side of the point of common coupling. To meet this criteria, the power for the microcontroller (MC) is provided via a linear voltage regulator in parallel with the output of the power electronics. While this takes away from the overall power produced and does draw power from the battery upon initial connection, the amount of power used by the MC is minimal. In the event that the battery is disconnected during operation the power still provided by the generator will continue to power the MC until it is able to signal a digital high to the relay and complete the turbine shutdown.

Electrical Safety

Several factors were key to ensuring the safety of the turbine. All power electronics were safely isolated from the tower via an electrically isolated ventilated box. The ventilation will be via small holes that wildlife will be unable to access. Secondly, all wiring and connection points are insulated or isolated as needed. The isolation of this box involve an additional grounding wire to be dropped from the turbine box to ground. The grounding of the turbine should follow relevant US NEC/FCC standards. At the turbine box the front will be accessible via a door that allows for lock out tag out procedures to be followed. The door to the electronics would also have a combinational lock for locking the box when maintenance is not being performed. The box will have weatherproof warning labels fixated, both in English and the local dialect of the installation site, to provide notice of electrical hazard. A warning label would also be placed near the grounding wire.

Testing and Results

Airfoil Selection

As per the QBlade analysis, the first set of blades tested were NACA 0018 airfoil with a 6 cm chord length and 1° angle of attack. However initial testing revealed that the blade did not perform as well in practice as simulation may have suggested. The subsequent blade selections were made through consulting technical documents concerning VAWT's, as well as general engineering judgement from observations made during wind tunnel tests. A summary of the blades tested as well as the factors held constant are presented in Table 4 below.

Test	Airfoil	Chord Length	Diameter	Solidity Ratio	Description
1	NACA 0018	6 cm	45 cm	.40	Originally selected as per the QBlade analysis that indicated the highest C_{P}.
2	NACA 0018	10 cm	45 cm	0.67	Constant radius, increased chord length.
3	NACA 0018	10 cm	30 cm	1	Constant chord length, reduced radius to observe effect on performance.
4	NACA 3312	16 cm	30 cm	1.6	Increased chord length with nearly constant solidity and camber, to further investigate the effect of chord length for small scale wind.
5	NACA 4418	10 cm	30 cm	1	Constant solidity, effect of camber observed.
6	NACA 4418	10 cm	20 cm	1.5	Constant chord length, reduced radius to further observe effect on performance.

Table 4: Summary of tested airfoils.

Configuration

The modularity of the prototype design allowed for testing of multiple configurations of the WiscWind VAWT. Each of the airfoils in Table 4 were 3D printed as helical blades swept 120° around the corresponding radius of the turbine. All turbine tests were conducted in the campus wind tunnel through collaboration with the University of Wisconsin Department of Engineering Physics. A summary of the ultimate prototype configuration is presented in Table 5 below.

Type	Parameter	Value
Mechanical	Airfoil	NACA 4418
	Angle of Attack	2.5°
	Chord Length	10 [cm]
	Diameter	20 [cm]
	Height	45 [cm]
	Blades	3, Helical (120° twist)
Generator	Type	3-Phase PM, 4 Poles
	Voltage Constant (K_V)	0.06 [V/RPM]

Table 5: Summary of testing configuration.

Although many other diameter, airfoil and generator configurations were tested, the team was unable to produce substantial power until the configuration in Table 5 was explored. The team believes that the first five test configurations employed a radius too large to achieve a TSR that allows for efficient power generation. However, the smaller (20 cm) radius allowed the turbine to achieve a substantially higher TSR, especially because the reduction in rotational inertia allowed for a large increase in rotational velocity compared to the other configurations.

Procedure

The team experienced problems optimizing the cut-in speed with the smallest (20 cm) diameter turbine. This is because the lift force generated by the airfoil is applied at a comparatively smaller radius, resulting in less applied torque necessary for cut-in. In an effort to collect data regardless, the turbine needed to be coerced into rotation manually. Once rotating, the turbine would quickly spool to sufficient rotational speed to produce power. The team is currently working to address the cut-in speed of the turbine, by developing additional airfoil shapes and radii to optimize the tradeoff between available torque and achievable RPM.

With the prototype configuration outlined above, data was recorded to create the power and C_P-λ curves seen in Figure 16 and Figure 17 on the following page. The maximum power produced was calculated via the following relationship:

$$P = \frac{V^2}{R}$$

Here, V is the voltage across the rectified generator, and R is the resistive load applied. R was varied in such a way that the turbine would reach a steady state RPM (and thus steady state power production). The strategy was to apply a large resistive load, allow the turbine to reach steady state RPM, and calculate the associated power. This process was repeated until the resistive load was sufficiently small to dynamically brake the turbine such that it could not reach a steady state RPM. The maximum power produced between this range of resistive loads was tabulated to form Figure 17. The same process was used to form Figure 16, wherein the different curves represent different wind speeds tested.

Results

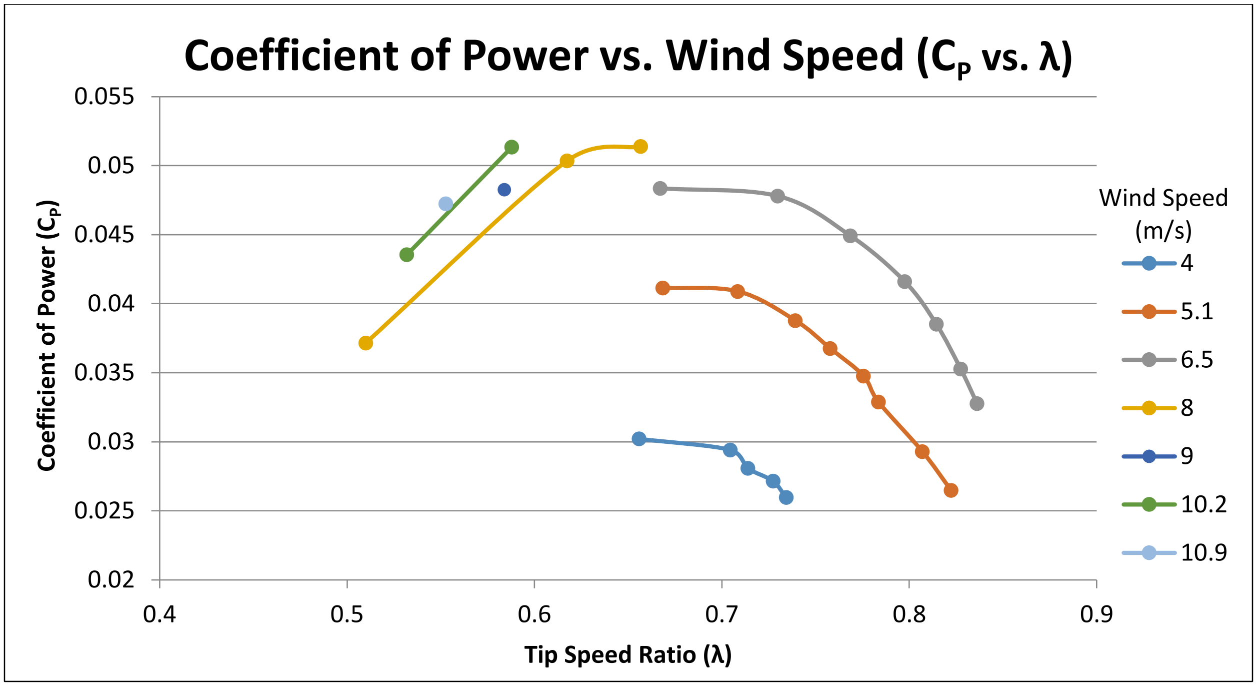


Figure 16: C_P-λ curve for WiscWind prototype.

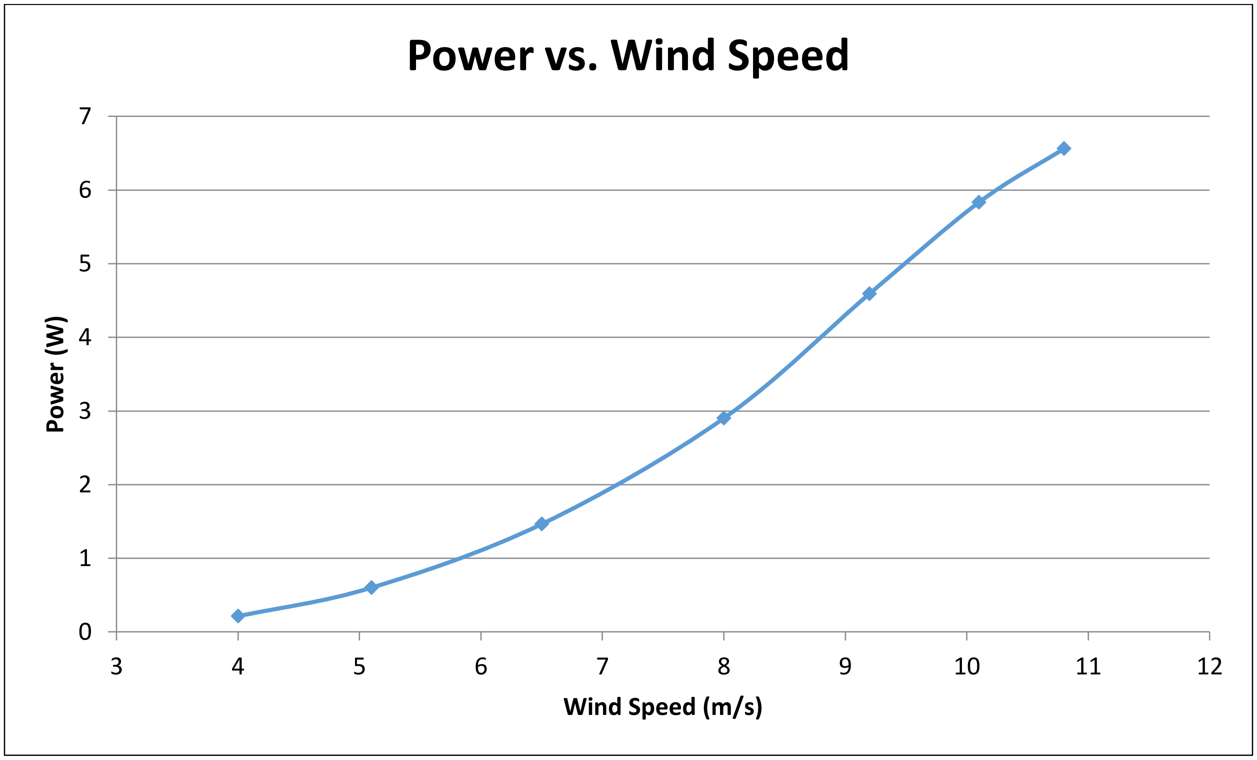


Figure 17: Maximum power achieved vs. wind speed for WiscWind prototype.

Deployment Strategy

Overview

The market potential of WiscWind is based on understanding the nationwide and local failures of the Indian power generation system. India has a great potential for wind energy generation on the local scale, and in particular for offsetting diesel generation of power for distributed uses. The WiscWind system will provide a much needed solution for commercial and residential off-grid usage and for the frequent blackouts that are common for the less developed regions throughout India.

Modern India has made great strides in recent years but the gains from its economic growth are not being equally shared across regions. For example, the Indian power generation system is quite modern in the more developed regions, but throughout the less populous regions there is a lack of grid connectivity and reliability similar to other developed nations. Throughout India, power generation is often lower than the demand leaving many without power from rural villages up to large cities. Beyond the lack of generation potential there are large swathes of India that are disconnected from the grid leaving people without even the possibility of electricity. Many Indians are left lacking due to geographic isolation, lack of grid infrastructure, or reliant on severely outdated and inefficient systems. These factors leave millions of India's citizens without power, but provide an excellent opportunity for distributed wind energy as a solution for the widespread infrastructure failure.

In grid sectors such as the "Southern Region" there is a peak power deficit of nearly 20% according to the 2015-16 *Load Generation and Balance Report* from the Indian government. Of the five major power grid sectors depicted in Figure 18, the Southern Region is the largest to see such deficiencies in supply.

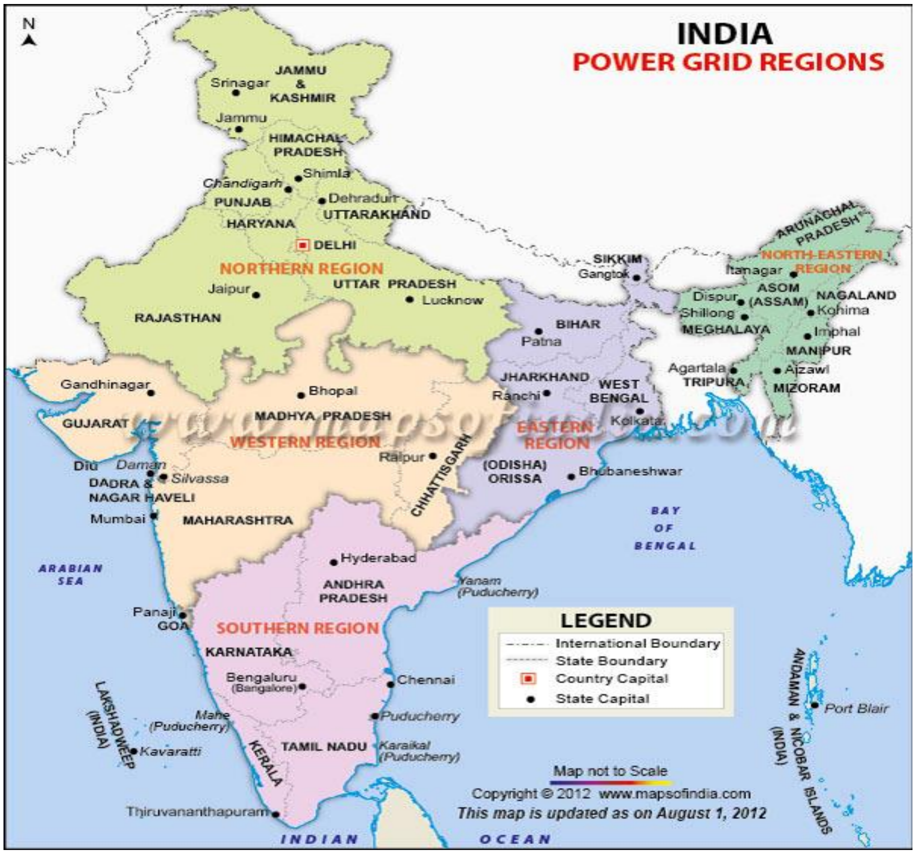


Figure 18: Map of India's Power Grid Regions (courtesy of www.mapsofindia.com)

However, the Southern Region has the potential for largest wind power deployment throughout the entire nation. It is for these reasons that the WiscWind Deployment Strategy will focus its efforts within this area of greatest economic opportunity.

Stakeholder Identification and Communication

A successful deployment of wind energy requires all affected stakeholders to have an opportunity to comment and suggest improvements to any deployment plan. This is especially important for the deployment of unfamiliar technology. The simplicity of WiscWind's small-scale wind technology greatly reduces environmental impacts by minimizing construction, land acquisition, and airway interference to the area of interest. By incorporating the WiscWind system onto existing cell towers the need for land purchasing agreements, construction sites, and the impositions they create on nearby communities are minimized and often eliminated. With incorporation into the existing towers also comes the benefits of basing installments on familiar technology, making it less likely to cause pushbacks from local communities from view-shed disruption. Furthermore, WiscWind will drastically improve the affected areas air quality by eliminating pollution from existing generation systems that rely on diesel and demonstrate the benefits of wind energy to Indians in other capacities or uses.

It is of the utmost importance to have an understanding of the people that will be affected by the product and their concerns and criticism regarding the proposal. Furthermore, distributed small scale deployment is dependent on expert local knowledge of wind conditions, and locals may serve as an excellent resource for the specific wind energy potential in their communities. WiscWind will provide due diligence to make sure that individuals that are negatively affected by the deployment are well informed and compensated for any impacts imposed. In addition to those directly impacted by an installation, WiscWind will cooperate with the individual cell tower providers to make sure all possible parties are acknowledged, informed, and kept updated on the projects; including their impacts and possible dangers surrounding the required electrical equipment. Through the use of extensive community engagement through media and meetings, WiscWind is dedicated to reducing the negative impacts made at all sites and minimizing ecological disruptions as well as understanding local concerns regarding deployment of the system.

Model Project Site

For the purpose of modeling a project site for our final design, the city of Anantapur was selected to represent the portion of India most suited for deployment that will demonstrate Wiscwind is a viable and feasible solution. In addition to proving the wind resource, it was also important to collect data supporting the solar irradiance available to the proposed system. For this purpose, the city of Palasa, along the eastern coast, was selected to make an initial determination of these viabilities in India's Southern Region power grid. While Palasa doesn't lie exactly within the ideal intersecting target areas for power demand and available wind resource, it does have the desired average monthly wind velocities and demand conditions within the southern power grid. These cities and their locations within the Indian subcontinent can be found in Figure 19.

These sites were selected to emulate the wind conditions at a selected project site inland that would have similar wind and solar resource availability. This is the ideal representation of the Indian market outlined by our Business Plan. It is within this area that the interest in available cellular industry towers, and other opportunities, shall be focused.

Figure 19: Palasa and Anantapur in Andhra Pradesh

Site Evaluation and Selection

Monthly Average Wind Velocity Profile

Through market research and considerations made in the design for low-wind speed conditions it was determined that to have a viable, productive system, our turbine would require a minimum monthly average velocity of at least 3.5 to 4 m/s in near surface measurements. It was determined that these speeds should be easy to find in the "Southern Region" described earlier, therefore the specified model wind profile had to reflect these requirements. Initial data was collected at 10 meters off the ground (the

Once certain that there was indeed opportunity, as well as available resource for low cut-in speed application, the model shifted its focus inland to Anantapur. Gathering airport wind velocity data from the online National Oceanic and Atmospheric Administration (NOAA) database, it was compiled into a spreadsheet and analyzed to create an approximate Weibull Distribution of the various wind velocities over the course of the past five-year period (2010-2015). While the collected data was erroneous and inconsistent at times in its attempts at recording every third hour, it still aggregated to a good approximation of the distribution of wind speeds into bins for future energy estimates yet to be made. This distribution can be seen Figure A1 in the

Appendix. It can be seen where errors appear, showing zero representation in the 4, 6, 13, and 14 m/s bins. It is believed that, for the 4 m/s bin, there were several points improperly categorized as 3 m/s by the airport data, and similar occurrences in the other bins. There is also a recurrence of empty recordings and an assumed default zero recording that cause an unknown degree of error. Making acknowledgement of this, the approximated Weibull Distribution with shape factor k=1.5 and scale factor $\lambda = 7.3$ still displays enough viable data to make a trend model for use in the estimation of project viability.

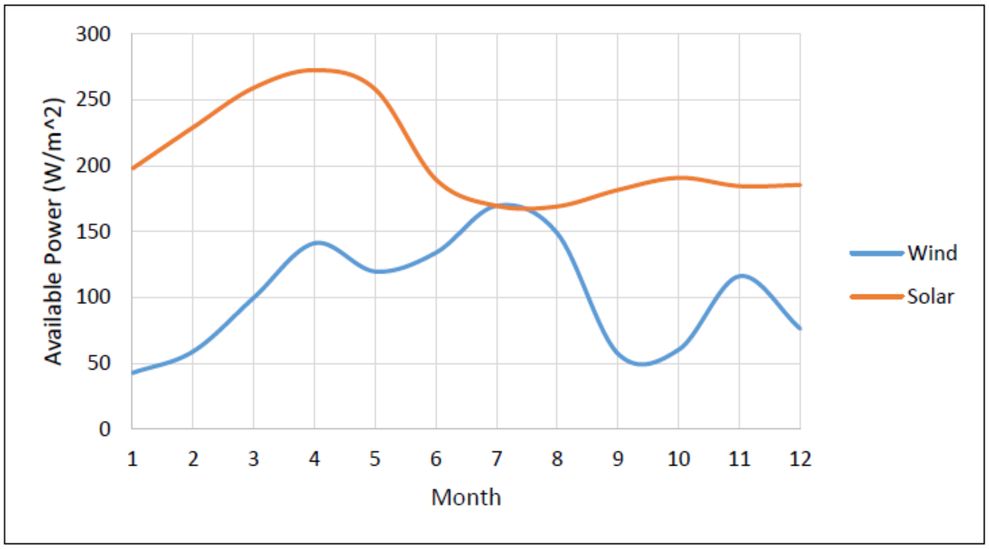


Figure 20: Palasa Monthly Average Power Densities for Solar Radiation and Wind for Palasa, India

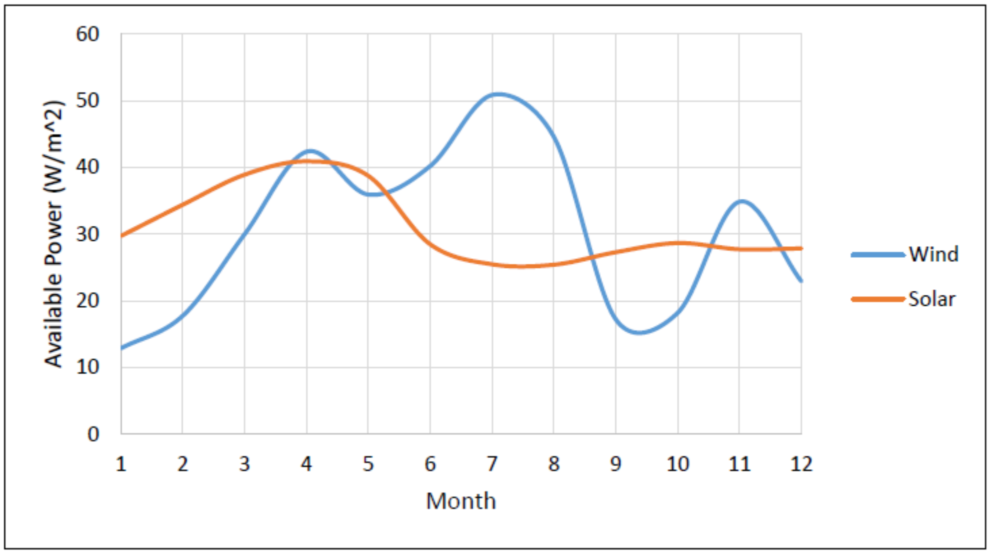


Figure 21: Efficiency Adjusted Power Average Power Densities for Palasa, India

In summary, the ideal conditions that will be sought when evaluating a site in the southern grid regions of India should reflect those found within our model site analysis and include, but not be limited to:

1.) Near-surface average monthly speeds displaying the ability to meet the 5 m/s design cut-in speed. This will help ensure productivity throughout the year.

2.) Winds that show either a competitive advantage with the solar energy industry, or at least the ability to provide substantial relevance in the market. There should be enough wind available to consider it as an alternative to solar, while avoiding investment where solar resource substantially outweighs available wind power.
3.) Rural expansion of the cellular industry into areas within the southern region of the power grid where supply of electricity is inconsistently available and cell towers rely heavily on diesel power to meet demand.

Environmental Concerns

To ensure a project is beneficial to the community it is introduced into, there must be due diligence paid to the environmental concerns of introducing a turbine to a site. A simple definition for sustainability is to leave a site in no worse condition than when it was found, while aiming to improve the existing conditions. This should be the central goal of the environmental analysis of a site. This includes, but is not limited to, maintaining local habitats, making best effort to retain native species and their populations, avoid interfering with migration patterns (a large concern for wind projects), and keeping project contaminants out of the natural water cycle. According to the World Wildlife Foundation, the Indo-Malayan ecoregion that engulfs the designated model project area is in a critical or endangered state of habitat already. Therefore, if projects are to be implemented in these areas, mitigation plans should be drawn to protect local species of flora and fauna similar to the stringent environment provisions found in the United States Federal Migratory Bird Treaty Act.

Deployment

Each project will vary slightly in its schedule, but will in general follow through the steps listed in the model project timeline found below in Figure 22. Projects will start with a preliminary stage where planning, financing, and tower selection. From here, the project will begin with a site assessment where the wind resource will be assessed using historical wind data gathered from weather databases and airport data or, in rare cases, from wind studies performed on site (from anemometers placed on the towers for an observation period that would in turn extend the project duration). Using this data, an initial concept design can be made for the specific blades and turbine to closely match the required load and resource. Once the turbine has been chosen for a site, the permitting process can begin while performing an analysis on the tower to ensure the structure itself is structurally sound, as well as the design of the coupling system for installation. After all designs have been finalized and approved, the installation of the entire power system can proceed, including turbine, panels, and battery storage. The final stages of the deployment will be the testing of systems before they go online. From here, it will be recommended to perform operation and maintenance every month for the first 2 years after installation, to ensure that everything is operating at optimal conditions, as well as to keep track of the condition of mechanical parts and the structural integrity of the supports. After this initial period of observation, it will be at the discretion of the owner to perform regularly scheduled maintenance over the remainder of the project life, which is currently estimated to be in the range of 15-20 years, much like similar small-scale wind projects currently in operation around the world.

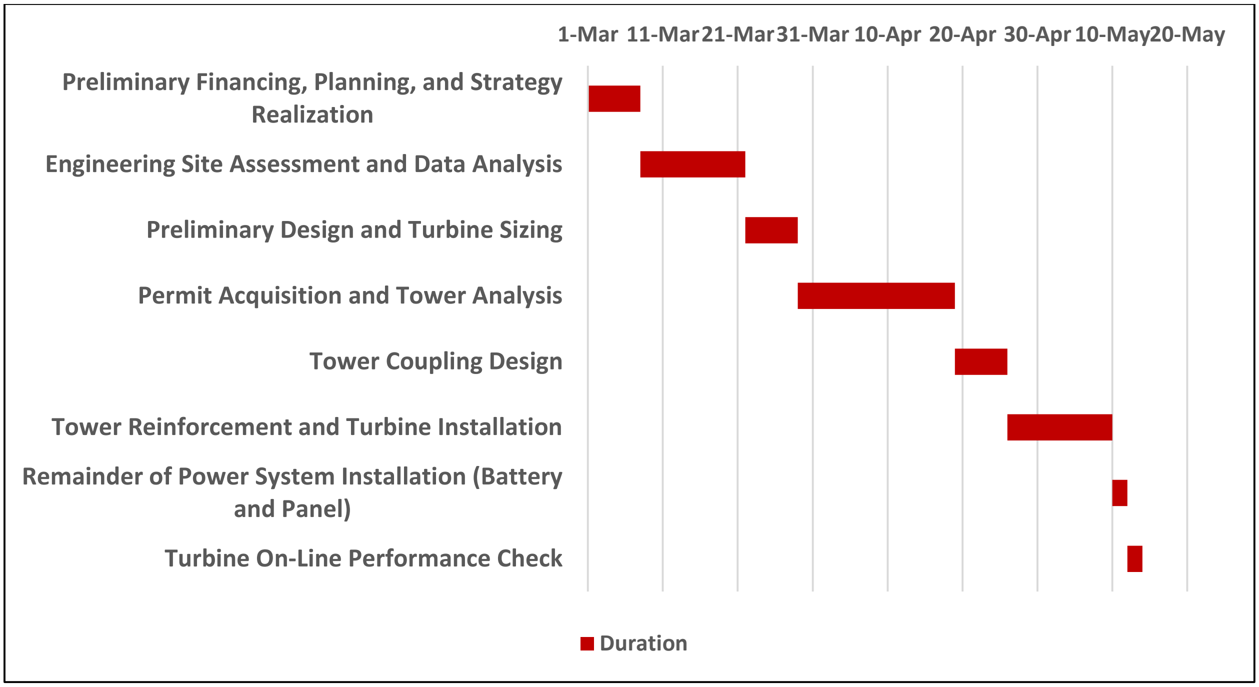


Figure 22: Model project timeline.

Installation and Maintenance Strategy

Figure 23: Cypress Midwest telecom installation in Scandinavia.

Before a system can be installed, the critical stage of permitting must be handled. It can often turn into a significant barrier to wind projects around the globe. This is why it Is a significant project risk and is included in a larger portion of the schedule, due to its uncertainty. While the permitting processes vary from state to state in India for wind projects, the current state of policy in India is to support off-grid wind-solar applications. There are significant policy considerations for on-grid applications and larger installations, but there are few apparent regulations for off-grid and small scale applications. Therefore, similar to the United States, federal airway or communication regulations will likely be the most significant source of permitting issues.

Much like the project schedule, the individual installations will vary from project to project depending upon the conditions that arise from the Site Assessment and Tower Analysis stages. Again, however, the installation of each project will follow a general strategy for ensuring stability, safety, and productivity. To ensure stability and safety, a preliminary examination of each designated tower for imperfections, damage, or any other detriment to the structural integrity of the structure must be performed and checked by a licensed professional engineering staff, whether it be WiscWind or a third-party firm. This analysis should provide the information to determine whether a tower can support the added moments and stresses caused by the drag on a system. For new construction, WiscWind can provide suggested reinforcement to be added to the tower before erection.

To supply the ~3kW load required by a standard cellular site, it was determined with the wind resource available at the model site location that the most effective arrangement would be two sets of triple-stacked turbines rated at 350 W average capacity each. While the coupling structure will vary, the systems will be installed similar to the Cypress Midwest model featured in Figure 23, showing the stacking arrangement as well as a tower-coupling design. As previously mentioned, the remaining 1 kW would be supplied by a complimentary solar system.

To ensure productivity of a project, during the Site Analysis phase of deployment, not only will data be collected in terms of the wind velocities, but also their direction. This allows for the development of a wind rose such as the one found in Figure 24, depicting the frequency of various wind speed bins in relation to their angle of approach. Here, it can be easily observed that the majority of winds in Anantapur blow in the East and West direction, almost exclusively according to the collected data. From this information, the system can be optimized by putting the dual turbine sets on the North and South faces of the tower, thus guaranteeing that they will have access to the winds at all times of year as they blow past, with little interference of the tower structure itself. This is another area of advantage for the VAWT design, operating in winds from either direction without needing redirection into headwinds. Similarly, the only direction that would lack productivity would be those interfered with by the structure. Therefore, using the wind rose data to optimize the permanent placement of the turbines can effectively eliminate the need for additional directional equipment, reducing overall project costs.

While installations will be performed by WiscWind, the duties of maintenance will be outsourced and subcontracted out to local firms to afford growth in opportunity for communities. WiscWind will offer services to maintain efficient and safely operating turbines and develop a training regimen for the local workforce for the maintenance duties and basic repair procedures to provide for local job specialization and growth. Having a skilled local workforce will enable WiscWind to ensure rapid-response repairs limiting any downtime losses. This is an opportunity to make apparent another of the advantages of VAWT technology: whereas a horizontal axis turbine generally relies on complex gearboxes and pitch and yaw components confined within a nacelle, our simplified design allows for simpler and less costly repairs.

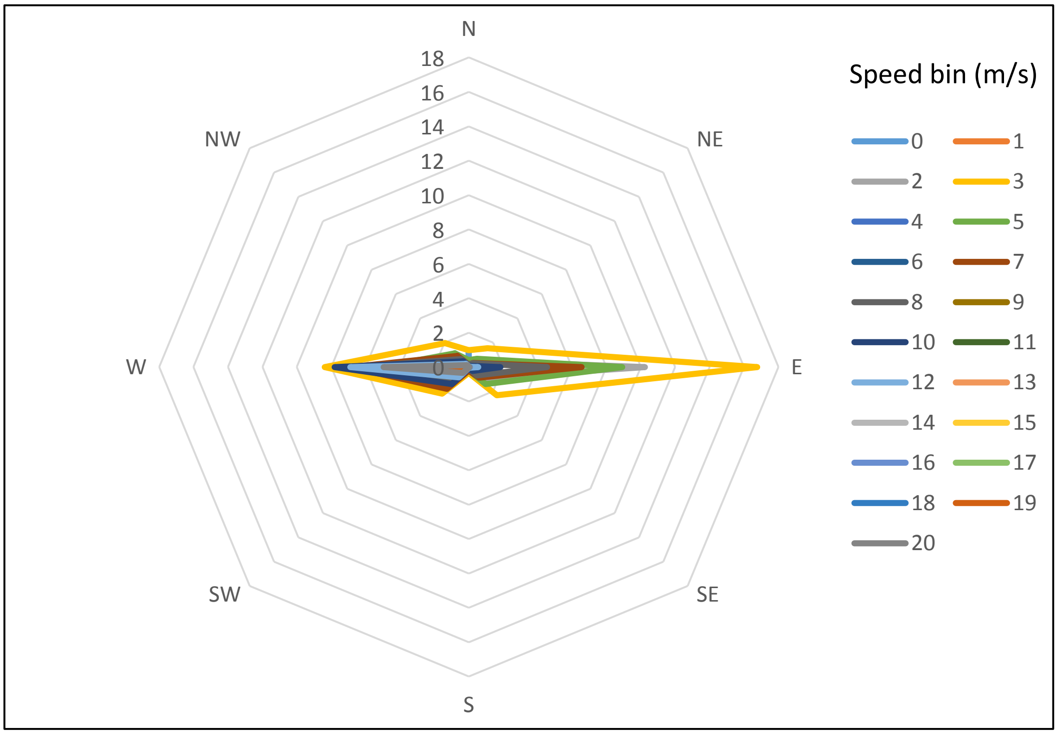


Figure 24: Wind rose illustrating wind direction, Anantapur, India.

Reliability and Risk Management

Wind resource reliability is essential to assess potential performance. By performing a diligent site evaluation and acquiring historical or self-procured wind data that accurately represents the yearly wind speed trends of the selected site allows for more accurate designs. Reliable data collected during the site investigation as well as interaction with local wind experts from the Indian equivalent of the NREL, the Ministry of New and Renewable Energy. Coordination with local experts in the process of data acquisition will be essential given the unreliability of historical annual wind models. For instance, in estimating feasibility with the above models there is notable discrepancies with empty speed bins, but the sample size was sufficiently large for a five-year period and had an expected range of velocities recorded such that the profile was deemed acceptable for modeling. Similarly, this reliability has an effect on the risk of placement of the turbine on a tower. Using a site specific wind rose enables installation staff to determine the side of the cell tower most suitable for the turbine and reduce inefficient from poor placement and directional alignment.

The remainder of the risks imposed upon the project are likely to come in the form of legislative and local ordinance changes that may occur over the life-cycle of an installation. The current political state in India is one which supports and encourages the development of renewable energy solutions however this trend may shift over the entire course of the project. Changes in national and local siting policy are a part of the volatility of wind projects on a whole, and therefore advantage should be taken whenever the government is willing to increase the financial leverage of an installation with tax credits or other incentives.

Appendix

WiscWind Design Specs

	Test Turbine	Market Scale - Turbine
Rated Capacity (W)	10	1 kW
Rated Speed (rpm)	1000	300
Rotor Diameter (m)	0.2	1.5
Type	Helical Vertical Axis	Helical Vertical Axis
Rotation Direction	Clockwise	Clockwise
Airfoil	NACA 4418	NACA 4418
Number of Blades	3	3
Design Tip Speed Ratio (TSR)	1.5	1.5
Generator	3-Phase AC Permanent Magnet	3-Phase AC Permanent Magnet
Yaw Control	n/a	n/a
Braking System	Electrodynamic	Electrodynamic + Mechanical
Cut-In Wind Speed (m/s)	8	<4
Rated Wind Speed	11	11
Cut-Out Wind Speed (m/s)	13	15
Survival Speed (m/s)	18	25
Tower Type	Single	Mounted to existing
Tower Height (m)	0.2	25-35

Table A1: WiscWind turbine design specifications.

Additional Figures

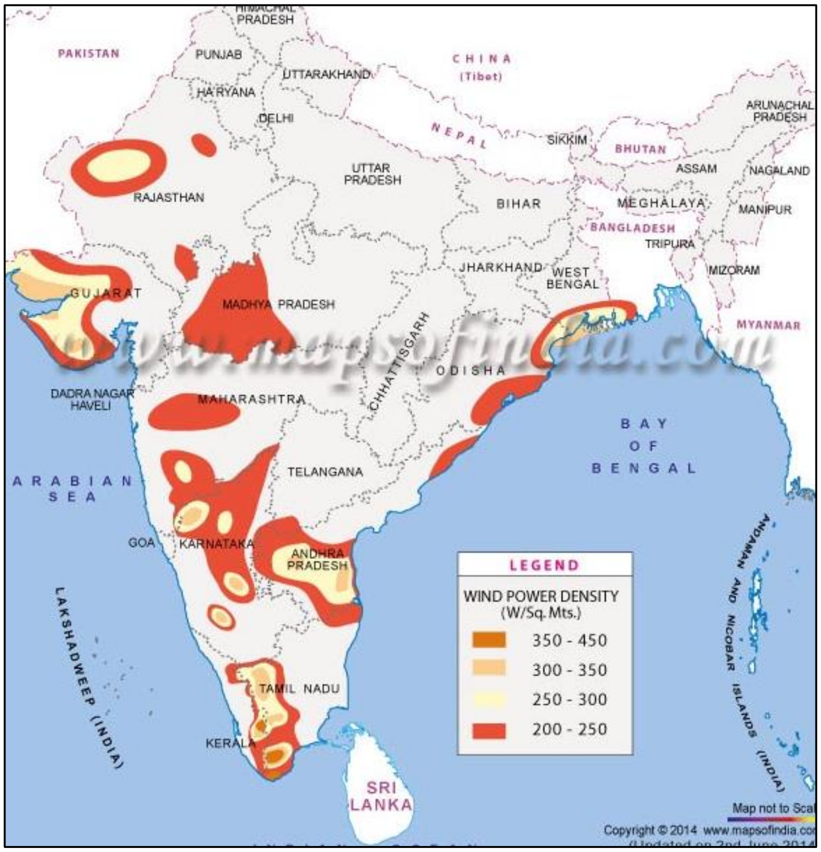
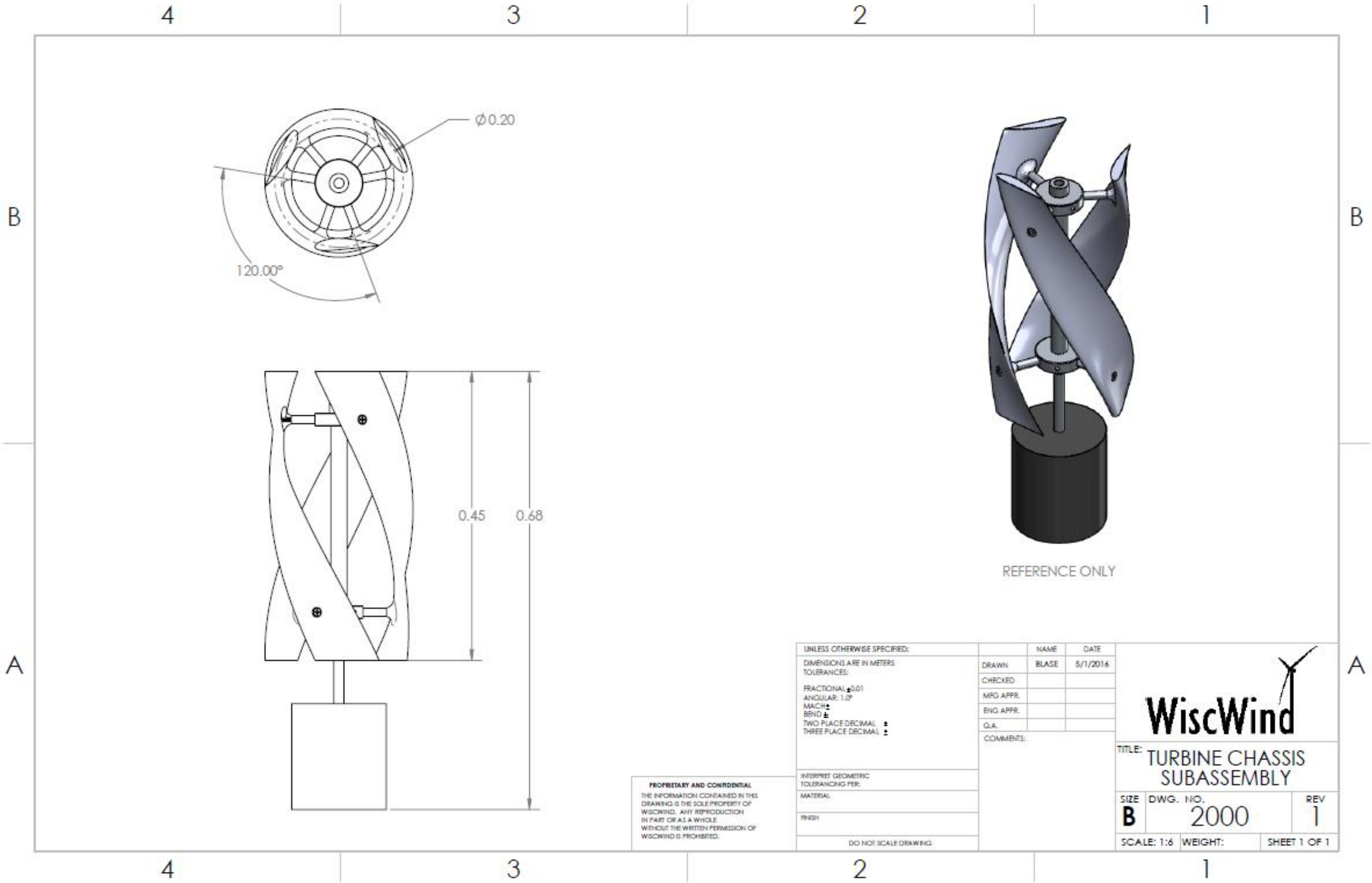
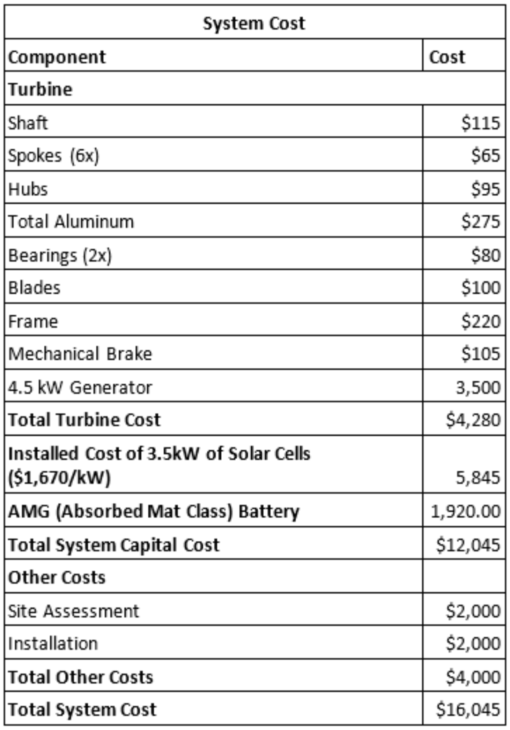


Figure A1: India’s Approximate Wind Resource (courtesy of www.mapsofindia.com)

Prototype Assembly Drawing



WiscWind Cost Assumptions and Pro Forma



System Cost	
Component	**Cost**
Turbine	
Shaft	$115
Spokes (6x)	$65
Hubs	$95
Total Aluminum	$275
Bearings (2x)	$80
Blades	$100
Frame	$220
Mechanical Brake	$105
4.5 kW Generator	3,500
Total Turbine Cost	$4,280
Installed Cost of 3.5kW of Solar Cells ($1,670/kW)	5,845
AMG (Absorbed Mat Class) Battery	1,920.00
Total System Capital Cost	$12,045
Other Costs	
Site Assessment	$2,000
Installation	$2,000
Total Other Costs	$4,000
Total System Cost	$16,045

Income Statement				
	Pilot Period	**2017**	**2018**	**2019**
Net Sales	$0.00	$240,000.00	$620,000.00	$630,000.00
Cost of Goods Sold	$12,045.00	$80,225.00	$160,450.00	$160,450.00
Gross Margin	-$12,045.00	$159,775.00	$459,550.00	$469,550.00
Operating Expenses				
Advertising	$1,000.00	$10,000.00	$10,000.00	$10,000.00
R&D	$2,000	$50,000.00	$50,000.00	$50,000.00
Site Maintenance and Operation	$1,000.00	$2,500.00	$7,500.00	$10,000.00
Insurance	$0.00	$12,000.00	$31,000.00	$31,500.00
Salaries & Wage	$0.00	$64,000.00	$65,920.00	$67,897.60
Rent	$0.00	$30,000.00	$30,000.00	$30,000.00
Travel	$1,000.00	$9,000.00	$18,000.00	$18,000.00
Excise / Service Taxes (12.36%)	$0.00	$29,664.00	$76,632.00	$77,868.00
Total Operating Expenses	$5,000.00	$207,164.00	$289,052.00	$295,265.60
Net Profit	-$17,045.00	-$47,389.00	$170,498.00	$174,284.40
Income Tax	$0.00	$0.00	$52,683.88	$53,853.88
Net Income After Taxes	-$17,045.00	-$47,389.00	$117,814.12	$120,430.52
Cumulative Profit	-$17,500.00	-$64,434.00	$53,380.12	$173,810.64

Table A2: WiscWind system cost and income statement.

	Pilot Period	Year 1												Year 2				Year 3
		January	Feburary	March	April	May	June	July	August	September	October	November	December	Q1	Q2	Q3	Q4	
Assets																		
Current Assets																		
Cash	$20,000.00	$227,910.00	$211,865.00	$195,820.00	$239,775.00	$299,775.00	$359,775.00	$343,730.00	$327,685.00	$311,640.00	$295,595.00	$279,550.00	$263,505.00	$355,370.00	$487,235.00	$607,235.00	$787,235.00	$1,256,785.00
Accounts Receivable	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Inventory	$0.00	$32,090.00	$48,135.00	$48,135.00	$48,135.00	$48,135.00	$48,135.00	$64,180.00	$80,225.00	$96,270.00	$112,315.00	$128,360.00	$144,405.00	$160,450.00	$160,450.00	$128,360.00	$80,225.00	$80,225.00
Total Current Assets		$260,000.00	$260,000.00	$243,955.00	$287,910.00	$347,910.00	$407,910.00	$407,910.00	$407,910.00	$407,910.00	$407,910.00	$407,910.00	$407,910.00	$515,820.00	$647,685.00	$735,595.00	$867,460.00	$1,337,010.00
Fixed Assets	$1,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00
Total Long Term Assets	$1,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00	$61,500.00
Total Assets	$21,500.00	$321,500.00	$321,500.00	$305,455.00	$349,410.00	$409,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$577,320.00	$709,185.00	$797,095.00	$928,960.00	$1,398,510.00
Liabilities																		
Current Liabilities	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Accounts Payable	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Total Liabilities																		
Stockholder Equity																		
Owner Working Capital	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00	$20,000.00
Total Stockholder Equity	$21,500.00	$321,500.00	$321,500.00	$305,455.00	$349,410.00	$409,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$577,320.00	$709,185.00	$797,095.00	$928,960.00	$1,398,510.00
Total Liability and SE	$21,500.00	$321,500.00	$321,500.00	$305,455.00	$349,410.00	$409,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$469,410.00	$577,320.00	$709,185.00	$797,095.00	$928,960.00	$1,398,510.00

Table A3: WiscWind balance sheet.

	Pilot Period	Year 1	Year 2	Year 3
Net Income	-$17,045.00	-$47,389.00	$117,814.12	$120,430.52
Adjustments				
Depreciation	$0.00	$8,785.71	$8,785.71	$8,785.71
Increase in Inventories	$0.00	-$144,405.00	$64,180.00	$0.00
Gain on Sale of Property	$0.00	$0.00	$0.00	$0.00
Net Cash Flow from Operations	$0.00	-$183,008.29	$190,779.83	$129,216.23
Sale of Land	$0.00	$0.00	$0.00	$0.00
Purchase of Plant & Equipment	-$1,500.00	-$60,000.00	$0.00	$0.00
Cash Flows from Investing Activities	-$1,500.00	-$60,000.00	$0.00	$0.00
Investment of Owner Working Capital	$20,000.00	$0.00	$0.00	$0.00
Sale of Bonds	$0.00	$0.00	$0.00	$0.00
Issuance of Common Stock	$0.00	$300,000.00	$0.00	$0.00
Cash Flows from Financing Activities	$20,000.00	$300,000.00	$0.00	$0.00

Table A4: WiscWind statement of cash flow

References

[1] M. Nouni, S. Mullick and T. Kandpal, "Providing electricity access to remote areas in India: Niche areas for decentralized electricity supply," *Renewable Energy,* vol. 34, no. 2, pp. 430-434, 2009.

[2] The World Bank, "Access to electricity (% of population)," 2012. [Online]. Available: http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS. [Accessed December 2015].

[3] A. V. S. B. S. E. I. Garg, Interviewee, *Power Watch India.* [Interview]. 2015.

[4] Olamide Eniola Victor, Norsiah A. Aziz and Abdul Raza, "Privatization of Electricity Service Delivery in Developing Nations: Issues and Challenges," *International Journal of Built Environment and Sustainability,* vol. 2, no. 3, pp. 1-9, 2015.

[5] U.S. Department Energy Office of International Affairs, "U.S.-India Energy Cooperation," 2016. [Online]. Available: http://energy.gov/ia/initiatives/us-india-energy-cooperation. [Accessed 27 April 2016].

[6] The Climate Group, "A Business Case for Off-Grid Energy in India," The Climate Group.

[7] Marketline, "Marketline Industry Report: India - Wireless Telecommunication Services".

[8] Intelligent Energy, "The True Cost of Providing Energy to Telecom Towers in India," 2012.

[9] Assessment and Standards Division, EPA, Office of Transportation and Air Quality, "Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling," EPA, 2002.

[10] R. Howell, N. Qin, Jonat and N. Durrani, "Wind tunnel and numerical study of a small vertical axis wind turbine," Department of Mechanical Engineering, University of Sheffield, Sheffield, 2009.

[11] B. K. Kirke, "Evaluation of Self-Starting Vertical Axis Wind Turbines for Stand-Alone Applications," Griffith University, Brisbane, 1998.

[12] MatWeb, "Overview of materials for Nylon 12," 2016. [Online]. Available: http://www.matweb.com/search/datasheetText.aspx?bassnum=O2640. [Accessed 1 5 2016].

[13] Performance Composites Inc., "Fiberglass and Composite Material Design Guide," 2016. [Online]. Available: http://www.performancecomposites.com/about-composites-technical-info/122-designing-with-fiberglass.html. [Accessed 1 5 2016].

[14] M. P. Mike Roosa, Interviewee, [Interview]. 8 February 2016.

[15] K. Schmidt, "Cell Phone Tower Types and Information," 14 July 2013. [Online]. Available: http://www.steelintheair.com/Cell-Phone-Tower.html#.VyI0DvkrLIU. [Accessed 28 4 2016].

[16] Eagle Steel, "Carbon Steel Grades," [Online]. Available: http://www.eaglesteel.com/download/techdocs/Carbon_Steel_Grades.pdf. [Accessed 28 4 2016].

[17] Deloitte, "Indian Tower Industry: The Future is Data," 2015.

[18] N. Atkinson, "Quick and Curious Facts About the Mars Science Laboratory Mission," 1 August 2012. [Online]. Available: http://www.universetoday.com/96553/quick-and-curious-facts-about-the-mars-science-laboratory-mission/.

[19] P. E. Ben Polito, Interviewee, *Customer Discovery Interview.* [Interview].

[20] L. F. Garcia, J. E. Jaramillo and J. L. Chacón, "Aerodynamic Analysis of the Airfoil of a VAWT by Using 2D CFD Modeling".