U.S. Department of Energy
Collegiate Wind Competition

University of Wisconsin – Madison

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Executive Summary

In 2016, a group of students at the University of Wisconsin-Madison came together to start a company that would make a positive difference in the world. The mission was simple, to create safe and sustainable electricity from wind and hybrid energy resources. This resulted in the ambitious goal of integrating wind and solar energy into the cellular tower market in rural India. The vertical axis wind turbine array, the Ventus 3k Series, was created and tested at the Collegiate Wind Competition in New Orleans, Louisiana and WiscWind, LLC was born. Since the Ventus 3k Series, the WiscWind, LLC team has been hard at work in hopes of expanding their portfolio of manufactured wind turbines. At the same time, re:charged systems, LLC has been exploring economical applications of this turbine.

re:charged systems is a micro-grid developer specializing in public electric vehicle (EV) charging stations. As a developer, their expertise includes acquiring customers, organizing project financing, investing sponsor equity, and driving the development of micro-grid projects. re:charged systems will utilize the Ventus 4k Series turbine, designed and manufactured by WiscWind, LLC, for their projects. The team is optimistic about the exponential growth in the EV charging station market, and looks to build their brand and become a leading project developer in the space.

WiscWind, LLC has designed and built a prototype turbine to be tested at the Collegiate Wind Competition in Chicago, Illinois in May 2018. This turbine is meant to mimic aspects of the market turbine used in the re:charged systems micro-grids, with a few notable differences. Both turbines are horizontal axis designs that aim to cut in at low wind speeds while generating stable power at a wide range of wind speeds. These objectives are met by using lightweight, composite blades and an axial flux generator. The generator eliminates the need for a gearbox and simplifies the design. The power produced by the turbine is converted for use by the electrical control. Controls differ significantly between the two turbines. The prototype turbine utilizes passive pitch and yaw control to generate the maximum amount of power while the market turbine employs active control.

WiscWind, LLC and re:charged systems are forming a joint venture to deploy wind turbines for EV charging station micro-grids. This document outlines the developments of the coordinated efforts of the two groups, specifically an investment opportunity highlighted in the **Business Plan** section, and a technical review of the Ventus 4k Series turbine, highlighted in the **Technical Design** section.

Business Plan

Business Overview

re:charged systems is a limited liability corporation that develops micro-grid systems for existing public EV charging stations. re:charged systems acquires customers, organizes financing, invests sponsor equity, and coordinates the development of micro-grid projects. It leverages relationships with cash equity, tax equity, and engineering, procurement, and construction (EPC) partners to execute projects. Furthermore, the firm utilizes a specific wind turbine designed and manufactured by its joint venture, WiscWind, LLC. This wind turbine, the Ventus 4k Series, has been specifically designed and tested to meet the needs of re:charged systems' development goals.

Via strategic market segmentation, re:charged systems has been able to create a list of "Tier 1" existing public EV charging station locations that will be targeted first as part of a strong go-to-market strategy. By further utilizing engineering modeling, relevant market trends, advantageous manufacturing/installation costs, and intelligent project financing, re:charged systems has been able to develop a strong economic case for its micro-grid projects. At this stage, re:charged systems is asking for an investment of $40,000 to cover its operating expenses for CY2018, which are expressed in the **Financial Analysis** section. During CY2018, re:charged systems intends to secure contracts for 20 projects, which will result in positive cash flow by the end of the year. This investment comes with it 25% equity in the company, with large potential for returns.

Market Opportunity and Analysis

Market and Technology Trends

In 2017, EV plug in car sales in the United States were almost 200,000 after accumulating to a total of 512,100 sales between 2010 and 2016, totaling roughly 712,100 total EVs in the US [1] [2]. The mid-term and long-term market outlook is promising, with Bloomberg New Energy Finance (BNEF) predicting the United States will reach 2 million EV sales per year by 2027 and 10 million by 2035 [3]. The EV infrastructure market has experienced similar growth, jumping from $27 million in revenue in 2011 to $182 million in 2016. This growth is expected to continue with the Electric Vehicle Charging Association predicting the EV charging infrastructure industry to grow at an annual compound rate of 46.8% through 2025, when it will reach $45.59 billion globally [4].

Presently, public access charging stations provide EV car owners the ability to charge their cars in a space away from their residence. Common spaces for these charging ports include parking garages, businesses, and interstate gas stations or hotels. Usually these charging stations are grid tied, receiving all of their electricity supply directly from their transmission connection. However, the demand from EV charging at public charging stations can be erratic, requiring quick response to sudden electricity loads. This results in poor economics for deploying EV charging stations in places with high electricity costs or challenging grid connections, especially in such places with strong renewable resources.

One potential solution to this challenge comes in the form of a micro-grid. A micro-grid is defined as "[…] a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A micro-grid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode" [5]. Micro-grids can be specially designed to fit the unique demand of a specified site, for example a micro-grid designed to meet the needs of a specific public EV charging station. For existing public EV charging stations, the addition of a micro-grid can reduce electricity costs from the grid, provide increased sales through a

"Green Image," and provide resilient energy to mitigate risks such as grid failure or high peaking energy costs.

The future of the cost of batteries (both for the EV and micro-grid energy storage) is central to the economics of EV charging micro-grids, as EV batteries account for roughly half of the cost of the car, and about $400 per kW-h for micro-grid usage [6]. Because battery costs are predicted to decrease by 77% between 2016 and 2030, the economic potential of EV charging station micro-grids will increase twofold [7]. First, the decreased cost of EVs will result in increased EV sales, and therefore more EV charging stations to meet demand. Secondly, project economics will improve with decreased battery costs holding battery capacity constant. BNEF anticipates these battery price decreases will result in a crossover point of 2025, where electric cars prices match gas car prices [7].

Total Addressable Market

Using the weighted average of total annual electric vehicle miles traveled (per driver) from 8 top selling electric vehicles, we estimate an average of 6,232 miles driven per year [8]. Using the 712,100 electric car total from the above section, we have 4,438,000,000 total electric miles driven per year. However, 80% of charging is residential, so we multiply by 20% to get 890,000,000 electric vehicle miles driven on public charging [9]. Furthermore, the average EV requires about 30 kWh per 100 miles driven so we multiply the 890,000,000 miles by .3 kWh/mile to get 270,000,000 kWh [10]. Finally, multiplying by the average US commercial electricity rate, 10.47 cents/kWh, the Total Addressable Market is $ $28,000,000 However, it is also important to note BNEF's forecast of EV sales reaching millions per year by 2027 and 10 million per year by 2035 [3]. As a result, this Total Addressable Market figure is expected to increase exponentially.

Management Team and Company Structure

CEO, Co-founder: Charlie Oster will assume the role of CEO of re:charged systems. Charlie is a visionary thinker, whose skillset sits on the intersection of technical and business knowledge, making him an excellent fit for this role.

CFO, Co-founder: Todd Bates will assume the role of CFO of re:charged systems. Todd's in-depth knowledge of energy economics and practical project financing makes him a perfect fit as CFO.

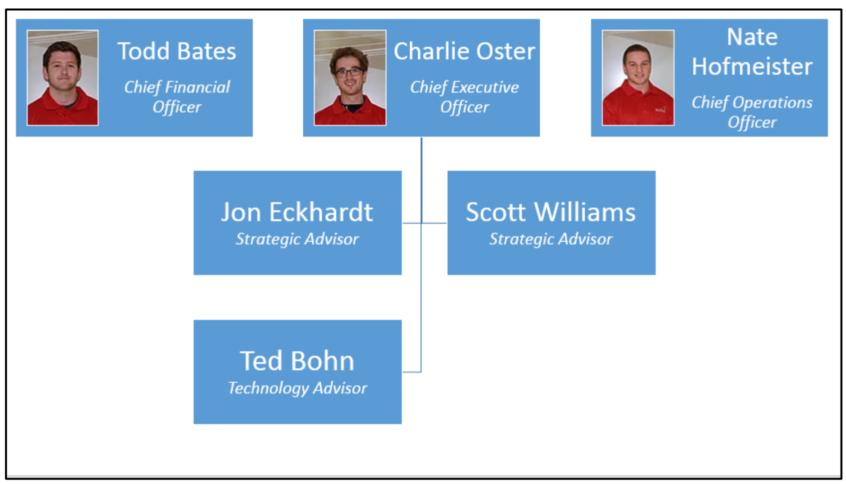


Figure 1: re:charged systems company structure

COO: Nate Hofmeister has joined the team as the COO of re:charged systems. Nate's experience in engineering project management and operational costs through WiscWind, LLC makes him an invaluable addition to the team.

Strategic Advisor (Scott Williams): Scott Williams has assisted the team as a strategic advisor to the CEO. In addition to his knowledge, Scott's connections to the technologists and forward thinkers in the renewable energy, EV, and micro-grid spaces through his employment at the University of Wisconsin-Madison and the Wisconsin Energy Institute have been extremely valuable in strategic decision-making processes.

Strategic Advisor (Jon Eckhardt): Jon Eckhardt has assisted the team as a strategic advisor. Jon's knowledge and connection in the startup space have been crucial in understanding how the company may grow and expand. Jon is a co-founder of the startup accelerator gener8tor, a nationally recognized incubator in Wisconsin and Minnesota, the Executive Director of the Weinert Center of Entrepreneurship at the University of Wisconsin-Madison, and has advised countless successful startups.

Technology Advisor (Ted Bohn): Ted Bohn has assisted the team as a technology advisor. Ted is a researcher and inventor employed by the Argonne National Laboratory in Illinois, with his lab located Madison, WI. Ted's work in the field of electric machines, embedded controls, and codification of EV charging systems is quite impressive, and his knowledge of the direction EV charging technologies has been key to long term strategy. One of his technologies is utilized by re:charged systems' micro-grids.

Location Segmentation & Sales

To begin market capture, re:charged systems has conducted significant market and background research in order to create a shortened list of public EV charging stations that will be targeted first as potential project sites. The parameters considered for locations with strong potential for a successful micro-grid development included locations with high grid electricity prices, strong wind and solar resources, and realistic siting feasibility. By carefully examining these parameters, re:charged systems has been able to gather a list of roughly forty “Tier 1” customers, from the tens of thousands of EV charging stations across the country. These locations are graphically displayed below in Figure 2. Further market capture beyond "Tier 1" customers will take place once re:charged systems is able to become cash flow positive, into further potential locations such urban EV charging stations.

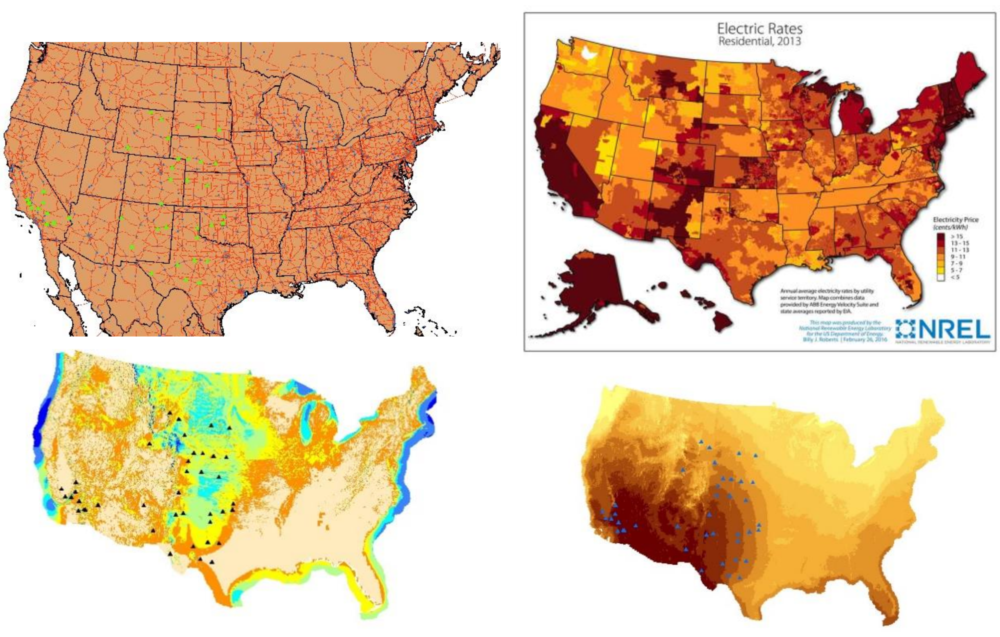


Figure 2: "Tier 1" project locations plotted on the following graphs. Upper left: Major interstate highways. Upper Right: Electricity Rates (locations not plotted). Bottom Left: Wind Resource. Bottom Right: Solar Resource.

Once financial backing is secured, re:charged systems will be able to begin work on creating further branded supporting materials and to be used in sales pitches. A first round of cold calling to EV sites will be undertaken, explaining the development opportunity, value proposition, and project financing strategy. Successful interactions will be moved to teleconference and, budget allowing, traveling for face-to-face communication. Once locations become secured for project development, further conversations will need to be had with potential cash and equity investors, as is highlighted in the **Project Finance** section.

Table 1: Input Variables and Sources used in HOMER software modeling.

Input Variable	Spatial Location	Average Daily Load	Grid Electricity Cost	Buyback Schema
Comments	Spatial input data in the form of geocoordinates was used to estimate wind and solar resource in HOMER.	An average daily load of 4000-8000 kWh was used to represent 50-100 EV "fill ups" per day. This load was modeled with a sporadic load curve, with peaks in the mid-morning, noon, and mid-evening to represent common public recharge times.	Electricity rates for each project was modeled with a commercial sector, state-specific average cost of electricity	A location specific Grid buyback schema and price was inputted, to account for state/utilitiy specific buyback policies and pricing.
Source	Geospatial wind data encoded in HOMER software	Geospatial solar data encoded in HOMER software	https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a	http://programs.dsireusa.org/system/program/detail/372 (Example for the state of NV)
Input Variable	**Wind Turbine Cost**	**Solar PV Panel Cost**	**Microgrid Battery Cost**	**Discount Rate**
Comments	WiscWind, LLC has estimated the cost of a single 3kW Ventus 4k Series wind turbine to be $18,000.	re:charged systems is agnostic about what solar PV manufacturer we purchase from. All else being equal, the lowest cost option will be utilized. For the purposes of this exercise, a price of $305 per kW	re:chared systems is agnostic regarding battery manufacturers and will chose the lowest cost option. For this exercise, the prepopulated Homer estimate of $400/kWh was utilized.	A discount rate of 8% was used to model the time value of money. This is an industry standard, and the long term average of the S&P 500.
Source	WiscWind, LLC. This cost is based on the cost of materials and labor used to design the prototype wind turbine, accounting for increased costs associated with a scaled up model.	https://news.energysage.com/comparing-top-solar-manufacturers-sunpower-vs-lg-panasonic-solarworld-suniva/	Average cost of one 1 kW-h battery, encoded in HOMER software	https://www.forbes.com/forbes/welcome/?toURL=https://www.forbes.com/sites/financialfinesse/2012/06/20/why-your-investment-returns-could-be-lower-than-you-think/&refURL=https://www.google.com/&referrer=https://www.google.com/

Project Description & Deployment

From the list of "Tier 1" locations, re:charged systems has selected five locations to serve as a model of locations with strong potential for micro-grid development. This section highlights the deeper analysis that is undertaken in order to prove the economic feasibility of the project, as well as provide a sense of the early projects in re:charged systems' pipeline. These five projects were modeled using HOMER Pro x64 micro-grid modeling software, which utilizes location and input data to model thousands of potential micro-grid options. A list of the descriptions and sourcing used for the input data can be seen in Table 1. The resultant micro-grid systems designed from the modeling software can be seen in Table 2.

As can be seen from the results, these "Tier 1" locations will employ wind, solar, and batteries. The wind turbine will be a 3kW Ventus 4k series manufactured by WiscWind, LLC. Refer to the **Market Turbine** section for more information. re:charged systems has not contracted with a specific solar or battery manufacturer, and rather used reasonable prices for these estimations. Upon receiving financial backing,

Table 2: Modeled micro-grid design information

Tier 1 Location	Desert Hills Premium Outlets; Cabazon, CA	Trinidad Fuel Stop; Trinidad, CO	Holiday Inn Express; Ogallala, NE	Mobil 38; Perry, OK	Love's Travel Stop; Midland, TX
Number of 3kW wind turbines sited	1	2	1	1	1
kW of solar PV panels sited	2.6	3.1	2.6	2.6	2.6
Number of 1 kW-h batteries used	0	9	0	0	4
AC/DC Converter?	Yes	Yes	Yes	Yes	Yes
Total Upfront Cost	$25,813.48	$49,411.99	$25,813.48	$25,813.48	$27,631.05

re:charged systems will research manufacturer options to assure the lowest possible price, and will consider exclusive partnerships and sponsorships to lower costs.

Load Management Sub-meter

re:charged systems has been able to secure a strategic partnership with Ted Bohn, Electrical Engineer and Researcher through the ANL. Ted Bohn and his team of researchers have designed a compact sub-meter specially designed for EV charging stations seen in Figure 3. This apparatus is used to strategically handle load control in order to more efficiently and quickly charge EVs that are using the station, and can be easily installed at the charge point.

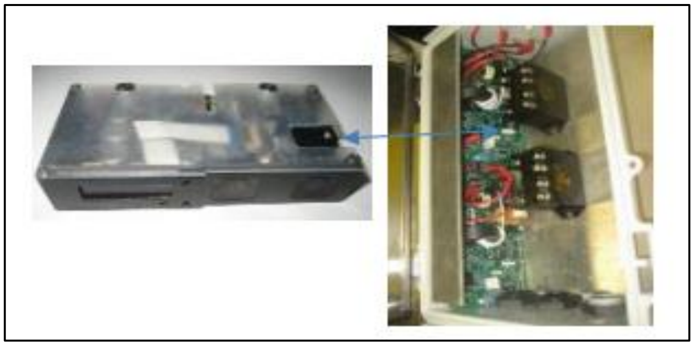


Figure 3: Compact sub-meter's placement at the charge point.

> "With no a prior knowledge of the PEV arrival or charge session finish time, the algorithm implements local automatic load regulation by evenly dividing the available power resource (up to 198A) between the active charging ports (up to 8). If the combined EVSE load is below the source limit (160A-198A) no regulation is required. Once the resource limit is reached, or if the [electricity] resource drops below the PEV charging total, the EVSE available current command is reduced proportionally on all active EVSEs until the total load matches the available source. […] The local control loop can balance the net load until the EVSE demand again falls below the total resource, where no de-rating (below 16A/30A EVSE limits) is required" [11].

This technology will be useful particularly with Level 2 "Fast" charging ports, as it will allow EV owners to more quickly and easily recharge their vehicle, providing more a more quality service and experience. This technology will be offered as an optional add on for $1,000.

Market Turbine

WiscWind, LLC has partnered with re:charged systems to be the exclusive manufacturer of wind turbines used in micro-grid project development. A major challenge re:charged system faced was the inability to site large (>10kW) wind turbines as a small startup, especially since these wind turbines would need to be utilized on-site in small scale micro-grids. Understanding the constraints, WiscWind, LLC created the Ventus 4k Series, with several special design features. First, the blades are strong and lightweight, which makes them ideal for cut-in at lower wind speeds associated with shorter wind towers. Second, the axial flux topology reduces cogging torque, which in turn eliminates the need for a gear box. The simplicity of the overall design is favorable for manufacturing costs, especially with economies of scale. For more detail on the market turbine, see the **Full-Scale Turbine** section.

Deployment

Engineering, Procurement, and Construction

Re:charged systems plans to partner with EPCs to provide expertise regarding the design and construction of our micro-grid projects. EPCs will require a fee of 10% of the project up-front cost (similar to developer fee) [12]. EPCs who have excelled at building micro-grids will be selected in order to decrease technology risk for our investors. Furthermore, the EPCs will be contracted to perform ongoing maintenance on the projects. These costs are considered in Figure 4.

Value Proposition

The value of a re:charged systems micro-grid to an EV charging station owner is three-fold and listed below. These economic values will be used primarily for future sales pitches to EV charging station owners, in order to secure project contracts.

First, a re:charged systems micro-grid will provide the charging station owner a direct economic benefit via the need to rely less on the grid for their electricity supply. The levelized cost of electricity resulting from re:charged systems' micro-grid is on par with grid prices presently and will remain constant for the life of the micro-grid, likely 25 to 30 years, whereas utility rates have historically fluctuated, and have increased over time, approximately 4% over the past 10 years [6] [12]. This provides the charging station owner a direct hedge against these price increases, as well as increased energy resiliency again risks such as grid failure.

Secondly, re:charged systems' micro-grids rely purely on sustainable, green energy. Since EV cars have historically been more expensive than gas-based competitors, EV car companies have relied on a "green image" as a major selling point. According to EV Obsession, over 40% of EV car owners named protecting the environment as a reason for purchasing EVs, the second most popular choice behind only reducing fuel costs [13]. re:charged systems offers EV charging station clients an opportunity to capture these consumers by differentiating themselves from charging station competitors relying on utility electricity power, usually created by coal and natural gas. The systems will be visible from the plug-in area so the consumer can see the electricity is being sourced directly from clean, renewable energy.

Thirdly, our micro-grid will assist the charging station's competitiveness with traditional gas stations. The price of a gallon of gas has historically ranged between $1.50 to over $3.50, with an average price of $2.20 [14]. For a 14-gallon tank, this means a fill-up can range from $21 to $49 dollars and if the consumer fills up once per week, this can result in a yearly (multiplying by 52) cost ranging from $1,092 to $2,549. Our micro-grid's electricity prices will be constant, and range between $12 and $18 per fill up, therefore undercutting as well as lowering fuel price risk [13]. As the growth of EV sales continues over the life of the micro-grid's lifetime, this price competition between EV and gas-based fill-ups will become more and more important.

Financial Analysis

Project Development Costs

Project costs are those associated with the origination and execution of our micro-grid systems. First, traveling expenses will drive our customer acquisition costs as we plan to pitch potential customers face to face. Second, lawyer fees will make up our project execution costs, as our project finance process will require legal counsel to put the project equity splits into contracts and complete Purchase Power Agreements (PPA).

Project Finance

Building micro-grids and reaping the benefits over the lifetime of the 25-30 year PPA is not suitable for a thinly capitalized startup like re:charged systems, due to the company's low tax liability and need for short-term cash flows. Therefore, a developer fee will be the main source of revenue for the company.

In order to maximize the value of the projects, depreciation benefits and tax credits will be utilized. In order to do this, re:charged systems will form partnerships with both tax equity and cash equity investors as needed. The role of this tax equity and/or cash equity investor will be pitched first to the electric charging station owner, and then opened up to further private equity parties. Once the project investors are contracted, a partnership flip deal structure will be implemented. This allows the tax equity investor will own the project for roughly the first 5 years in order to take advantage of the MACRS accelerated depreciation, bonus depreciation and the federal tax credits. Then, after meeting their required return, the ownership will 'flip' to the cash equity group, who will take the long-term cash flows of the project for the remainder of its lifetime. If the tax and cash equity investor are the same entity, this deal structure will still be used, but the 'flip' will remain in the same organization.

The percentage ownership for each project varies, though as a template, the tax equity will be the 94% owner for the first 5 years, and then a 5% owner afterward. Similarly, the cash equity will be the 5% owner for the first 5 years, and then the 94% owner until the PPA expires. Throughout this project lifetime, re:charged will take a 1% stake in the projects in order to create a long-term value and revenue stream. Further, by the developer taking a stake in the project, the confidence in project execution of the investors and EV charging station owners will increase, and serve to align the interests of all parties involved [15] [16].

Revenue Streams

The primary revenue stream will be the developer fee, which is paid to the developer as a percentage of the project value. The developer fee is paid to the developer upon construction completion, allowing for short payback periods. Developer fees can range from 3-20% of project value, as defined by the United States Treasury (for taxable basis purposes) [16]. re:charged systems will assume a 10% developer fee.

Further, in order to create long-term value, the re:charged systems will take minority ownership in the projects the company develops. This provide give access to cash flows generated from the projects themselves. These streams will include renewable energy credits (RECs), which can be sold on REC markets to utilities, and cash flows from the PPA contract.

Finally, this minority share will allow re:charged systems to utilize the tax benefits available to renewable energy projects. These include federal tax credits, the Investment Tax Credit, and the Production Tax Credit. The Investment Tax Credit is 30% of solar project value and the Production Tax Credit is 2.3 cents/kWh for energy generated by wind [17].

Revenue	2018	2019
Developer fee revenue	$ 61,792.02	$ 77,240.03
Project Revenue	$ 1,029.87	$ 1,050.46
Annual Total	$ 62,821.89	$ 78,290.49
Expenses		
Office Lease & Supplies	$ 1,920.00	$ 1,920.00
Salaries & Compensation	$ 20,000.00	$ 20,000.00
Traveling Expenses	$ 10,000.00	$ 10,000.00
Lawyer Fees	$ 5,000.00	$ 5,000.00
Commercial Liability Insurance	$ 500.00	$ 500.00
Advertising/Branding	$ 600.00	$ 600.00
Net Operating Expenses	$ 36,920.00	$ 36,920.00
Net Operating Income	$ 25,901.89	$ 41,370.49
Depreciation Expense	$ 2,363.54	$ 3,781.67
Before Tax Cash Flow	$ 23,538.34	$ 37,588.82
Income Taxes (15.3%)	$ 3,601.37	$ 5,751.09
After Tax Cash Flow	$ 22,300.52	$ 35,619.40

Figure 4: Pro forma Income Statement

A pro forma income statement is provided in Figure 4 to demonstrate how re:charged systems will generate income. The developer fee, project revenue, and depreciation expense were estimated based on the upfront system costs generated in HOMER. The assumption is 20 systems developed in 2018 and 25 in 2019.

Investor Opportunity

By utilizing estimated operation costs shown in the income statement, re:charged systems in requesting an investment of $40,000 for 25% equity in the company. This investment will allow re:charged systems to maintain day to day operations and execute the initial pipeline projects scheduled for 2018. After tax cash flows will be invested into the company in order to create branded sales and outreach materials, expand EPC/Manufacturing relationships, make new hires, and grow the pipeline of projects. This investment comes with it the opportunity for a large return due to the expected exponential purchasing of EVs and EV charging stations.

Technical Design

Design Summary

WiscWind's development and design for the prototype turbine focused on optimizing performance at cut in and low wind speeds and maximizing the turbine power output over all wind speeds. This is achieved through several power saving features such as passive yaw and pitch control, blades optimized for low speed efficiency, and a generator design which eliminated cogging torque. The mechanical design also focused on structural integrity and advanced composites manufacturing practices. Converting the mechanical energy captured by the wind into electrical energy is accomplished with a custom made three phase axial flux generator. Power electronics control AC to DC conversion, power regulation, and emergency braking. The technology from the development of the prototype turbine will be integral to the development of the full-scale market turbine.

Mechanical

Overall Design Objectives

WiscWind's top priorities in its design were achieving both a low cut-in speed and stable power curve. In order to meet these criteria, the blades and control systems have been designed with the balance of these requirements in mind. The blade geometry controls the cut-in speed of the wind turbine and the control systems ensure that the power curve is stable and predictable across a wide range of wind speeds. As this is a small-scale wind turbine, both the pitch and yaw control were designed to be operated passively, so that the maximum amount of energy could be extracted. The prototype blades were designed and later redesigned with the intention of striking a balance between these two objectives. While there are many other subsystems of the wind turbine including the nacelle and tower subassemblies, they do not have as much of an impact on the desired performance abilities of the wind turbine as the blades and control systems.

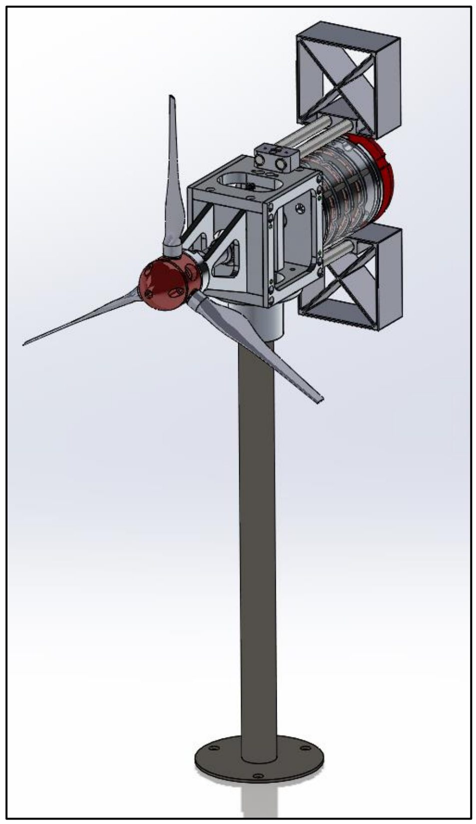


Figure 5: Full prototype turbine assembly

Prototype

Objective

The design objectives of the prototype were driven by the Rules and Regulations of the Collegiate Wind Competition. Three major criteria were considered in accordance with these regulations:

Size Constraints - The turbine must fit within a 45cm x 45cm x 45cm cube area centered 60cm above the bottom of the wind tunnel.

Power Production – in order to maximize the points for power production, the turbine was designed with several key subassemblies. The passive pitch control mechanism allows the blades to perform at higher efficiency over a broad range of wind speeds. The direct drive axial flux generator further reduces mechanical losses by eliminating the need for a gearbox. The yaw system reduces the control system power consumption by acting passively.

Durability - the turbine must withstand 20 m/s wind, including various wind-speed profiles.

The design process of the prototype turbine is described below, beginning with preliminary airfoil selection and ending with the relationship between the prototype and market turbine. The full prototype turbine can be seen in Figure 5.

Blades

WiscWind's blade design focused on choosing the best airfoil shape and blade size for balancing a low cut-in speed with performance at higher speeds, as well as choosing fabrication-capable materials that are both inexpensive and durable. This process required use of multiple simulation programs and databases, as well as contact with industry and on-campus resources.

Blade Design

The WiscWind team used XFOIL, an open-source airfoil analysis software for the preliminary design stages of the blades [18]. Using an in-house MATLAB program which interfaces with XFOIL, lift and drag characteristics were analyzed for several hundred airfoils at rated test conditions. The blade itself was then designed around the profile which produced the best lift to drag ratio while meeting other selection criteria including a minimum thickness and smooth shape to mitigate potential areas of stress concentration or sharp performance variations with slight changes in the angle of attack. The NACA 3210 airfoil was consequently selected as the baseline airfoil, with thicker versions of the NACA 32XX series used closer to the hub. From this starting point, QBlade, a wind turbine design software based on the XFOIL solver, was used to design and model the blade from 20 distinct sections whose chord and twist distributions were computed from the Betz optimal propeller theory [19]. Finally, QBlade was used to simulate the blade's ideal power output at various tip-speed ratios (TSRs) in order to fine tune each section for optimal performance, as seen in Figure 6. As the blades were designed to perform optimally at a tip-speed Ratio of 6, we plan to optimize the controls systems during testing to achieve as close to this as possible.

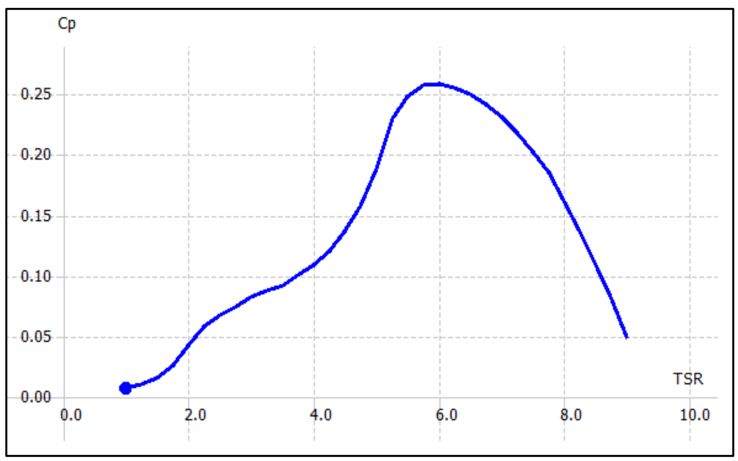


Figure 6: Coefficient of performance vs. tip-speed ratio for the NACA 32XX blade design

Manufacturing

Preliminary manufacturing of the blades consisted of 3D printing through the Makerspace on UW-Madison's campus and a third party, Midwest Prototyping. 3D printing may be used for mocking up pitch control components as well and the final nacelle will likely by 3D printed. Figure 7a and Figure 7b show the final blade modeled in Solidworks and 3D printed version respectively.

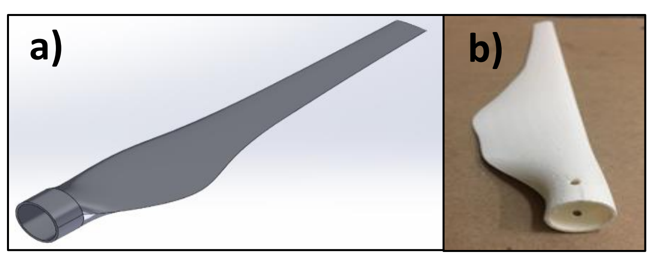


Figure 7: **a)** Prototype Turbine Blade in Solidworks and **b)** 3D Printed

The final blades will be made from carbon fiber using a bladder molding method. Bladder molding is often used as a low-cost method to manufacture complex parts of high quality. Hollow parts are also ideal for bladder molding and WiscWind decided to create hollow blades to reduce weight. Lightweight blades should rotate more easily at low wind speeds and will ensure low cut-in speed.

Bladder Molding

Bladder molding consists of laying up pre-preg or traditional carbon fiber in two clamshell molds with a silicone or latex bladder between the two halves. The bladder is inflated to push the fiber against the mold edges. This setup is then cured in an oven for a curing temperature specific to the carbon fiber. The cured part is removed from the mold and trimmed to the design specifications. Figure 8 shows an open and closed mold with a bladder.

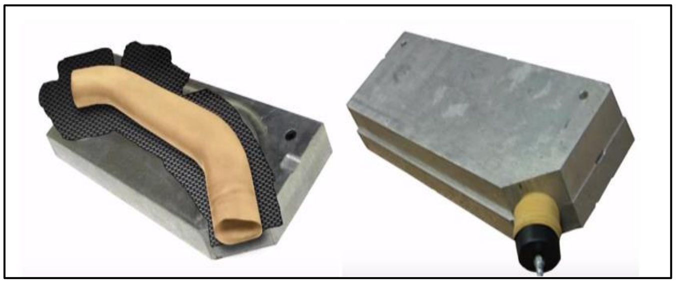


Figure 8: Open and closed latex bladder mold **[33]**

Pitch Control

It is essential that a wind turbine has some sort of pitch regulation so that it does not exceed its mechanical capacity at high wind speeds. Pitch control can also help a turbine more closely achieve its optimal angle of attack at a range of wind speeds, improving performance.

Passive Control

It is common for large wind turbines to incorporate some type of active pitch control system, usually electric or hydraulic [20]. These systems provide a high degree of control, but require some power to rotate the blades. WiscWind instead uses a passive pitch control system which makes use of the existing forces acting on the turbine to drive mechanical assemblies and does not draw from the generated power.

WiscWind's pitch control system, shown in Figure 9 and Figure 10, is inspired by a fly ball governor system with three masses rotating and moving outward from the main shaft. The shaft connects to an eccentric pivot on the blades, causing them to rotate approximately 40 degrees at full extension. Using Figure 9 as a guide, one of three masses are shown at location 1. Compressive springs (not pictured) will hold the masses in place. The mass moves outward from its starting position (see Figure 10) and the coupler at location 2 transfers the rotational motion from the mass to translational motion applied to the base of the blades at position 3. The blade is then rotated an angle of "ϴ" from its starting position. Using the equations of motion for F_1, F_2, and F_m shown in the figure below, the pitch angle, ϴ, was related to mass, m, and rotational speed, ω, by:

$$tan\phi \frac{T}{r_h sin\theta} = m r_m \omega^2 \quad \textbf{(1)}$$

Where ϕ is the angle between the coupler and the mass linkage, T is the torque applied to the base of the blade, r_h is the distance between the linkage and blade base in the hub, and r_m is the distance between the axis of rotation and the centroid of the mass. This relationship was used to estimate values for the masses and spring constants to be used during testing. During testing, we plan to iteratively test springs of different stiffness to achieve the closest to optimal blade angle of attack at each test condition.

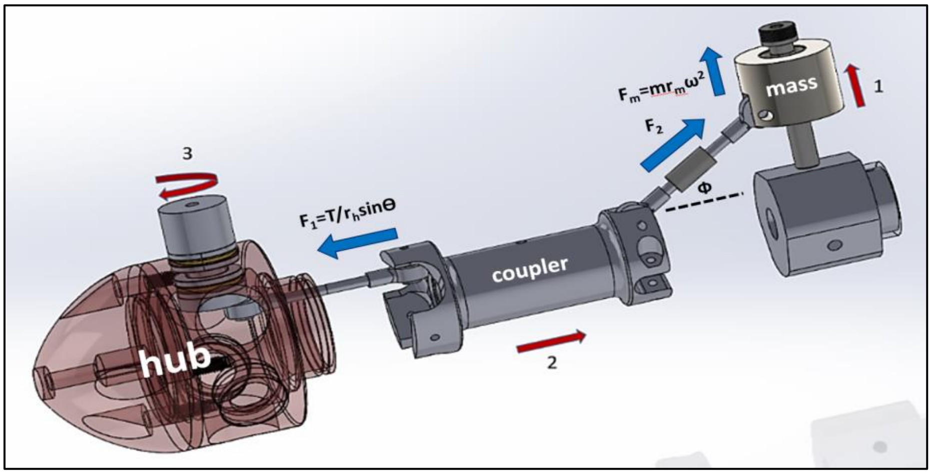


Figure 9: SolidWorks assembly showing equation of motion for pitch control

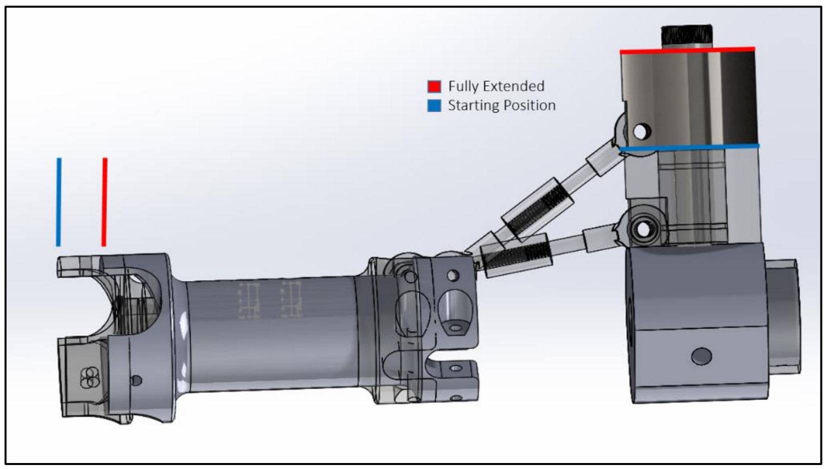


Figure 10: SolidWorks assembly detailing the pitch control system and the difference in positions

Yaw Control

To maximize the available kinetic energy of the wind with a traditional horizontal axis wind turbine (HAWT), the structure must be oriented such that airflow is parallel to the rotor. Therefore, the nacelle must be able to freely rotate about the tower in a plane parallel to the ground.

Grid Fin Design

The previous WiscWind turbine in 2017 experienced shaking and rapid oscillations where the nacelle met the tower. Therefore, the design this year was modified to provide a rigid, yet responsive rotation as the apparent angle of the wind changes. Box-shaped fins (i.e. grid fins), inspired by those used on the SpaceX Falcon 9 rocket, were used to increase surface area

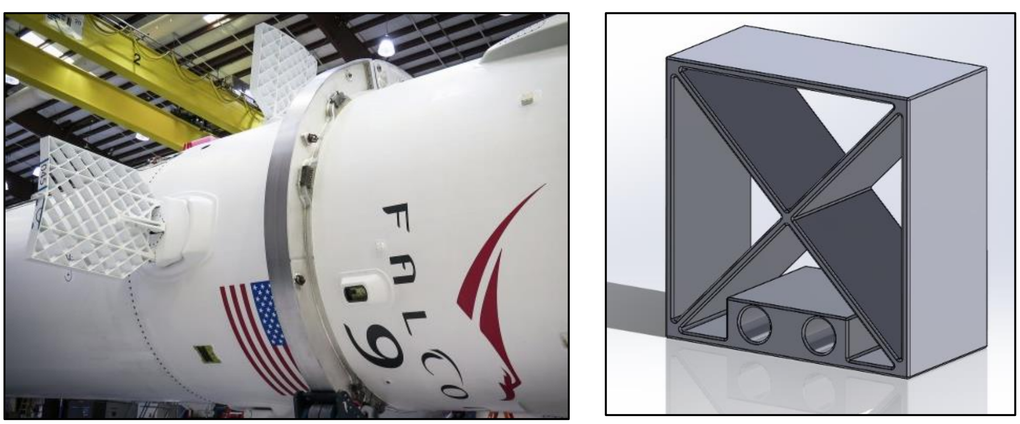


Figure 11: a) SpaceX Falcon 9 grid fin **[35]** and **b)** WiscWind grid fin

controlling the yaw angle. Figure 11a and Figure 11b show the Falcon 9 fins and WiscWind's fins respectively. Grid fins were used because the lattice shape increases the surface area perpendicular to the airflow. A larger surface area leads the turbine to responds both quickly and to variations in the wind direction. The minimum surface area of the fin is relative to the swept area, which is calculated using **(2)**:

$$A_{swept} = \pi R^2 \tag{2}$$

Where R is the radius of the rotor. Efficient fins are larger than 5% of the swept area [21]. Staying within the constraints of the competition, the maximum allowable swept area is 0.16m^2, therefore, an efficient fin should be sized to be at least 80cm^2. Using a pair of grid fins, one above and below the nacelle, will provide more than enough area.

Nacelle-Tower Coupler

Another improvement on the 2017 design in order to mitigate oscillatory behavior was the inclusion of large coupler which fits over the tower. The coupler in long enough to enclose multiple ball bearings held apart with aluminum spacers to provide more surface area and therefore stability. Figure 12a and Figure 12b show multiple views of the coupler.

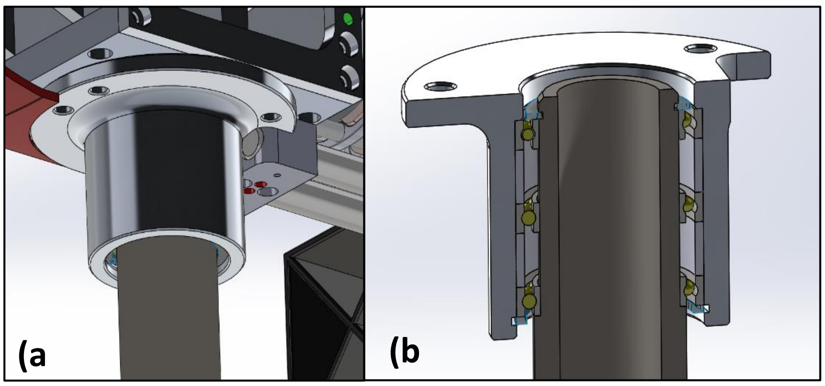


Figure 12: a) Coupler in turbine assembly and **(b)** cross sectional view of the coupler

Tower

To maintain safe operation, the tower needs to be able to withstand all the loads placed upon it by the varying wind conditions. Worst-case bending loads were analyzed through ANSYS Mechanical by modeling the maximum wind force and determining the deflection, stresses, and factor of safety present in the tower, shown in Figure 13. The minimum factor of safety for the assembly was 15. This indicates the team does not have to consider failure of the tower through too high of wind speeds.

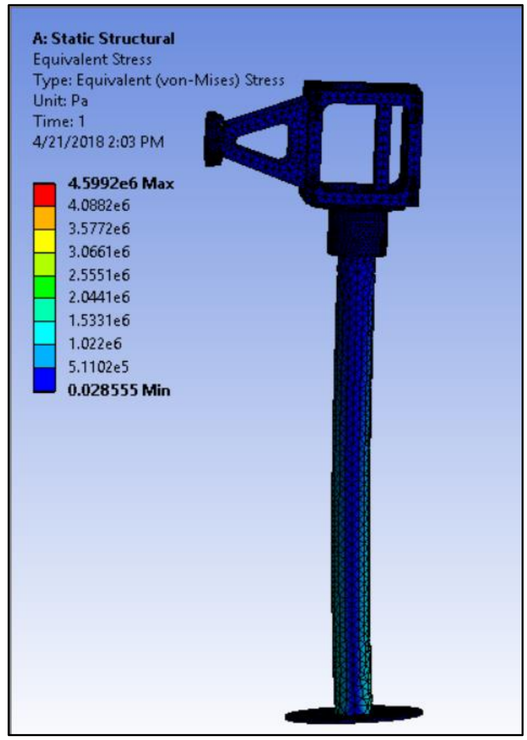


Figure 13: Von-Mises equivalent stress on the tower under maximum wind load conditions

Nacelle

The design of WiscWind's nacelle was based around size constraints where the maximum size was constrained by the competition guidelines and the minimum size constrained by the number of components needed to be housed within the nacelle. Within these constraints, the nacelle was made as aerodynamic as possible to minimize disruptions to flow around the blades.

Full-Scale Turbine

Objective: To make the proposed business plan economically feasible, the design of the market turbine will be centered on reducing manufacturing, installation, operation and maintenance, and material costs. WiscWind will use the knowledge gained in the development of the prototype turbine to focus on several key areas of the market turbine design.

Structure: The nacelle and tower will be designed to take advantage of cheap manufacturing and assembly processes. The nacelle will use a weldment design which be made with readily available steel tubing and common welding techniques. A weldment frame will be lightweight and high strength which will allow for simple analysis for the design and validation of the turbine structure. This design will reduce the required equipment and costs associated with manufacturing. Using a simple weldment design will allow for easy assembly, disassembly, and transportation of the turbine.

Blades: The blades will take advantage of similar construction methods used for the prototype turbine. WiscWind will use composite materials to produce high strength and lightweight blades. In order to reduce manufacturing costs, WiscWind hopes to investigate methods of making blades in a single piece, as opposed to a more complex two part construction method. The manufacturing will also reduce costs by reusing components like molds and bladders.

Generator: The generator will use an axial flux topology which will aid in the turbine's ability to produce power at a low wind speed. The generator will also eliminate the need for a gear box, which will greatly reduce the complexity and cost of the drive system. The generator will need significant analysis in order to minimize the size and cost of the rare earth magnets.

Condition Monitoring System: As up to 25% of the lifetime cost of a wind turbine can be attributed to operation and maintenance costs, a state of the art condition monitoring system will be implemented to ensure that operation and maintenance costs are kept as low as possible.

Notable Differences

Although the prototype turbine proved the concept of passive pitch and yaw control, the control system for the market turbine will both be actively controlled. The control systems will use a much smaller percentage of the total output power, and therefore will not make a large impact on turbine efficiency. The active control systems will also provide additional safety controls that passive control lacks. While the turbine controls are powered, the pitch system can offer full control over blade angle which could be used for turbine shut down and maintenance. An active yaw system would allow for the turbine to be moved out of the wind direction in case of an emergency.

Electromechanical

Overall Design Objectives

The generator design process was centered around the lessons learned from the generator made for the 2017 competition. The biggest take away from our expereince last year was the lack of full understanding of the other components of the turbine while designing the generator. When the generator was first being designed the mechanical and electrical systems were still in their inception. In order to account for this, the generator was designed to be fully modular to be able to adjust to the optimal operating points of the other turbine systems. This design process reduced pressure on the team when making design decisions where not all of the information was available at the time. The design also was created with structural integrity in mind. This means that the generator is able to achieve high rotational speeds without worry of excessive vibration or contact between rotating and stationary components. The design was also focused on creating a machine which could be easily manufactured, assembled, and could be contained in one concise package for use on different turbine chasis in the future.

Mechanical Design

Design Constraints

Without knowing the performance characteristics of the wind turbine, the mechanical constraints of the generator were chosen to reflect the wind turbine created for the 2017 competition. The size of the generator was chosen based on previous experience and consideration for the packaging and internal component layout of the generator. Too large of an outer diameter would affect the aerodynamics around the nacelle of the turbine which could reduce the performance of the blades and reduce overall power output. On the other hand, too small of an outer diameter would pose challenges with packaging and some components would become too small to effectively convert mechanical energy to electrical energy. An outer diameter of 4” and an overall length of 6” was used as a starting point for the design. Other than size constraints, the generator was designed to ensure it could handle the maximum rotational velocities expected by the team. The generator was also outfitted to interface with the turbine with a bolt hole pattern and a keyed shaft for power transmition.

Stationary Components

The generator main body consists of a tube and two end caps. The end caps have shoulder features which ensure concentricity and parallelism for the bearings and rotating assembly. This allows the generator to achieve smooth and stable performance at high rotational speeds. The end caps are drawn together using three 4” long shoulder bolts. These shoulder bolts also provide mounting points for the stators inside the generator. One end cap is outfitted with a bolt hole pattern which allows the generator to be face mounted to the back of the turbine. The other end cap has mounting points for the circuit board which sits at the back of the generator.

The stators proved to be one of the first manufacturing hurdles for the generator. The design uses a 3D printed ring which provides structure for the stator before the coils have been cast in epoxy. The coils were placed inside the ring and connected together with a soldering iron. Finally, the stators were placed into a mold and filled with epoxy.

Rotating Assembly

The rotating assembly consists of one main shaft which several rotors are mounted to. The rotors are connected to the shaft with a through pin which provides both the rotational and translational constraints. The pin is then held in place with a collar to prevent it from sliding out while the generator is rotating.

Like the stators, the rotors proved to be another manufacturing hurdle. The magnets were sourced from permanentmagnet.com. The provider produced very high quality and dimensionally accurate magnets. However, there were slight imperfections in the magnet geometry (which is to be expected of any non-ultrahigh precision manufacturing process). This means that the rotor backing, which hold the magnets in place, needed careful tolerancing to achieve the goals of structural integrity of the generator. Too loose of a tolerance would allow the magnets to move around on the rotor backing under high rotational speeds due to the outward angular acceleration. Too tight of a tolerance would cause the brittle neodymium magnets to shatter under compressive loads of a press fit.

Electrical Design

Design Constraints

Referencing the experience gained last year, it was decided that the generator output would be three phases of alternating current. Aside from the generator output, the only other major design constraint was the relationship between phase current and coil wire size. A wire size was chosen which provided adequate current overhead without the risk of burning out a coil or stator while remaining small enough to keep the coil fill factor high and overall generator efficiency high.

Coils

The number of coils for the generator was chosen as a baseline used last year. This number must conform to a specific ratio of coils to pole pairs, so setting the number coils to 12 locked in the number of magnets per rotor [22]. The shape of the coils we're chosen as trapezoidal, which most efficiently uses the space of the stator [23].

Once these parameters were set, the most ambiguous decision about the size of wire to use for the coils was tackled. The size of the wire used for the coils greatly affects their current carrying capacity. A wire gauge of 26 can handle 2.2 Amps, where a gauge of 28 can handle 1.4 A [24]. From simulations, it was estimated that the current output under normal conditions would be equal to or less than 1 A. However, because the team is relying on the generator to electrodynamically brake the turbine, the current could be much higher at times. This current is called burst current and causes the coils to heat up as power is dissipated through the generator [25]. Coil wire size also affects the coil packing factor, which affects the efficiency of the generator. Large wire sizes reduce the packing efficiency, while smaller wires allow for tighter packed coils. A packing efficiency of 0.6 was assumed, which is typical for helically wound coils [26]. Using the previous information and consideration, a coil wire size of 26 gauge was picked.

The final two parameters which were needed to fix the coils were found using EMWorks, a plugin for SolidWorks which provides tools which can simulate electromechanical machines [27]. Using this program, a design study was performed to find the optimal coil thickness and coil leg width. These two parameters directly influence the number of turns per coil. It would have been possible to set the desired number of turns but would not have been possible to update the geometry for each design and use the simulation software, which is why the geometry drove the number of coils and not vice versa. After the simulation was complete, the number of turns per coil was found to be 114 turns.

Coil Leg Width

Several different coil leg widths from 0.175" to 0.3" were simulated. The results from this study are shown in Figure 14. A coil leg width of 0.225" was chosen because it maximized the output power while allowed for a larger coil form, which simplified manufacturing.

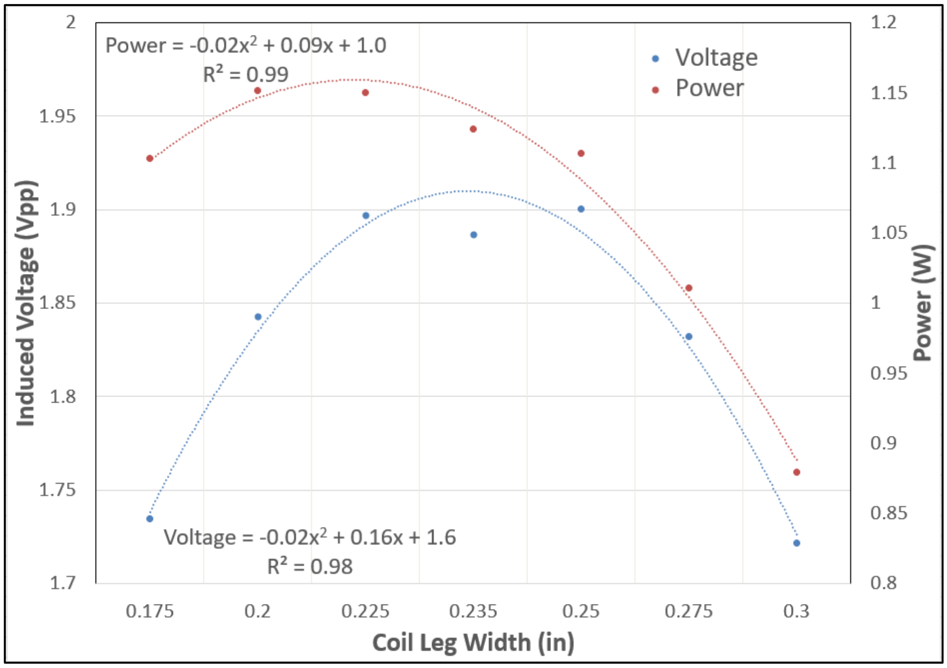


Figure 14: Induced Voltage vs. Coil Width

Coil Width

Several different coil widths from 0.075" to 0.3" were simulated. The results from this study are shown in Figure 15. A coil width of 0.225" was chosen because it maximized the output power. This finalized the coil geometry and fix the number of turns to 114 turns per coil with our assumed coil fill factor.

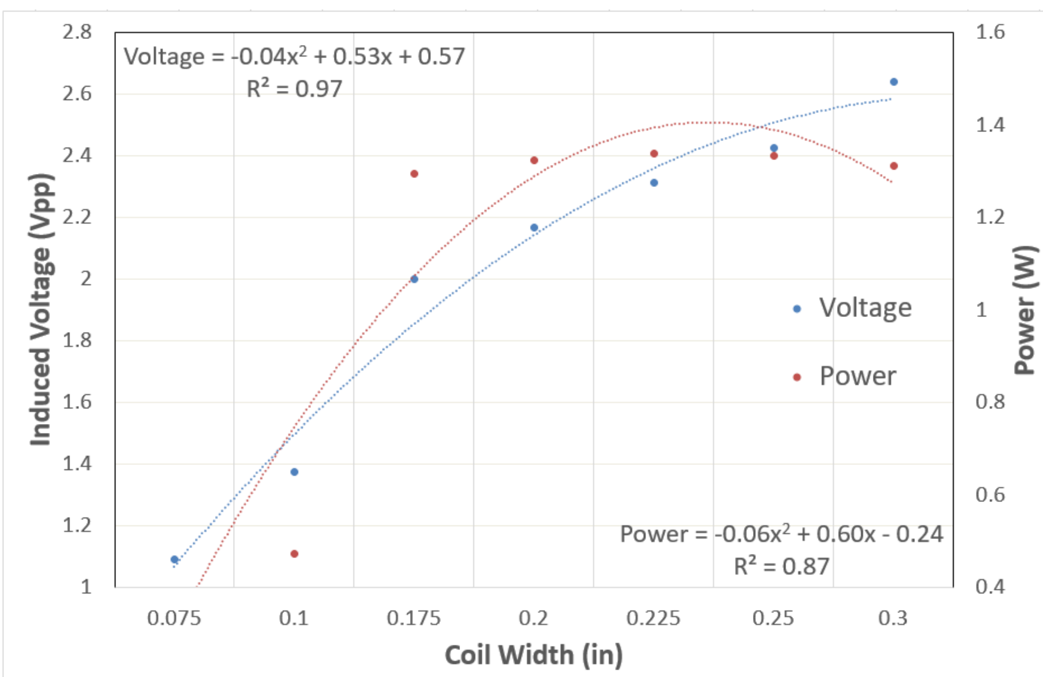


Figure 15: Coil Width vs Induced Voltage

Magnets

The shape of the magnets was set using the finalized shape of the coils. The inner and outer radius of the magnets were chosen to match the inner and outer radius of the empty area within the coils. The number of magnets was set to 9 using the 4:3 ratio of coils to magnets. The only other dimension which needed to be determined was the thickness of the magnets. Once again, EMWorks was used to determine the optimal magnet height.

Magnet Height

Several different magnet heights from 0.1" to 0.5" were simulated. The results from this study are shown in Figure 16. A magnet height of 0.375" was chosen. The results from the study showed that increasing magnet width increased power output, but the returns began to diminish at magnet heights over 0.375". The chosen dimension maximized the power output while keeping the magnet dimensions small enough to reduce manufacturing costs.

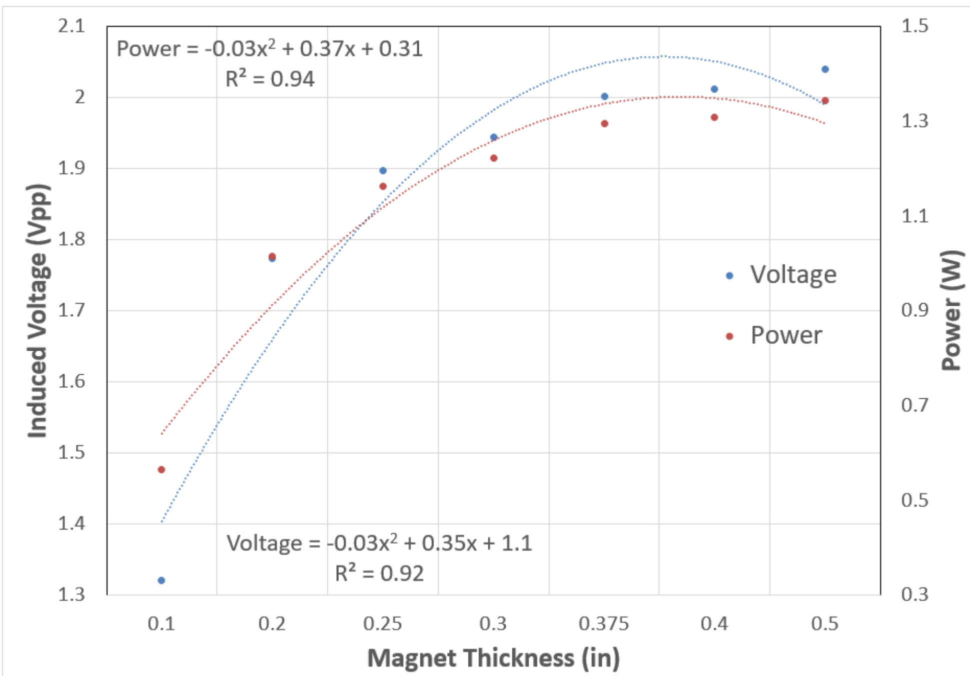


Figure 16: Magnet Thickness vs Induced Voltage

Iron Backing

In order to determine the optimal rotor iron backing thickness, EMWorks was used. A study was ran of iron backing thicknesses from 0.075" to 0.3". There were no large differences in output voltage or power between the simulations. This could be due to the fairly large magnet height dimension, which causes the magnetic feild between the rotors to be very strong without the need for strong iron backing. A dimension of 0.1" was chosen because the team felt that it was a minimum thickness necessary for manufacturing and structural integrity of the rotor while minimzing the rotational intertia of the machine.

Modular Design

In order to achieve the design goals for the generator, the machine needed to be able to adapt to a wide range of operating points from the other turbine subsytems. This allows the generator to be tuned to the capabilities of the turbine. If the turbine had a higher than desired cut in, sets of stators and rotors could be removed from the generator to reduced the input torque required at start up. The modular design of the generator also reduced the constraints on the electrical subsystem design. The generator could be easily modified to reduce or increase output voltage by adding or removing stator and rotor sets. The modular design extends to the circuit board located on the back of the generator. This board allows the stators to either be run in series (when all 3 stators are present), or in a parallel configuration. This allows the electrical output of the generator to be tuned to the needs and capabilities of the elctrical subsystem.

Electrical

Overall Design Objectives

To maximize the effectiveness of the electrical system, the main design objectives were to convert the generator's AC output to DC power, regulate this power to meet a specified load, and incorporate braking of the rotor through electrical means to maintain a constant output above rated conditions. A rectifier was used to convert the three-phase AC to DC. Next, it was determined that braking could be accomplished by shorting the generator phases together and that the effect was enough to successfully complete a "shutdown" event [28]. A voltage sense would read the output voltage from the rectifier and if the voltage is reaching above the desired range, for example at wind speeds above rated, our control logic would pulse the shorting of the generator phases to curb any increase in rotor speed and keep our power being produced within our desired limits. This is what will define our turbine performance and still meet the emergency braking requirements when engaging the manual shutdown or disconnecting the load. For the regulation we wanted to be able to control the voltage and current that is outputted to the load to achieve a maximum output power. A buck-boost convertor was chosen to be able to boost up our voltage at lower speeds and also ensure that we will be able to predict our exact operating values at higher speeds. We began the design process with a basic block diagram. This can be seen below in Figure 17.

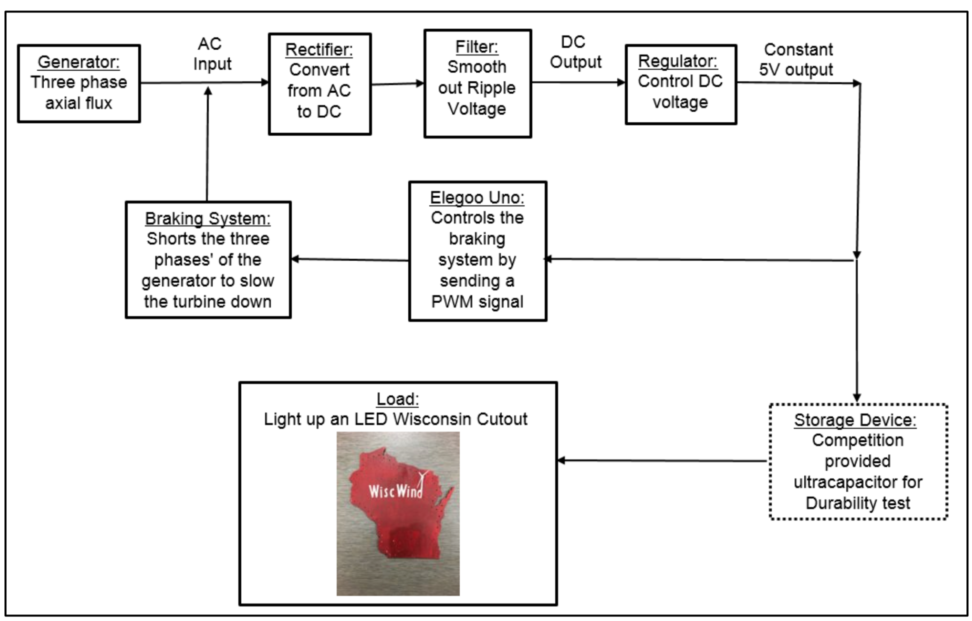


Figure 17: Block diagram of electrical design

A modular system, based off of work done by a professor in our department, was developed for testing purposes. Stand-alone PCB boards were constructed for the rectifier, braking, and regulation to allow for us to confirm each component is working as expected before adding it to the rest of the system. Because there is so much complexity is designing an electrical system to meet all of the competition task requirements, this modular approach saved us time and effort in our reengineering as we progressed with system testing. These boards are interconnected with screws and metal hooks to connect in series. Our final circuit design can be found in Appendix Figure 21. After completing testing and confirming our final design, we made a complete PCB featuring all the circuit elements from the combined modules.

Power Electronics

Power Rectification

The goal for power rectification is to take the AC three-phase power from our generator and turn it into useable DC power. After we decided on a design, the parts were purchased and a PCB was created in Altium for use in our modular system. The rectification circuit in featured in Appendix Figure 21 . The rectifier consists of six Schottky diodes. Because our generator is configured for higher current production, these components had to be rated to handle high power operation to a factor of safety above what we would expect. We will take advantage of this in the regulation to balance out the voltage to current ratio and result in the most usable power we can generate [29]. Diodes only allow for current to flow in one direction, but AC current flows in both directions in a sinusoidal fashion. Since the current can only flow one way through diodes, the circuit forces current to flow through different paths depending on the direction it is going. Each path is set up so that they all meet at the output but forces the current to only flow one way through the output. This creates DC current that can be measured at the PCC and that will supply the system load.

Braking System

For the braking system, two different situations need to be considered: loss of load, and manual or emergency shutdown. A diagram of the final design for the braking system along with the state diagram which was implemented in our microcontroller can be found in appendix Figure 21. The circuit consists of a three-phase input interacting with two different MOSFETs, with diodes and relay circuits fitted with a protective and dissipating capacitor and resistor pair. During a shutdown event, the microcontroller will close two normally open switches to short the generator phases together which will increase the torque required by the rotors to turn the generator windings and restrict the speed of the rotors [30]. Since there is no mechanical braking in this turbine model, we expect this electrical approach to satisfy the competition defined "shutdown" requirements of dropping below 10% of the maximum 5-s bin average rpm achieved during the power performance testing. We will use this same braking concept to regulate our input power at wind speeds above our turbine's rated 11 m/s speed. Up until wind speeds that result in rated RPM, this braking mechanism will not need to come into play. There will be a voltage sense after the rectifier that will relay the output voltage to the microcontroller. If the microcontroller reads that the voltage is getting too far above our set voltage range, it is a good indication that rotor speed is also increasing most likely due to an increase in wind tunnel wind speed. The microcontroller will then pulse that shorting of the generator phases accordingly, creating a braking effect through the back-EMFs that will maintain the rated rotor speed and output power as the maximum attainable values.

Regulation

The regulator we are using is a buck-boost converter which is a type of DC-to-DC converter. DC-to-DC converters use electrical switches to increase or decrease the voltage [31]. However, the power going into a DC-to-DC converter must equal the power going out of it. This is to say, if the input voltage needs to be increased, then the output voltage will be the input voltage multiplied by some factor that can be chosen. Due to the $P_{in} = P_{out}$ constraint, the output current will be lower than the input current. This expected loss of current is one factor that reinforced our decision to connect the generator to favor current over voltage.

Control Logic

Regulation

The output voltage of the electrical system is designed to maintain a constant 5 VDC. This voltage was chosen to maximize the turbine's performance over all of the wind tunnel testing tasks while still meeting the team's goal of simplifying the design to avoid unnecessary complexity. The first step to this implementation was to setup the phases of the generator in parallel. By doing this, the current produced by the generator is increased [32]. This is necessary because it was concluded through wind tunnel testing that the current will be the limiting factor in setting the rated power. At lower wind speed, some of the voltage produced will need to be power the microcontroller, but the regulation system will be set to boost the input voltage to 5 V output. Our competition load is designed to be optimized for this system and voltage level, but the use of the buck/boost convertor in the regulation will allow for the 5 V to be read at the PCC regardless of variation in the load. The braking system will ensure the RPM stays at its rated value at wind speeds ranging from 11 m/s to the competition maximum wind speed of 20 m/s which will keep the operating voltage at 5 V as well.

This method of regulation will result in predictable results for the power curve performance and simplify the sources of error for the durability task. For the durability task, the ultra-capacitor is connected to the system in parallel and will be fed by the buck/boost convertor. The ultra-capacitor should have sufficient charge to then provide the variable load with a 5 V supply after the initial charging period. Our power curve performance is slightly restricted by limiting our output to 5 V, but the predictability of the durability, strength of the braking mechanics, and simplified design met our initial goals.

Load

For our team's load, we chose a simple design to take advantage of our regulation. We chose to construct a wood cutout of the state of Wisconsin to be fitted with LEDs and painted with the WiscWind logo. The LEDs will light up on the border of the state when the load is connected and powered. This will visually display how much power is seen at the load and will be set by the regulator given enough input power to boost the voltage to 5 V.

Associated Software

Microcontroller

We used a microcontroller to run our braking system. To code the microcontroller, an open source coding software provided by Arduino was used.

Altium

For the modular PCB design, three modules were required for the entire system; the rectifier, the braking system, and the regulator. Additional boards were made for the generator phases and the microcontroller. The final schematic and PCB were designed in Altium.

Electrical Safety

Safety was one of the most important aspects of our design. In an effort to address the hazards associated with electricity and rotating machines, the electronics and controls are implemented to keep the turbine safe even in the most severe conditions and all electrically live components are properly insulated and isolated. The electrical braking system is reliable and implemented with a manual shutdown capability and a load disconnect shutdown capability, along with controlling the turbine's behavior is high wind situations.

Testing and Results

Optimization of Pitch Angle

Table 3: Experimental results for pitch angle optimization

Pitch Angle (deg)	Cut in Speed (m/s)
30	**7.9**
45	**5.7**
60	**6.2**
65	**7.7**
80	**8.8**

In order to function as a proof of concept for blade design and analysis and gather data for the passive pitch control system model, the turbine was decoupled from the generator to test cut-in wind speed of the turbine at various blade angles. Our experimental data shown in Table 3 indicates that the turbine produces optimal cut-in torque at a blade angle of approximately 45°.

Although the blade performed similarly to our assumptions in terms of blade pitch angle, we decided that even at the optimal blade pitch, our cut-in speeds were insufficient for competition and necessitated a rethinking of our blade design. Whereas our original blade design approach centered on maximizing efficiencies at higher speed, with the optimum occurring at rated power, the new design would place more emphasis on generating torque at low speed and cut-in. Using a similar process to that described in the 'Blade Design' section, this time with a lower optimal tip-speed ratio of 4, a new blade was decided upon. The new blade is based on the NACA 11XX airfoil series, which have less severe camber than the 32XX airfoils used originally. The new blade also has a substantially longer chord length and more twist than the original, which should provide better performance at low speeds at the expense of high speeds. The two designs are shown in Figure 18.

Figure 18: Comparison of first generation (right) and second generation blades (left)

Characterization of C_p-TSR

Using the new blades at a pitch angle of 45 degrees, the turbine underwent testing to analyze its performance at various wind speed by connecting to the regulator with an additional resistance of 300 Ohms. Figure 19 shows the power coefficient vs. the turbine tip-speed ratio for wind speeds from its cut-in at 8 m/s to 11 m/s. From this characterization it is apparent that we are operating well below the design tip-speed ratio of 4 for competition wind speeds and the power coefficient suffers as a result. From this we determine that for improved performance, it is necessary to either reduce the final load or redesign the blades to perform optimally at an even lower tip-speed ratio. Using the peak C_p as a conservative estimation of the value we expect to see in the competition returns an annual energy generation of 3100 kWh/yr considering the average wind production of three located investigated by WiscWind's siting team.

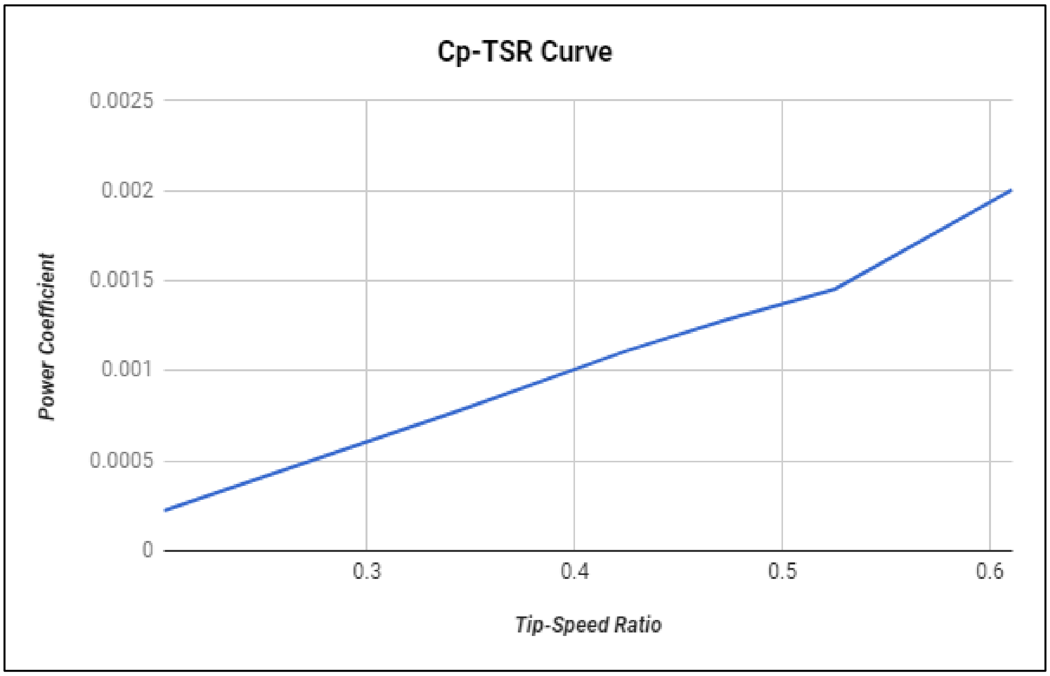
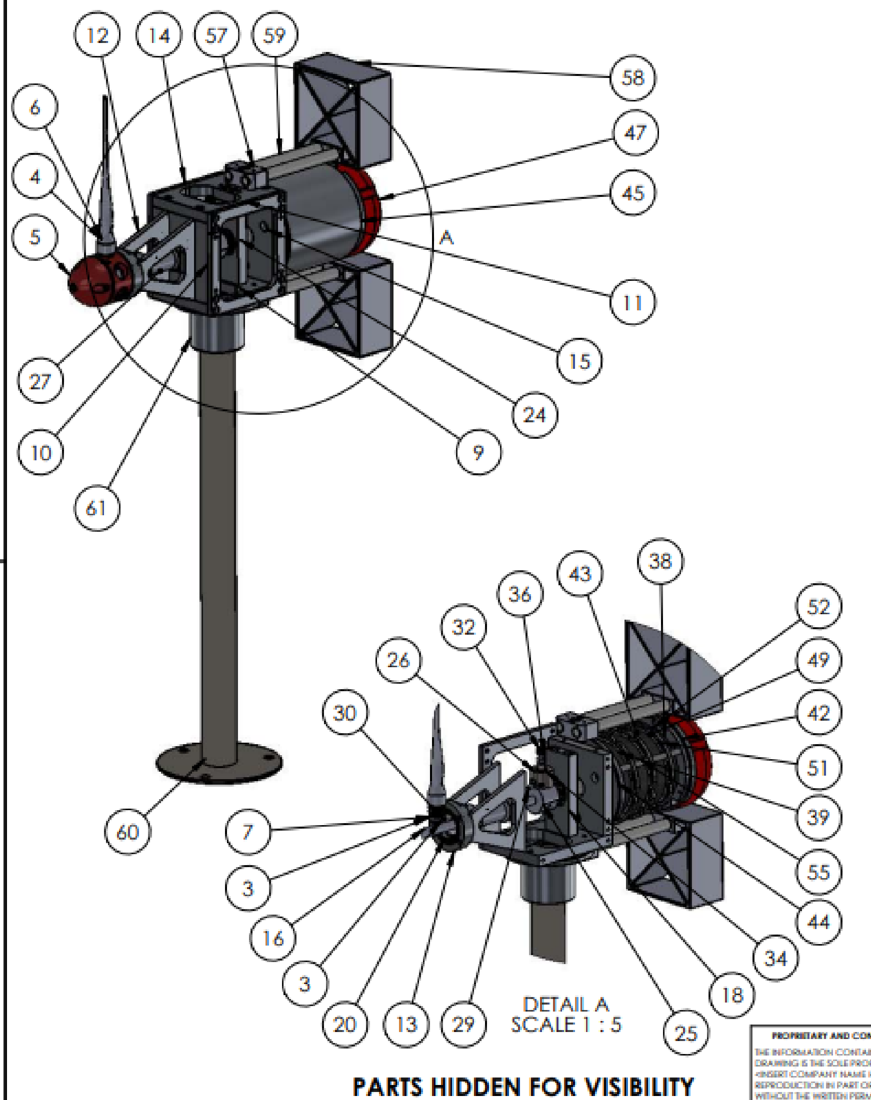


Figure 19: Preliminary performance characterization of power coefficient vs. tip-speed ratio

WiscWind

re:charged systems

Appendix



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
2	02-001	HUB	1
3	02-002	BLADE CONNECTOR	1
4	02-003	BLADE CONNECTOR	1
5	02-004	NOSE CONE	1
6	NACA32XX BLADE	BLADE	1
7	F10-18M	THRUST BEARING	2
8	9558K61	O-RING	1
9	03-101	BOTTOM PLATE	1
10	03-102	FRONT PLATE	1
11	03-103	TOP PLATE	1
12	03-104	TRIANGLE PLATE	2
13	03-105	MAIN BEARING ADAPTER	1
14	03-106	SIDE PLATE	2
15	03-107	BACK PLATE	1
16	03-108	MAIN SHAFT	1
17	03-109	NACELLE CASING	1
18	03-110	PILLOW BLOCK	1
20	61806	MAIN BEARING	1
23	6412K13	COUPLER	1
24	1614	BEARING	1
25	04-001	PITCH MOUNT	1
26	04-002	MASS	1
27	04-003	SLIDER	1
28	04-006	COLLAR	1
29	Steely 4-40 Rod End (Helm Joint) Base	CONNECTING ROD	4
32	91259A546	SET SCREW	1
33	IP6G	LINEAR BEARING	2
34	IP4G	LINEAR BEARING	1
35	95289A006	SET SCREW	1
36	9657K275	SPRING	1
37	05-101	GENERATOR SHAFT	1
38	05-102	ROTOR	1
39	05-102_B	ROTOR	1
40	05-103	MAGNET	72
41	05-104	COLLAR	4
42	05-106_RevA	END CAP	1
43	05-105	ROTOR	2
44	05-107	END CAP	1
45	05-108	TUBE	1
46	05-109	SPACER	1
47	05-110	GENERATOR COVER	1
48	05-111	SPACER	1
49	05-201	RESIN	3
50	05-202	COIL	27
51	05-203	STATOR RING	3
52	05-204	WIRE GUIDE	3
53	97395A432	DOWEL PIN	4
55	90298A559	SHOULDER SCREW	3
56	1614	BEARING	2
57	06-101	YAW BLOCK	2
58	06-103	GRID FIN	3
59	1346K17	YAW ROD	4
60	07-101	TOWER	1
61	07-102	TOWER COUPLER	1
62	07-104	SPACER	2
63	35239	RETAINING RING	1
64	113533	RETAINING RING	1
65	61807	BEARING	3

Figure 20: Mechanical Assembly

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NEXT ASSY | USED ON | APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	NATE	4/20/18
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE: WISCWIND PROTOTYPE TURBINE

SIZE B | DWG. NO. 00-000 | REV

SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1

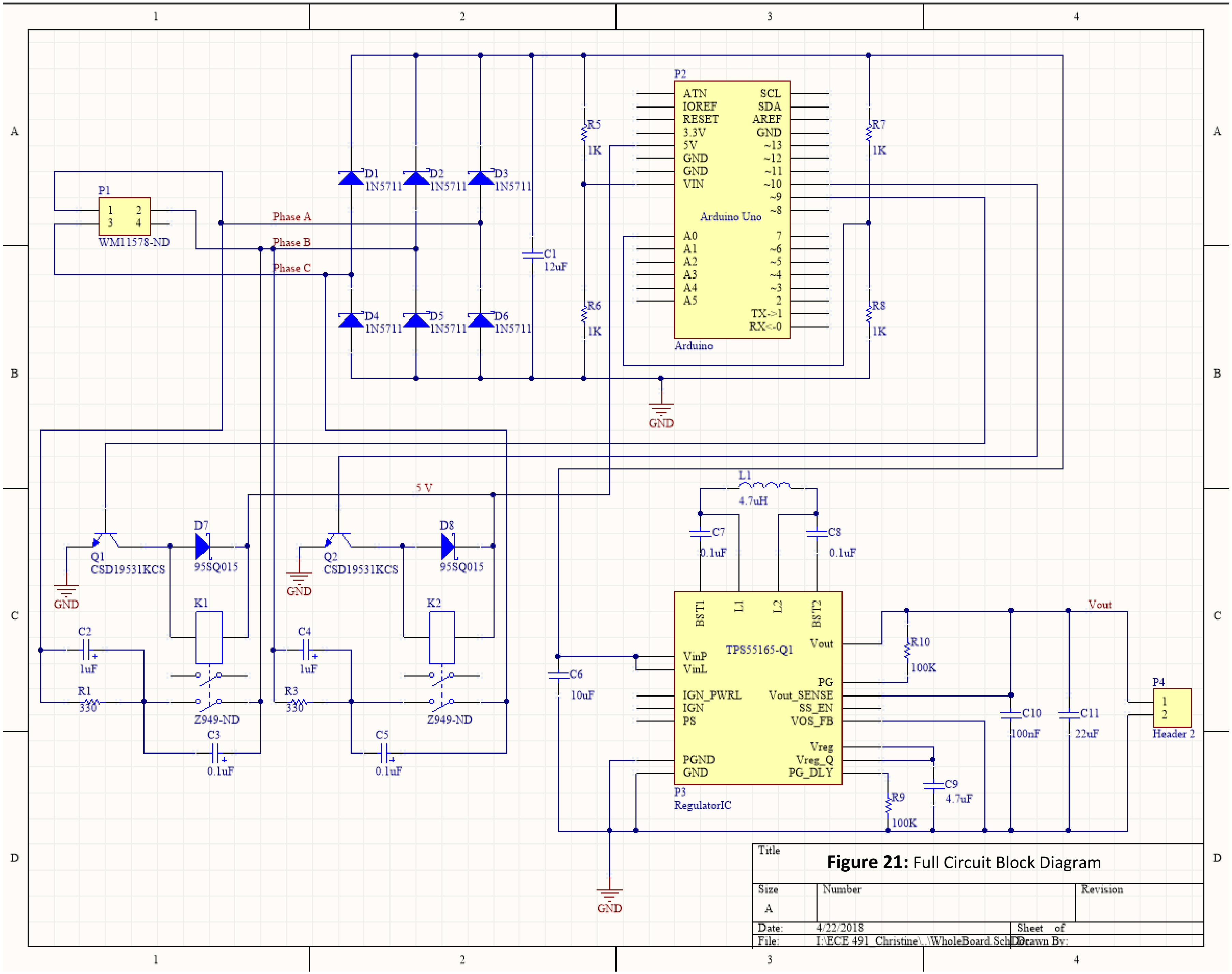

Figure 21: Full Circuit Block Diagram

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