Off-the-Grid Wind Turbine System

Semester Progress Report

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Abstract

We designed and started construction on a wind turbine system at Woodland Harvest Mountain Farm in the fall semester of 2020. The design and construction was informed by an extensive research process during the first half of the semester. We conducted a site assessment for two locations and designed a twisted Savonius turbine for a 3 kW generator. Furthermore, we chose appropriate materials for the system's shaft and blade. During the construction process, we built a tower on the roof of the barn, installed the electrical conversion system, and assembled the shaft that connected through the roof to the generator inside the barn. Documentation for the wind turbine system can also be found on the wind turbine system Wiki page. Due to COVID-19 related delivery delays, we plan to assemble the blade the next semester.

Our special thanks go to Jeff Dusek for his great assistance with this independent study and Michael Easton who generously offered us the generator and electrical conversion system. Thank you for enabling this incredible project and learning experience.

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1 Introduction

During the COVID-19 fall 2020 semester, fifteen Olin College of Engineering students and Wellesley College alumni independently organized an experimental semester at an off-grid permaculture farm in North Carolina, Woodland Harvest Mountain Farm. Please refer to our website OlinAtWoodlandHarvest.com for more information on this educational communal living experiment. The first students arrived in August, and the last people left in late December. Prior to the students' arrival, the farm had no internet connection and their electricity consumption was limited to the very basics of charging three phones and a laptop twice a week. One 250 W solar panel was enough to cover their needs. However, upon the arrival of fifteen students, some of whom took classes, and a newly added satellite internet connection, we upgraded the off-grid electricity system with five additional 200 W solar panels. We also reintroduced an existing 80 W micro-hydro turbine to the electricity system. The electricity load from the large group of students created demand for another renewable energy system that was reliable during the winter months. While the sun set behind a mountain at 2 PM starting in late November, the wind was the strongest during those months. Therefore, a wind turbine system seemed to be a reasonable addition to the electricity system. We collectively made these decisions prior to our arrival. Our work during the semester was split up into a research/assessment phase and a construction phase. The addition of a wind turbine system did not only mean more electricity, it also created the opportunity to expand our electricity net and build new infrastructure in a barn that was a two-minute walk away from the main house. Very much in the homesteader spirit, it allowed us to create a new space for our community and engage with parts oft the land that were inaccessible from a technological perspective.

This report leads you through a background knowledge section with brief insights, followed by a close-up on low-speed vertical-axis turbines, and two inspirational examples. Section 3, design and construction, captures our progress towards a twisted Savonius turbine, the mechanical and electrical design. Site assessments for two locations, by observation and data-logging, explain why we built the turbine further away from the main house. It further captures the prototypes and final system for the semester. Lastly, we offer conclusions from the semester in the work-flow and technical domains. The appendix includes tables of all the crucial components and expenses.

2 Research and background knowledge

This section is a summary of insights from our research period and the *Wind Energy Coursera* course that informed our site choice, design process, and construction.

2.1 Statistical analysis of wind speeds and turbulence

Wind speed data is collected by using an anemometer to measure the wind speed and a wind vane to determine the wind direction. For most non-industrial projects, a cup anemometer is a cost-effective solution for measuring the wind speed in a specific spot. Remote wind speed sensing technologies, however, allow for data collection in locations that are difficult to reach (i.e. in front of a large turbine, close to the blades). LIDAR SODAR Doppler shift measurements are a pricey alternative to deliver precise remote data. If several remote anemometers are on site, a three-dimensional fluids analysis can be performed. A simple statistical analysis of the wind data includes the mean wind speed and standard deviation of wind speeds, which yields the turbulence intensity. In most wind turbine projects, an averaging period of ten minutes is used to level out smaller fluctuations [2].

For small wind turbine systems that are significantly below the boundary layer, however, we recommend an averaging period of at most two minutes. A longer averaging period would level out short periodic gusts that occur in hilly or densely grown areas. The Inspeed Vortex wind sensor is a commonly used cup anemometer in the range of $50 that can easily be connected to an Arduino data logger. Please note that this specific anemometer uses a mechanical relay, which creates a switch bounce effect. Therefore, a debounce circuit is recommended to prevent double counting [1].

2.2 Wind energy extraction

A wind turbine extracts energy from the wind by slowing down the wind and converting the wind speed into a rotational motion. The more the wind is slowed down, the more energy is extracted. However, if we attempt to use all of the wind's kinetic energy, we stop the flow of the air on the turbine. Consequently, there is a limit to which we can extract energy from the wind without majorly affecting the air flow. The Betz limit describes this maximum ratio of power extraction. The maximum power coefficient for any wind turbine is 59%. The only way to increase this efficiency is to channel the wind from other locations toward the turbine.

Once we have an estimate for the turbine's power coefficient C_p, the swept area of the turbine A, the average wind speed V, and the air density ρ, we can calculate the mechanical power P created by turbine with the following equation [3].

$$P = \frac{1}{2}\rho A V^3 C_p \tag{1}$$

2.3 Types of wind turbines

Wind turbine systems that are designed to produce electricity consist of a rotor, a generator, a shaft, potentially a gearbox, a braking system, control and conversion electronics, and surrounding structures such as a tower or foundation. Most wind turbines can be classified to be either vertical or horizontal axis wind turbines.

Depending on the design and size of the turbine blades, every turbine has a power coefficient below the aforementioned factor of 0.59. While some turbine blades make use of the air drag, others use lift or a combination of lift and drag to create a rotational motion. Turbines that are based on lift have generally speaking higher coefficients but lower starting torque. High starting torque is especially useful in areas with low wind speeds to ensure that the turbine starts to spin. For instance, a Savonius turbine will start at a lower wind speed than a Darrieus turbine even though a Darrieus turbine is more efficient once it is started. Therefore, Darrieus turbines are oftentimes started with an electric motor to overcome the generator's initial resistance. Please refer to figure 2 for images of the different kinds of turbines.

Most commercial wind turbines are horizontal-axis, fast spinning, lift-based wind turbines, meaning that their axis of rotation is in the horizontal plane. As their main shaft lies in the horizontal plane, the generator is located at the top of the turbine right behind the blades. Smaller wind turbine systems, including our system, are oftentimes designed to spin in the vertical axis because it is structurally easier to keep the generator on the ground. Furthermore, vertical axis wind turbines (VAWTs) do not need to be pointed into the wind, which removes the need for an orientation mechanism.

Figure 1: A combination of a Savonius (inner part) and Darrieus (outer blades) turbine [9]

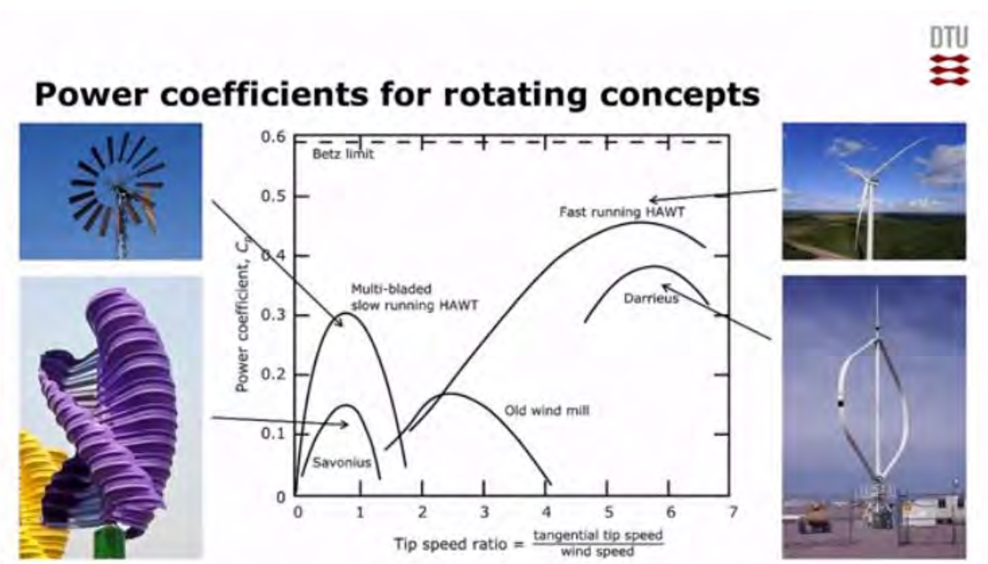

Figure 2: Betz power coefficients for common types of wind turbines [3]. The Savonius turbine in the lower left corner is twisted to decrease shaking.

2.4 Small scale vertical axis wind turbines

In the United States, most small vertical axis wind turbines are designed for wind speeds below 10 m/s. Such wind speeds are considered low for lift based applications. Therefore a hybrid-construction of Savonius and Darrieus turbines is a suitable solution. The cup-shaped Savonius blades create high torque and allow the turbine to self-start. Once the turbine is started, the spinning thin aerofoils of the Darrieus turbine create further torque at an efficiency that is up to three times higher than a Savonius turbine [4]. Vertical axis wind turbines are easier to maintain and construct than most of their horizontal counter-parts. The generator can be placed right below the rotors. They are also structurally safer as most of the wind force that tries to push the turbine over is absorbed at the bottom of the turbine. Guy wires are easy to install at the top of the turbine [10].

The original Savonius design had two buckets that were connected to a pole and created an S-shape. The two buckets did not allow air flow from one bucket to another. As an improvement to the original design, an offset between the two buckets allows air to flow from one side of the S to the other side. Air flow between the two sides of the rotor dramatically increases the blade's efficiency [4].

The original Darrieus turbine design can be seen in figure 2 in the lower right corner. The depicted design can lead to strong shaking as the angle of attack changes during every rotation. Similarly to Savonius turbines, modifications for the original Darrieus design exist that shape the blade in a spiral around the shaft. Such turbines are often referred to as Gorlov turbines and inspired the design of the commercially available Quiet Revolution 6.

2.5 Inspiring designs

We came across a variety of interesting ideas that ranged from hybrid designs to cone-shaped and inflatable turbines [6]. A common adjustment among many designs is the addition of blades to get rid of pulsating loads often experienced on Darrieus turbines.

Figure 3: The Gorlov-like Quiet Revolution 5 turbine (left) and WePOWER (right) turbine [6].

The Quiet Revolution 6 turbine is a Gorlov turbine that is optimized for low wind speeds in urban areas at a cut-in wind speed of 1.5 m/s. We were particularly interested in the Gorlov design as one of our wind turbine sites is encompassed by tall trees similar to an urban setting. The Quiet Revolution turbine was designed to be placed on top of buildings. When air passes above buildings, there is an area of accelerated airflow. Ideally, the turbine would sit right in this area to receive the channeled wind. This design inspired us to consider to place our wind turbine on top of the available roofs on our property. The fabrication of twisted airfoils, however, posed a large challenge [8].

Our prototyping phase was heavily inspired by the vertical-axis WePOWER turbine. The WePOWER turbine has six straight, vertical blades that are arranged in a circle around the center of the turbine. The blades are shaped in a way that creates drag as well as lift. This design enables the turbine to self-start and perform well with low wind speeds. Furthermore, it is more rigid than a Gorlov turbine [6].

3 Design and construction

We decided early on to design a vertical axis wind turbine as our capabilities for lifting the 15 kg heavy generator were limited. Furthermore, it simplified the connection between the shaft and generator and allowed us to keep the generator inside the barn to protect it from the elements.

3.1 Site assessment

The assessment of the property started as an observational gathering of wind directions and speeds and was followed by a quantitative data collection in two distinct locations, the main house (1) and barn (2). The main house is located in a valley that leads down Bluff Mountain. The garden area and parts of the hill around the main house were cut down leaving an indentation in the forest landscape. The second location was located on nearby horse pastures that were cut short hundreds of feet around the barn.

3.1.1 Qualitative assessment

We started our site assessment in August, which is known to be one of the less windy months. During the warm months August through September, we observed only small wind gust that never exceeded a speed of approximately 6 m/s. Wind speeds in the warmer months were disappointingly low. With the arrival of the hurricane Delta in early October, the local climate started to shift resulting in strong constant winds and gusts.

Most trees around the main house (1) were 100 ft (30 m) tall or even taller. Fruit trees close to the house were planted a few years ago and ranged from 1-10 ft (0.3-3 m). While the trees' tips indicated constant wind even throughout the warmer months, they protected the main house from the high up winds. We estimated the surface roughness of our property to be around 0.8 m. However, this number only reflected the difference in tree tip height and did not take the indentation of the main house in the forest into consideration. See figure 5 for surface roughness grading. We neglected calculations on the difference in wind speeds based on the potential height of the turbine as our capabilities to reach above the boundary layer were limited. The wind at the main house followed the valley down the mountain resulting in a predominant wind direction from the west. Constant winds were very rare as the main house was located in the turbulent sections of the boundary layer that spanned across the mountain's valley. We considered building the tower on top of the main house's roof to gain extra height as reaching the tip of the trees posed a challenge.

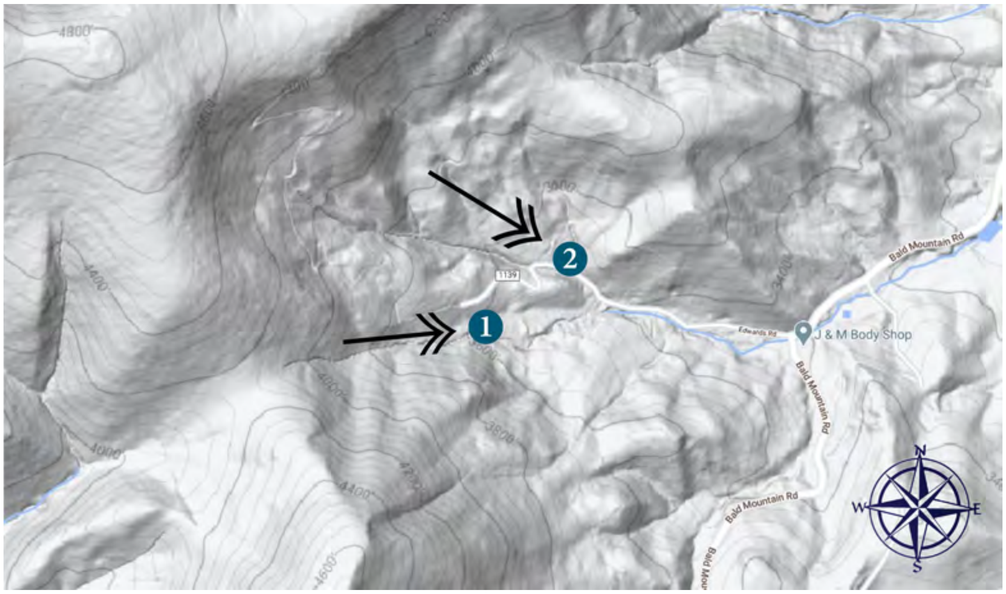

Figure 4: Topographical map of the surrounding mountains [5]. The blue circles indicate the main house (1) and barn (2). Arrows represent dominant wind direction and strength.

The second location, the barn, was surrounded by horse pastures that showed only a few trees but mostly grassy fields for hundreds of feet. Winds were more constant and followed the descending incline of the mountain. The wind blew predominantly from the north east as indicated in figure 4. As we concluded early on that a vertical wind turbine would suit our needs better, the wind direction was only of minor interest for us. We estimated the surface roughness around the barn to be around 0.05-0.1 m.

Z_0 [m]	Terrain surface characteristics (land use)
1.50	Sparse forest
1.00	City
0.80	Dense forest
0.50	Suburbs
0.40	Shelter belts
0.20	Many trees and/or bushes
0.10	Farmland with closed appearance
0.05	Farmland with open appearance
0.03	Farmland with very few buildings/trees
0.02	Airport areas with some buildings and trees
0.01	Airport runway areas
0.008	Mown grass
0.005	Bare soil (smooth)
0.001	Snow surfaces (smooth)
0.0003	Sand surfaces (smooth)
0.0002	Water areas (lakes, fjords, open sea)

Figure 5: Look-up table for varying surface roughnesses [2].

Based on these observational insights, we concluded that the wind turbine rule "The higher the better" applied strongly to location (1). We either had to reach the tip of the trees or choose location (2) with open appearance.

3.1.2 Quantitative assessment

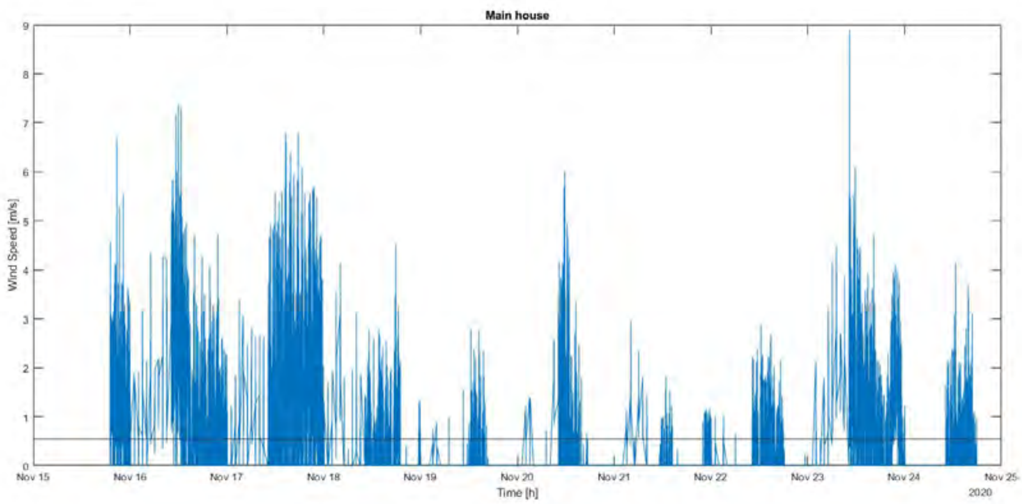

Figure 6: Wind speeds over the course of ten days at location (1), the main house. One can see windless hours during the night and increased activity during the day. Horizontal line indicates the mean wind speed.

We installed anemometers at the main house (1) and barn (2), see figure 4. We chose heights for the anemometers that aligned with the planned tower height. An Arduino micro-controller averaged the speeds every 10 s and saved them to an SD card. Please refer to *this page* for the anemometer code. The quantitative analysis of the wind behavior gave insights into repetitive characteristics and the speed, for which we optimized the wind turbine. The 2020 hurricane season was the busiest hurricane season on record [7] and influenced wind speeds in the beginning of November.

Figure 6 shows a ten day wind behavior measured on top of the main house. We observed windless hours during the night and increased activity during the day. However, the hurricane season influenced night activity from November 16th through November 19th.

Figure 8 shows an anemometer recording from the barn, location (2), after the hurricane season. The readings from the barn anemometer were significantly higher than the recordings from the main house. For the given data collection at the barn, figure 8, we calculated a mean wind speed of 2.2 m/s and a standard deviation of 1.75. In comparison, at the main house, we calculated a mean wind speed of 1.5 m/s on a very stormy day and a standard deviation of 1.2.

Please note that this data collection is incomplete. We ran into technical issues towards the end of the semester and were not able to record wind speeds at the barn over the course of several days. However, our data collection gave us enough insights into the wind behavior at the two potential wind turbine sites. We confidently chose the barn, site (2), as the location for the wind turbine.

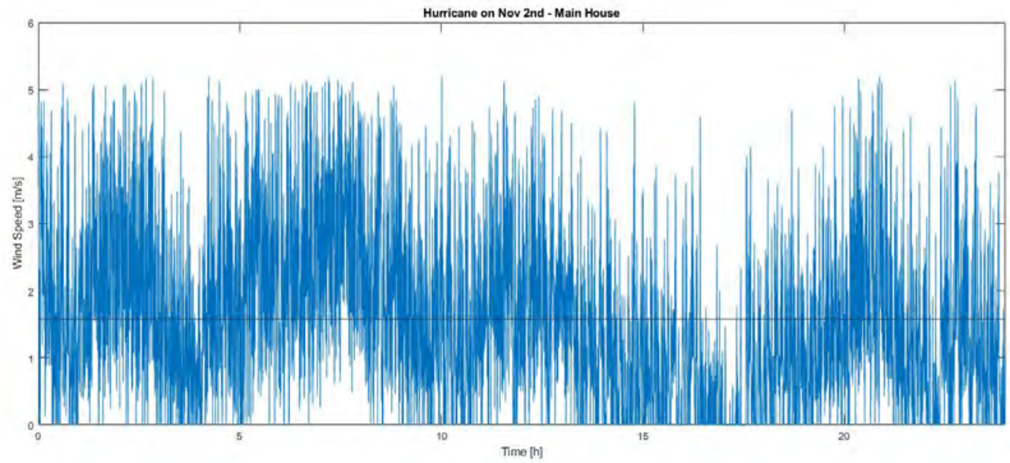

Figure 7: This recording was taken during the light impact of a hurricane at the main house. Horizontal line indicated the mean wind speed.

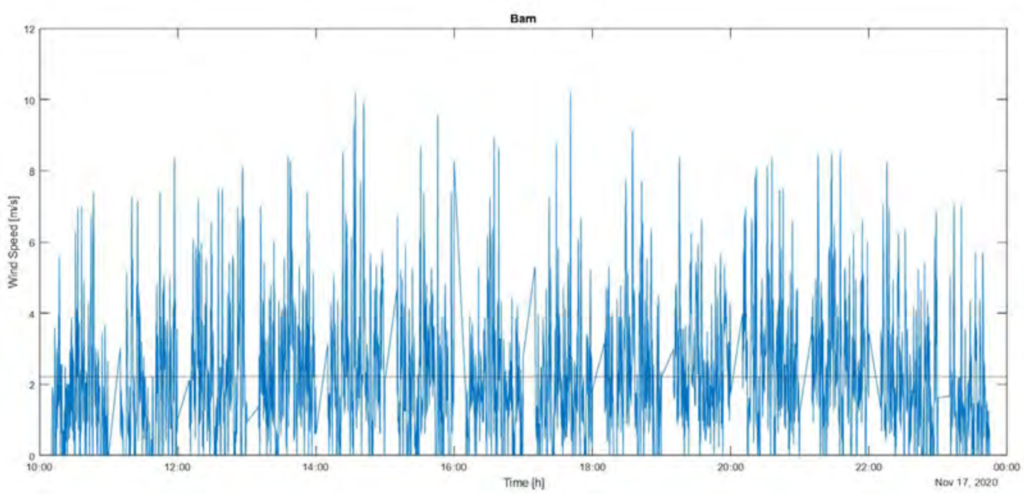

Figure 8: Wind speeds at the barn were higher and also more turbulent. Visible interruptions in the plotted data were due to a coding mistake that created incorrect data savings. Horizontal line indicated the mean wind speed.

3.2 Prototyping

Our site assessment and research insights created a strong tendency towards a twisted VAWT. Drag-based turbines such as the Savonius turbine are easier to manufacture than its lift-based counterpart, Gorlov turbines. We decided to test out the manufacturability of a twisted Savonius turbine and prototyped a small-scale version. We chose a twisted blade design over a regular two-scoop system to reduce shaking.

We used easily-available poly-carbonate roofing sheets to construct the blades. PVC-tubing held the twisted blades in place. Please refer to figure 9 for a photo of the prototype.

Inspired from the WePOWER design, we created a small-scale CAD model in Solidworks of a vertical-axis drag and lift-based turbine that we sought to 3D-print. Such a turbine could be placed

Figure 9: Twisted Savonius turbine prototype with poly-carbonate blades and PVC-tubing.

at the top or bottom of Darrieus design. We logistically failed to order the 3D-prints from Olin but seek to iterate on our design in the following semesters.

Figure 10: WePOWER inspired CAD design of a lift and drag-based prototype. The blades are kept open to rechannel the air.

3.3 System design

The main components of our wind turbine system were the wind turbine tower, shafts, bearings, blades, generator, rectifier, and inverter. We built the small tower on top of a barn to gain extra height. The shaft led through the metal roof to the generator that was located inside the barn. Every wind turbine system converts the force of the wind into torque on a shaft. In our case, we sought to convert the rotation of the shaft into electricity by connecting the shaft to a generator. We aimed to create electrical infrastructure for a study nook in the barn, in which the electrical system of the wind turbine was located.

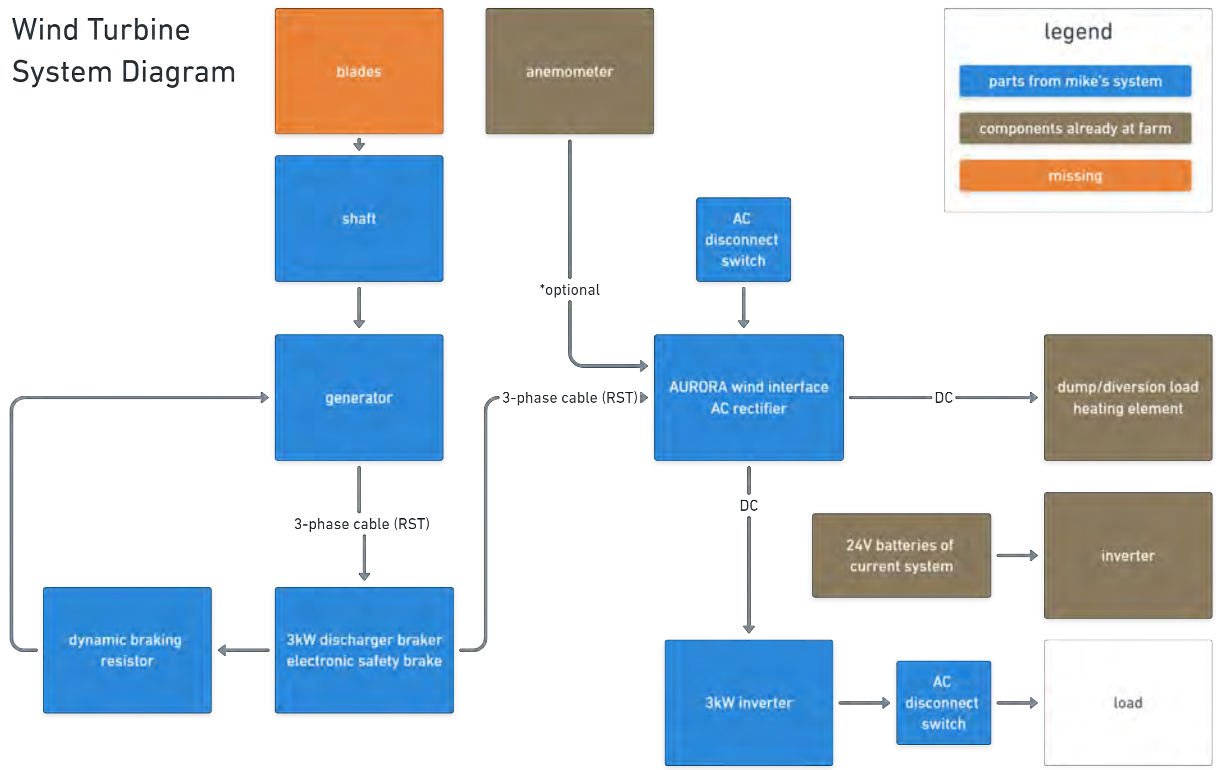

Figure 11: The blades are indicated as missing because their delivery was delayed.

3.3.1 Mechanical design

The mechanical design drew most from our resources in a timely and monetary sense. You can find a detailed table of all the mechanical components below. In the mechanical realm of our design, we had to build a tower to hold the shaft and blade in place, connect the blade construction to the shaft, and link the shaft to the generator. We chose pressure-treated 2x6s for the 1.2 m tall tower and pressure-treated 2x4s for the cross beams. The tower was bolted into the roof's rafters on all four contact points. The lower end of the blades was calculated to be at a height of 5 m. Attached to the tower, a mounted ball-bearing held the shaft in place. The shaft consisted of two pieces to ease disassembly and was a total of 3.66 m (144") long. To prevent rust build-up on the shaft, we chose 304 stainless steel at a thickness of 3.4 mm. At this thickness, the shaft was the biggest investment of the mechanical system. We justified this purchase with the high torque and horizontal forces on the shaft. We built our own shaft coupling with a slightly wider piece of stainless tubing that connected the two shaft pieces.

The hole in the roof posed a threat to the generator and had to be sealed appropriately. A plastic shield for air conditioning propellers came in handy to create the appropriate seal. Another advantage of the two part shaft was the modular assembly of the blades. Smaller stainless steel tubes lead through the upper part of the shaft to hold the twisted blades in place.

The assembly of the blades was delayed due to COVID-19 related delivery difficulties on the supplier's end. The planned span of the blade system was 5.5 ft in width and 6.5 ft in height (1.67 m x 1.98 m). We chose flexible and weather resistant low-density polyethylene to shape the two blades. For peak wind speeds of 10 m/s 1, we estimated the kinetic power on the shaft to be

Figure 12: The tower with the disassembled shaft and anemometer in the background.

around 250 W with a blade efficiency C_p of 12%. For lower wind speeds around 6 m/s, the energy output would drop to 50 W. It is apparent that the our energy ratings for this system are below the electrical system's capacity. However, we intentionally kept the blade size reasonably small to allow for easy adjustments in the future. Please note that this system is not yet finished and a larger blade would only complicate future iterations and increase expenses.

Figure 13: Twisted Savonius concept with low-density polyethylene blades.

3.3.2 Electrical design

The purpose of the elctrical system was to convert the generator's dirty alternating current output to a clean US-outlet appropriate voltage and frequency. An electrical break was part of the electrical system to slow down or even stop the wind turbine when high wind speeds were reached.

The TCMG-3kW Taechang N.E.T. generator outputted an alternating current (AC) to the AURORA wind interface rectifier. The input range for the rectifier was 40-400 Vac. The rectifier converted the alternating current from the generator to an appropriate direct current for the 3 kW inverter ranging from 50-600 Vdc. Finally, the inverter converted the direct current back to a nominal grid voltage of 240 V. This voltage is purposefully higher than the US outlet voltage (110-120 V) to allow for transformation to the appropriate outlet voltage.

The 3kW discharger breaker was connected the generator and a dynamic breaking resistor. When high wind speeds were reached, the discharger breaker took energy from the generator and re-channeled it into the thermal breaking resistor. The resistor dissipated the electic energy that was created from the turbine's kinetic energy resulting in a slow down of the turbine.

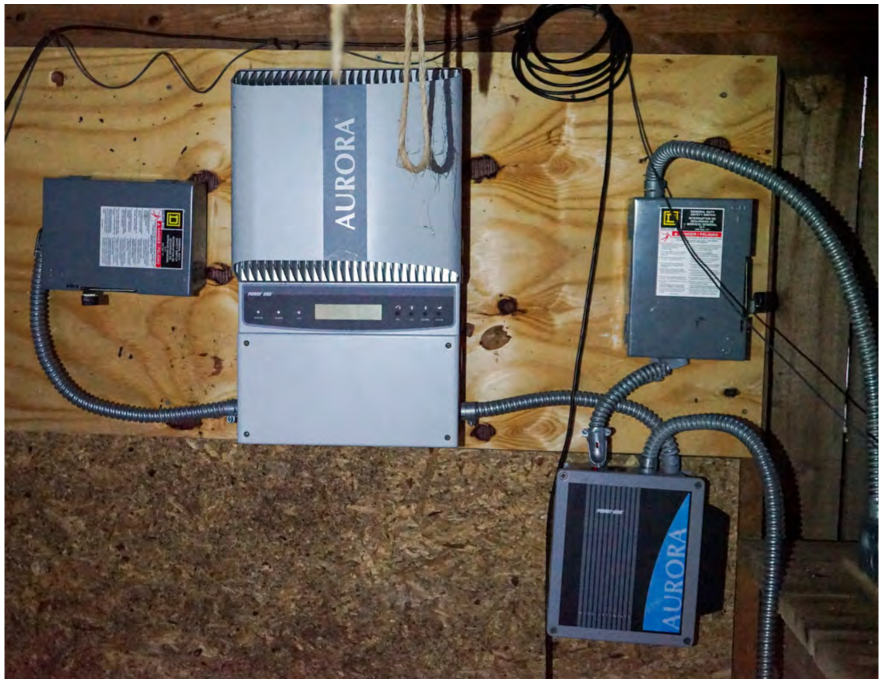

Figure 14: Parts of the electrical system, inverter (middle) and rectifier (lower left).

4 Conclusion and recommendations for continued work

While this report focuses on the technical aspects of our work on the wind turbine system in the fall semester 2020, this project was governed by a variety of real-world factors. Parameters that affected the progress of this project ranged from varying degrees of background knowledge to weather interruptions, labor availability among the student group, external logistics, financial shortages, and what we would call motivational flows and challenges. Therefore, our recommendations start with motivational and planning-related insights but also include technical recommendations.

4.1 How do we work well together?

This wind turbine project was one project among many other projects at Woodland Harvest Mountain Farm. Other projects included the construction and planning of three buildings and a tree house, the installation and maintenance of the micro-hydro and solar system, feeding our group with delicious foods, maintaining the garden and harvesting vegetables, as well as a variety of class-commitments and personal projects. This dynamically complex web of interests and energy resources lead to a tricky operational landscape for the wind turbine project.

The first half of the semester focused on research and acquisition of background knowledge, which lead to low engagement with the larger group on site. We believe that we should have introduced students earlier to this project. Furthermore, we should have assigned clear tasks to students to allow for a structured work flow. We noticed that the productivity of our group decreased when we showed them a list of project goals and asked them to choose one themselves. Such an approach seemed to be appropriate when the student was already heavily involved in the project but only intimidated and disengaged newly introduced students.

The creation of a timeline was useful for the head of the project but only created stress among other students when the timeline was not met. We recommend to keep negative feedback loops as far away from students and emphasize accomplishments over delays.

We further noticed that clear documentation is crucial. Documentation was oftentimes seen as a drag along the way to the finalized project. However, reasons behind decisions, component sources and sizes, and surrounding calculations are especially important to future students that will continue the work on this system.

4.2 Technical recommendations

For future work on this project, we recommend to focus on the blade design. The current Savonius design makes use of the air drag on the blades. However, Savonius turbines are among the least efficient turbine concepts. In the fall 2020 semester, we failed to prototype blades to combine Gorlov or Darrieus blades with the Savonius turbine. Such blades can be twisted (Gorlov) or straight (Darrieus). If several straight blades are arranged in a circular pattern, vibrations can be limited or even eliminated. The WePOWER turbine, figure 3, incorporates such a design and even uses a combination of both drag and lift. We further recommend to have a 3D-printer on site to dynamically prototype the blades.

On the electrical side, the system's output electricity needs to be adjusted for the US-outlet voltage and all electrical components need to be labeled. Clear instructions and documentation on all equipment pieces are necessary to allow for safe maintenance and improvements. Elaborate documentation should take place on the wiki page for this project (*wiki.olinatwoodlandharvest.com/index.php/Wind_turbine_system*).

Other recommendations for future work include an upgraded data logging system. To allow for insightful data collection, the bug in the anemometer code needs to be fixed and the wind direction sensor should be installed. Even though our turbine is direction-indifferent, direction data could be useful to determine a new wind turbine location in case the system needs to be moved.

Fluids analyses should be performed on all CAD models including the WePOWER-inspired design from figure 10.

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A Component and cost tables

Mechanical system			
Component	Description	Cost	Link
96” shaft	1.5” OD x 0.134” Wall x 1.232” ID Stainless Round Tube 304 Seamless	$216.82	onlinemetals.com
48” shaft	1.5” OD x 0.134” Wall x 1.232” ID Stainless Round Tube 304 Seamless	$142.15	onlinemetals.com
12” shaft couping	1.75” OD x 0.12” Wall x 1.51” ID Stainless Round Tube 304 Welded	$33.02	onlinemetals.com
Tower lumber	2-in x 6-in x 12-ft 2 Prime Pressure Treated Lumber	$26.54	lowes.com
Ball bearing	Mounted Ball Bearing with Nickel-Plated Iron Housing for 1-1/2” Shaft Diameter	$71.49	mcmaster.com
Blade sheets	1/16” x 48” x 96” LDPE Sheet	$109.94	usplastic.com
3x 84” Blade rods	0.5” OD x 0.035” Wall x 0.43” ID Stainless Round Tube 316 Welded	$46.2	onlinemetals.com

Electrical system			
Component	Description	Cost	Datasheet/manual
Generator	TCMG-3kW Taechang N.E.T. Generato	donated	online specs
Wind interface	Aurora wind interface box/rectifier	donated	manual
Inverter	Aurora 3kW inverter	donated	general specifications
Dynamic braking resistor	3kW Dynamic Braking Resistor	donated	manual
Electronic brake	3kW Discharger Breaker - 3K-DIS-001	donated	

Anemometer data logging system			
Component	Description	Cost	Datasheet/manual
Arduino	TCMG-3kW Taechang N.E.T. Generato	$18.99	amazon.com
Anemometer	Mechanical relay Inspeed Vortex wind sensor	donated	old.inspeed.com
Windsock	4o inch windsck	$10.99	
Wind direction sensor	Wind Direction Sensor 5v DC Supply 0-5v Voltage Output	$75	amazon.com
Handheld anemometer	BTMETER Digital Wind Speed Anemometer Handheld BT-100APP	$35.99	amazon.com

B Coursera wind energy certificate

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COURSE CERTIFICATE

Nov 10, 2020

Leon Santen

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Merete Badger, Alma Salnaja, Lars Pilgaard Mikkelsen , Ameya Sathe, Vladimir Fedorov, Tom Cronin, Torben Krogh Mikkelsen, Morten Hartvig Hansen, Niels-Erik Clausen, Bonnie Ram, Sven-Erik Gryning, Kim Branner, Poul Ejnar Sørensen, Hilmar Kjartansson Danielsen, Henrik Bredmose

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Completed by **Leon Santen**

November 10, 2020

5 weeks of study, 7-8 hours/week

Grade Achieved: 93.54%

Leon Santen's account is verified. Coursera certifies their successful completion of Wind Energy