MAE 4344 - INTERDISCIPLINARY SENIOR DESIGN

FINAL REPORT

THE

VERTICAL AXIS WIND TURBINE TEST BED

PROJECT

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1. Introduction

We are **Passing Wind**, an Interdisciplinary Senior Design group for the College of Engineering, Agriculture and Technology at Oklahoma State University. Our team consists of two Mechanical Engineers and two Electrical Engineers. We are committed to working together to combine our talents and create a functional test bed containing both a vertical axis wind turbine and power generation / analysis system. Our logo can be seen below.

2. Product Description

The aim of this project is to design a vertical axis wind turbine test bed, containing a power system and learning module for energy storage and analysis that will be housed on a mobile cart. Using our test bed, students and other CEAT patrons will be able to view live generation of power and implementation of electrical components as a demonstration and teaching tool for the MAE and ECEN departments.

3. Overall Solution and Subsystems

3.1. Overall Design

Our overall design consists of a vertical axis wind turbine mounted on a cart, turning wind power from our standing industrial fan into electricity through the attached gearbox and generator setup. Our power system analysis components will be below the top of the table on the metal shelf as shown. The entire design has plexiglass walls for safety.

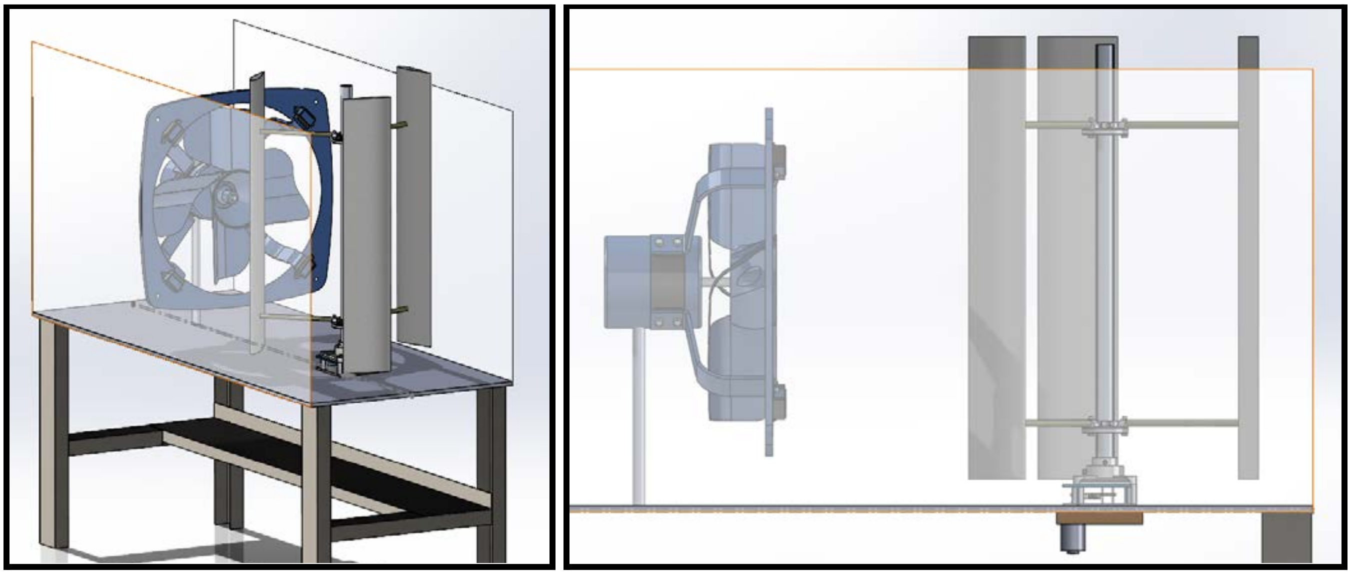


Figure 1: Overall Design of the cart, turbine, gearbox attachment, and a generic fan created in SolidWorks.

3.2. Generator

Choosing the generator was one of the first tasks of this project. The generator provides the link between the mechanical and electrical systems. It was important that this was considered first to allow both parts of the team to continue working. Based on our constraints and project description, we chose a generator that would output 36W. Because we purchased a generator and not building it ourselves, this limited our options. Many of the larger wind generators produce 3 phase AC power. With a limited power generation constraint, our selection was brought down to DC. This was ideal for our system because of our necessity to charge a 12V DC battery. We chose a Permanent Magnet DC generator because of the cheap cost and the ability to use the generator as a motor. The ability to use the generator as a motor is very important to our design. This function allows us to use the battery as a power source for the motor. In short, this functions as a bump start.

3.3. Fan

Our fan was the beginning of most of our turbine calculations as the theoretical power generated depended on how much air we could throw at our turbine. The most cost effective and highest CFM fan we could find was a Tornado 24in Heavy Duty fan with a CFM of 7800 on its highest setting. This fan's size and power fits fine into our design and has not caused any considerable constraints.

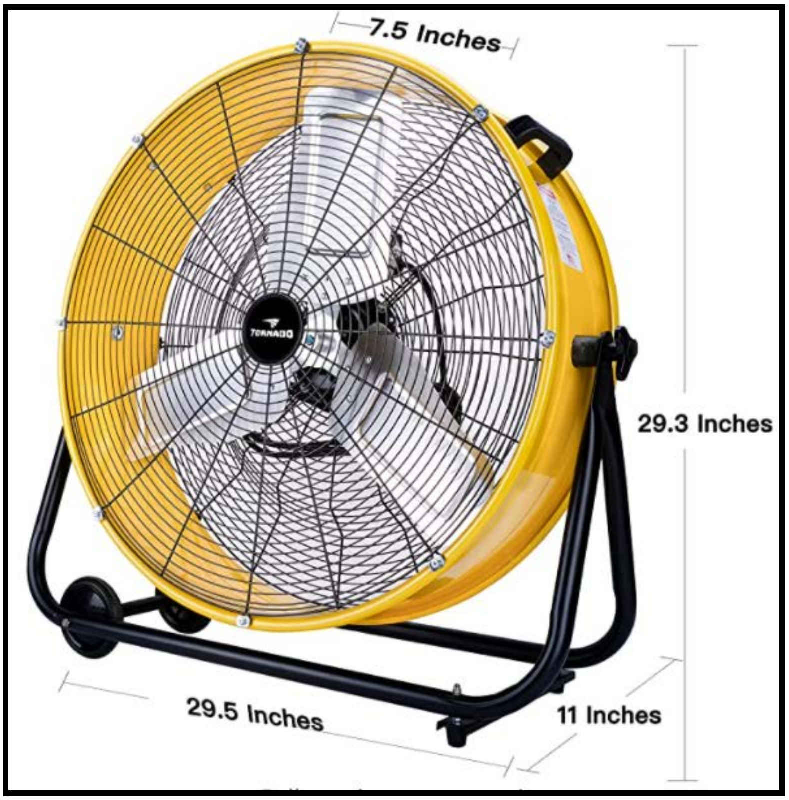


Figure 2: Tornado 24 inch Heavy Duty Fan.

3.4. Cart

The Cart was another prime factor in our design as it needs to be able to house and hold every single component within our project and be able to display it to the public well. Shipping time and price was a huge constraint here as we wanted a quality workbench from a reliable supplier. We chose a width of 30in so that there is a 3in clearance on each side for maneuverability through doors, and we chose a length of 72in to give plenty of room and space for air to flow onto our airfoil turbine blades efficiently. The Cart is also adjustable to a lowest height of 30in, giving us 48in of room for our turbine from the top of the cart table to the top of the door opening.

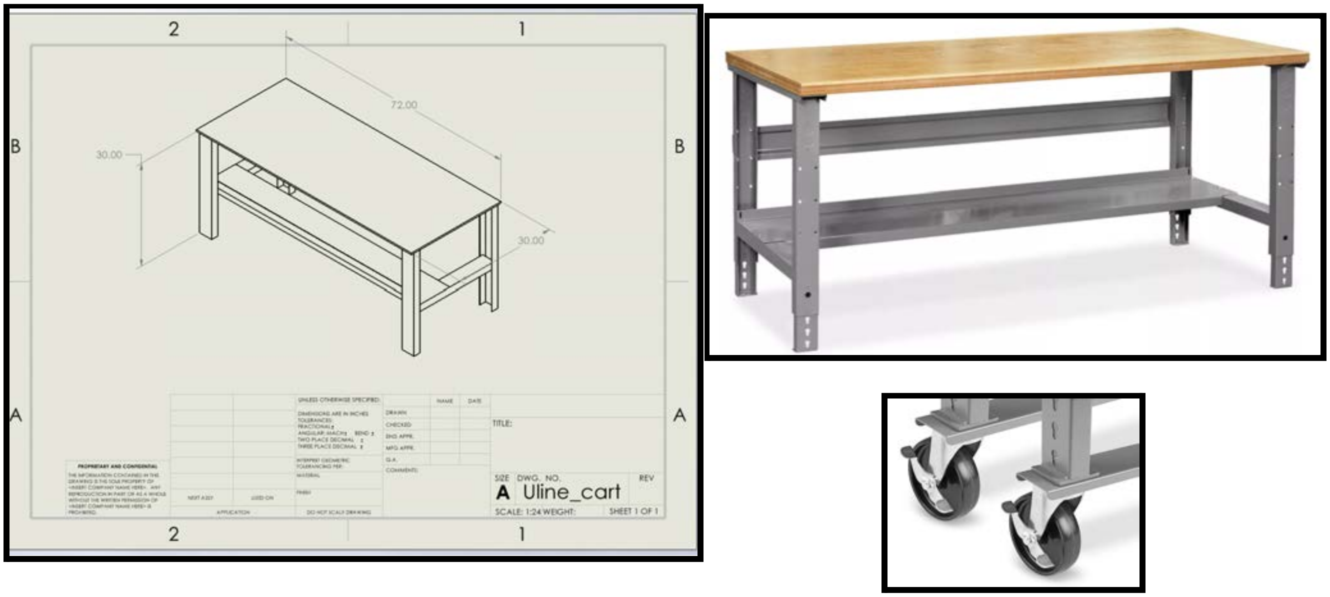


Figure 3: Drawing of cart, picture of cart and attachable casters.

3.5. Airfoils (Design / Material & Fabrication)

The airfoils chosen for this project needed to be suitable for the speeds that we would be controlling for our turbine, while still creating enough lift force to rotate the shaft. While following the design for a straight bladed vertical axis wind turbine (SB-VAWT).The S1046 profile was selected due to better aerodynamic characteristics and ease for manufacturing.

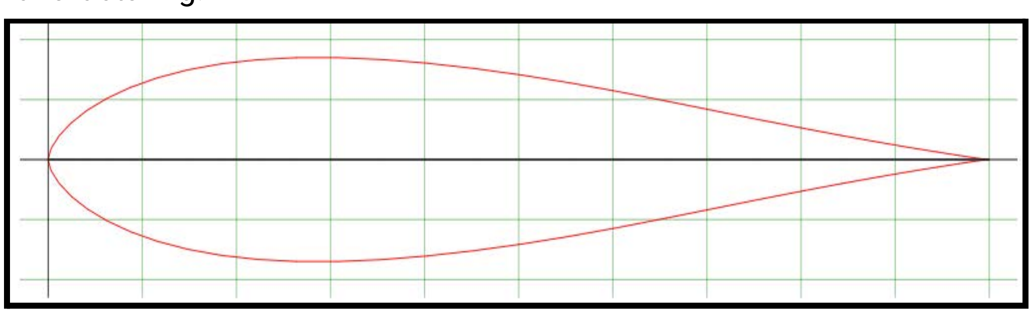


Figure 4: S1046 airfoil profile.

The sizing of the airfoils was estimated based on the speed of the wind that we could produce with our fan, which was rated for 7800, 6000, 5000 CFM for the High, Medium and low settings respectively. Using the volume flow rate and the cross sectional area of the fan we calculated the velocity of the air that would be moving through the fan for each of the three speeds. Using **equation 1** the swept area (A) of the turbine was found using: the coefficient of performance (C_p), air density (ρ), wind velocity (v). The results and assumptions used are shown in **figure 5**.

$$P_W = 0.5 * C_p * \rho * A * v^3 \qquad \textbf{(1)}$$

diameter (in)	24	radius (in)	12
Fan speed	High	Medium	Low
CFM	7800	6000	5000
Velocity ft/s	17.24	13.26	11.05
Velocity m/s	5.2553	4.0425	3.3688
Swept Area (m2)	1.0124	1.5079	2.6057
Swept Area (ft2)	10.8972	16.2313	28.0476
Radius (ft)	1.8624	2.2730	2.9879
Diameter (ft)	3.7249	4.5460	5.9759
Height (ft)	2.9255	3.5704	4.6935

Rated Power (W)	36
Density of air (Kg/m3)	1.225
Assume Cp	0.4

Figure 5: Excel calculations for airfoil sizing.

Due to our cart dimensions the estimated size of our turbine was too large to be housed on the cart and still be able to adhere to ADA requirements. Therefore, we kept the diameter at a fixed size that would allow room on each side of the turbine for the enclosure and calculated the height based on the same area. Shown in **figure 6** is the heights that correspond to each of the wind speeds. With a cart height, including casters, around 36 inches the calculated heights of the turbine combined with the cart greatly exceeding the constraints we have for ADA door height requirements. The only option was to reduce the height and plan to fine-tune our turbine in testing to reach our rated power.

Diameter (ft)	2	2	2	Fixed due to cart size
Height (ft)	5.45	8.12	14.02	
Area (ft2)	10.897	16.231	28.048	

Figure 6: Excel Calculations for airfoil sizing with a fixed diameter.

Using research journals on VAWTs we were able to determine a suitable cord length for our design size and wind speed using **equation 2** with: a target solidity (σ) around 1.1~1.28, a radius (R) of 12 inches, and number of blades (N_b) being three. The cord length found was around 4.80 inches.

$$c = (\sigma * R)/N_b \qquad \textbf{(2)}$$

Now with the estimated dimensions a solidworks model was made using all the values found.

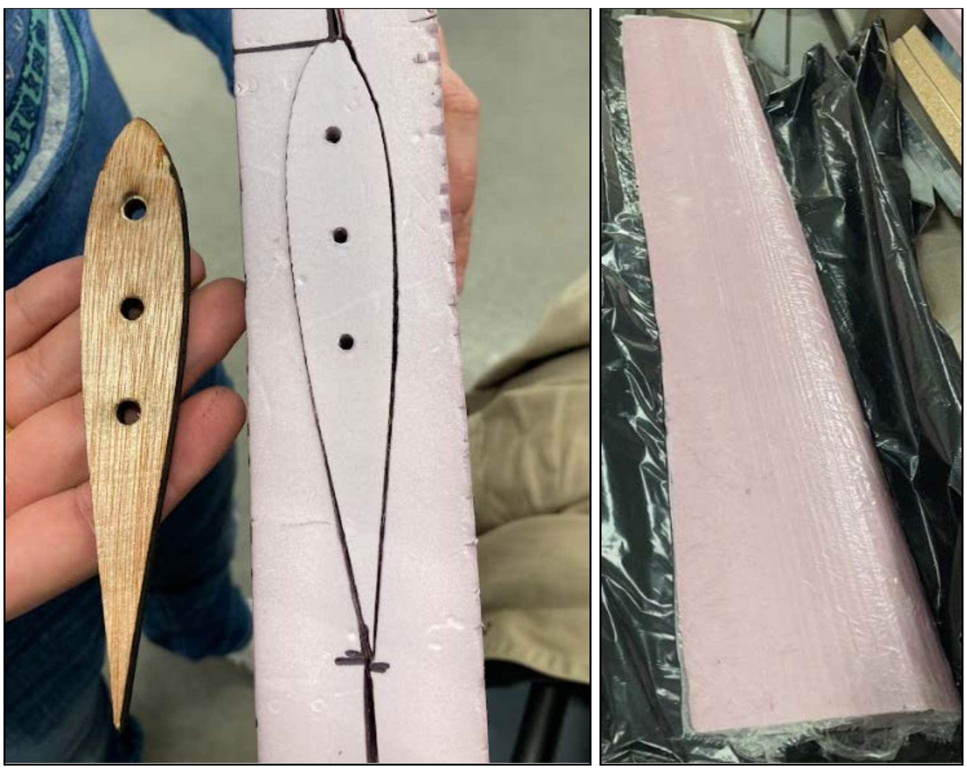


Figure 7: Laser etched airfoil profile, and finished airfoil.

With the airfoils having a design in place we sought the advice of Dr. Joe Conner at OSU for the material selection and fabrication information. We were advised to use a Hot Wire foam cutter as well as high-density foam to create the airfoils. Shown in **figure 8** is the airfoils being cut using a similar hot wire bow.

Figure 8: Using a hot wire bow unit to cut airfoils out of foam. **[1]**

The airfoils will have two layers of fiberglass epoxied onto the surface to help with fatigue and tensile strength. Lightweight fiberglass cloth was selected and Z-Poxy finishing resin was selected from recommendations of online airfoils hobbyists. In the figures below, the method for fiberglassing airoils is what we followed.

Figure 9: Method of applying fiberglass cloth with epoxy and curing airfoils. **[2]**

Through the airfoil Solidworks part, we were able to get the volume and surface area of the airfoils. Using these values we were able to estimate how much cloth and epoxy we needed to cover our airfoils, as well as the weight of each airfoil. Shown in **figure 10** are the final selected dimensions of the airfoils.

Final Dimensions-Airfoil		
Number of blades	3	unitless
Diameter	2	ft
Height	3	ft
Cord length	6.00	in
VAWT aspect ratio	3.00	unitless
Blade aspect ratio	6.00	unitless
Airfoil volume	88.56	cubic in
Airfoil surface	361.17	sq in
Foam Density	1.30	lb/f3
Fiberglass weight	0.75	oz/sq yd
Airfoil weight	0.093	lb
Airfoils weight	0.278	lb

Figure 10: Final dimensions of airoils.

3.6. Shaft

The shaft analysis was done based on the needed revolutions per minute (RPM) for our power generation. The first step was to use **equation 3** to calculate the tip-speed ratio (λ) (TSR) and then find the RPM with **equation 4**. After that, the torque (τ) was found using **equation 5**, which was used to find the shear stress (τ_{xy}) with **equation 6**. The variables not mentioned and are used in the equations below are: wind velocity (U_∞), radius (R), diameter (D), and Power output of turbine (P).

$$\lambda = \omega * R/U_\infty \quad \textbf{(3)}$$

$$RPM = 60 * U_\infty * TSR/(\pi * D) \quad \textbf{(4)}$$

$$\tau = (P/RPM) * (30/\pi) \quad \textbf{(5)}$$

$$\tau = (\pi/16) * \tau_{xy} * D^3 \quad \textbf{(6)}$$

The shaft stress was calculated with varying diameter to find an allowable stress for our design. Shown in **figure 11 & 12** is the shear stress in the high wind setting and low wind setting.

Diameter	2	ft						
Wind velocity	17.24	ft/s	High speed	Assuming no losses				
angular velocity	0.09	0.86	2.16	4.31	4.46	6.47	8.62	
TSR	0.01	0.1	0.25	0.5	0.517	0.75	1	
RPM	1.65	16.46	41.16	82.32	85.12	123.49	164.65	
RPS	0.03	0.27	0.69	1.37	1.42	2.06	2.74	
Torque (N-m)	208.795	20.880	8.352	4.176	4.039	2.784	2.088	
Diameter (in)	0.01	0.02	0.03	0.04	0.05	0.06	1	1.5
Diameter (m)	0.000254	0.000508001	0.000762	0.001016	0.001270003	0.001524	0.0254	0.038100076
Shear stress (Na/m2)	6.49E+13	8.11E+12	2.40E+12	1.01E+12	5.19E+11	3.00E+11	6.49E+07	1.92E+07

Figure 11: Shaft analysis for high wind setting.

Wind velocity	11.05	ft/s	Low Speed					
angular velocity	0.09	0.86	2.16	4.31	4.48	6.47	8.62	
TSR	0.01	0.1	0.25	0.5	0.52	0.75	1	
RPM	1.06	10.55	26.38	52.76	54.55	79.14	105.52	
RPS	0.02	0.18	0.44	0.88	0.91	1.32	1.76	
Torque (N-m)	325.792	32.579	13.032	6.516	6.302	4.344	3.258	
Diameter (in)	0.01	0.1	0.2	0.3	0.4	0.5	1	1.5
Diameter (m)	0.000254	0.002540005	0.00508001	0.00762	0.01016002	0.0127	0.0254	0.038100076
Shear stress (Na/m2)	1.01E+14	1.01E+11	1.27E+10	3.75E+09	1.58E+09	8.10E+08	1.01E+08	3.00E+07

Figure 12: Shaft analysis for high wind setting.

As seen, a diameter of 1.5 inches was selected and Aluminum 6061-T6511 was selected for the material, as it is able to withstand the load with a general factor of safety around 2. We bought the 1.5" aluminum shaft from *OnlineMetals.com* with a height of 4 feet, which does exceed our height, but we are planning on cutting a section off in order to do material tests to find the actual properties for our shaft. **[3]**

3.7. Fittings

The main proprietor of our design comes from our mounted ball-bearing with four-bolt flange. It is what holds our shaft to our gearbox and allows rotation. Our fittings are all sourced from *McMaster-Carr*, and are pretty standard when it comes to fasteners and screws. **[4]** Our screw and nut choices were picked specifically due to their vibration resistant design. Specifically our barbed inserts being serrated, to then be inserted into the fiberglass and foam to hold the airfoils to the carbon fiber tubes (strut bars). To hold our strut bars to our shaft, we are using two flange mount shaft collars and custom 3D printed strut-collar attachments to fasten to our shaft and have three strut bars going out from each collar to the airfoil. Our final unique fitting was using an aluminum locking rivet nut specifically for soft materials to mount our airfoils to our custom strut bars.

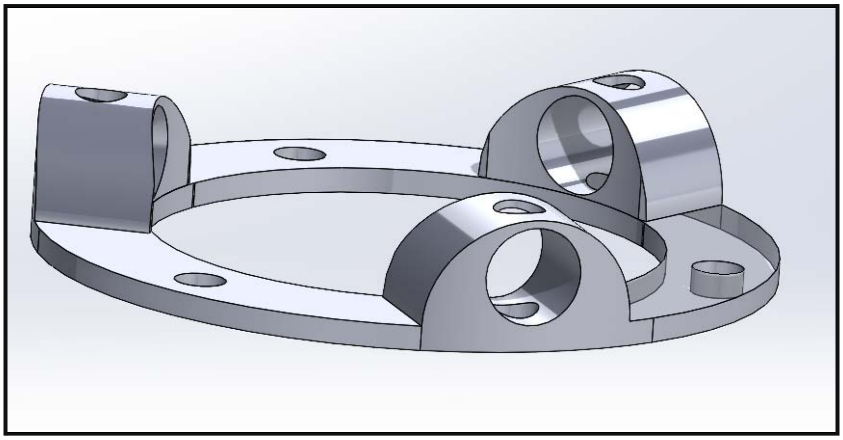


Figure 13: 3D Printed strut-collar attachment

Figure 14: Carbon fiber strut bar, Strut-collar attachment, and Flanged Shaft Collar assembly as well as flanged bearing

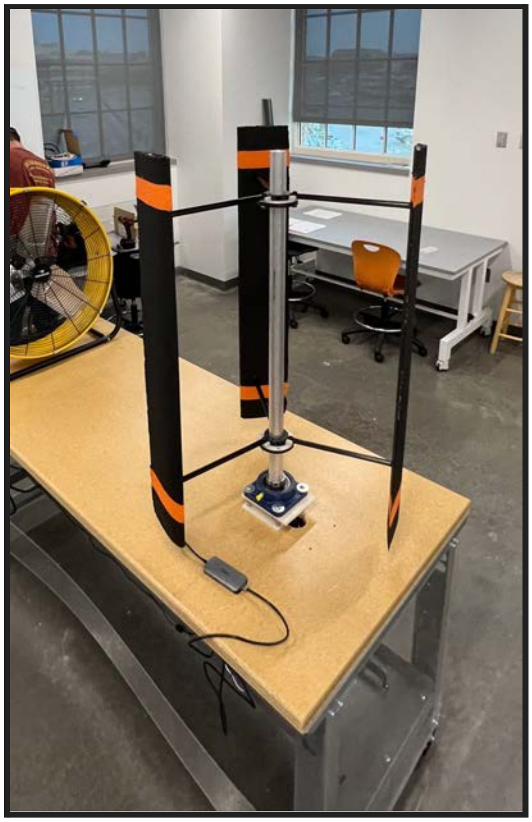


Figure 15: Strut bar assembly into Airfoils, showing locking rivet nut attachment.

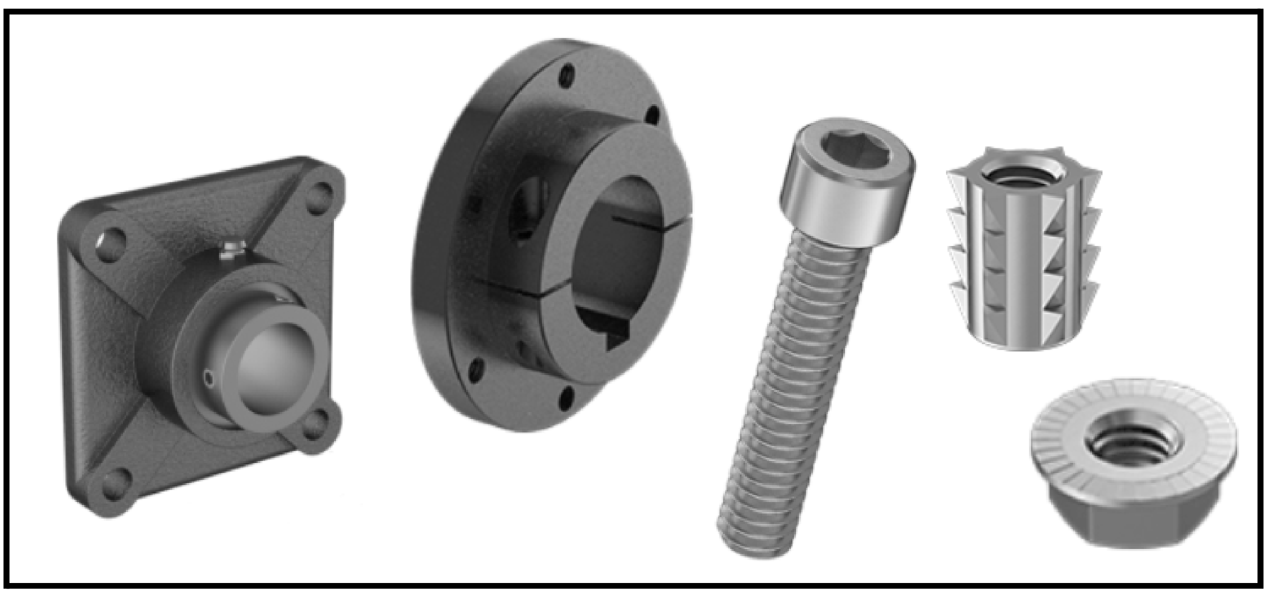


Figure 16: From left to right (Mounted Ball Bearing with Four Bolt Flange, Flange Mount Shaft Collar, Zinc-Plated Alloy Steel Socket Head Screw, Barbed Insert for Soft Materials, Steel Serrated Flange Lock Nut). [4]

3.8. Gearbox / Drivetrain

Our gearbox contains a set of 4 gears, all of which came with our generator and are rated for its 2600 RPM. We have created a custom gearbox consisting of a 3D printed high strength plastic top and bottom plates that will house the mounted flange bearing and sequential gearset. Each gear will be housed on its own vertical shaft with two bearings on each end to allow the gear to rotate. The biggest gear shaft however will have only one bearing on the bottom and a left handed screw thread on the top to allow secure fastening to our Turbine shaft. This design creates a 42.9:1 gear ratio, allowing our ~1 RPS turbine to achieve a rated ~2600 RPM at our generator.

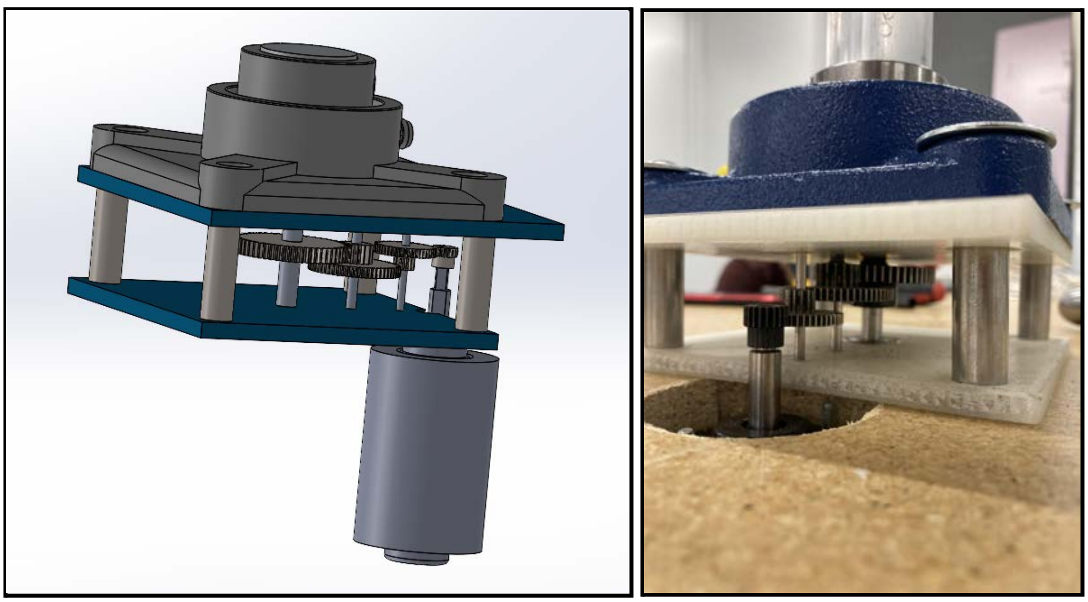


Figure 17: Gearbox assembly with mounted flange bearing, gears w/ gear shafts, 1.5” spacers, and the generator.

3.9. Control Diagram

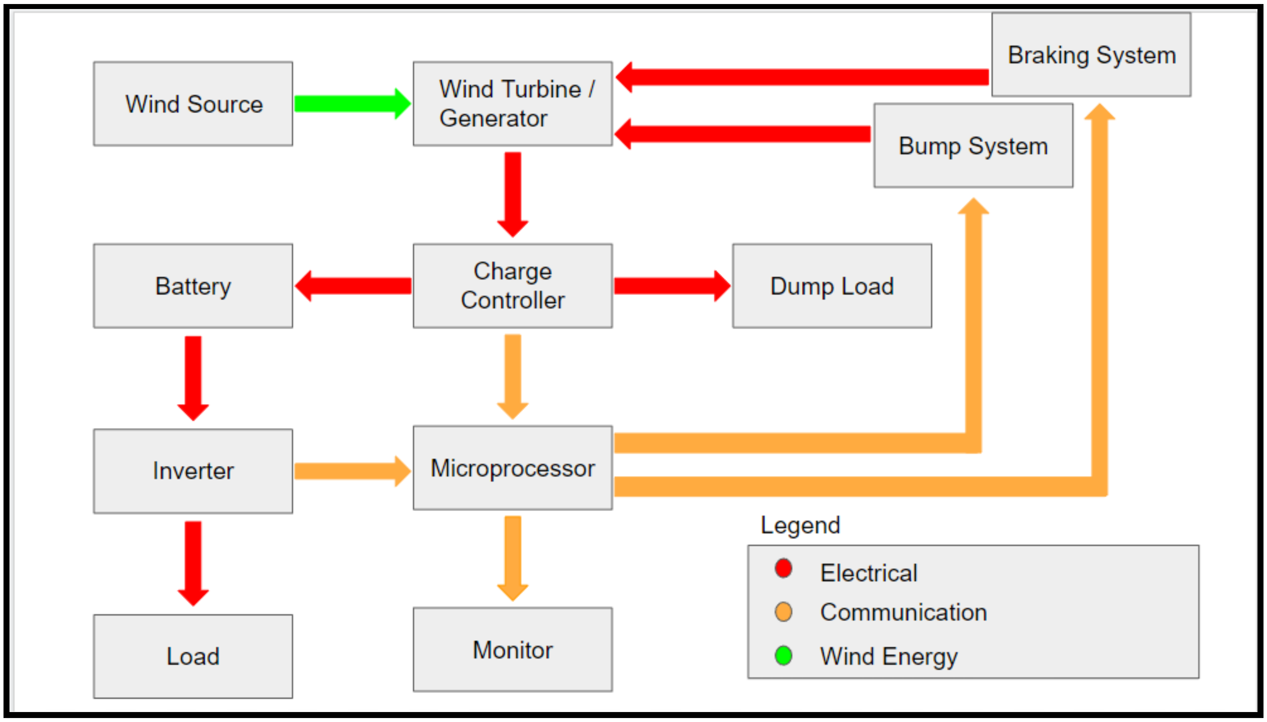


Figure 18: Control Diagram for all systems involved in project

3.10. Charge Controller & Wiring Diagram

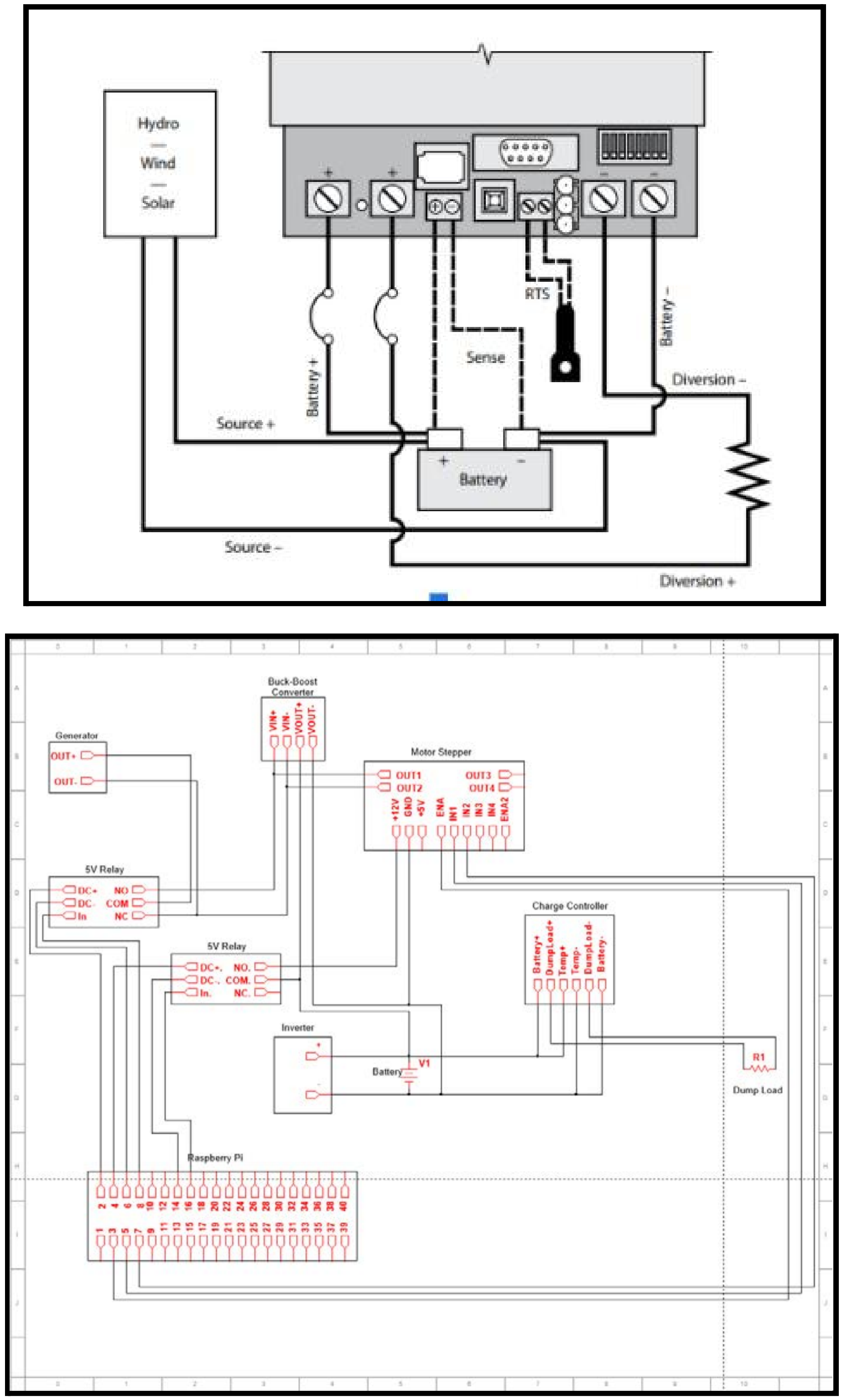


Figure 19: Charge controller example and the wiring diagram.

The charge controller that we selected is the Morningstar Tristar 45 Amp PWM controller. A charge controller is necessary for our design to protect the battery from overcharging. When the battery is full, the charge controller diverts excess current away from the battery. This power is then dissipated in the form of heat. The TS-45 controller comes ready for use in a wind turbine system. As can be seen from the charge controller diagram above, the generator was placed in a direct line of contact with the battery. To ensure that current will flow to the battery, a buck-boost converter was placed in between them. This raises or lowesr the generator output voltage to an appropriate battery charging voltage while altering the current. This converter also prevents the battery from powering the generator and becoming a motor system.

The Tristar charge controllers also come with MSView. MSView is a software available for tristar products that analyzes power. This software will measure voltage and current inputs and outputs. A simple ethernet connection to a monitor allows access to this software. The TS-45 also has customizable settings. DIP switches control the functionality of the charge controller. There are three functions of the controller: Solar, Load, Diversion Load. The function that we used for our system is diversion load. The DIP switches also control the voltage applied to the battery. WIth a microprocessor, these settings can be fully customizable using Modbus.

3.11. Heat Generation

During the process of the demonstration, heat is generated from various components of the system. One of the main sources of heat generation is the dump load. The purpose of the dump load is to ensure that a load is present on the generator at all times. Because of the charge controller configuration, a dump load is also necessary to prevent overcharging of the battery. When the battery becomes full, the charge controller opens a path for the current to flow into the dump load resistor. The resistor then dissipates the power into heat. We calculated the worst case amount of heat using a simple conversion into BTU/h **(7)**. This number can then be used to calculate the necessary airflow to prevent an excess rise in temperature **(8)**.

$$P(BTU/hr) \ = \ 3.412141633 \ x \ P(W) \qquad \textbf{(7)}$$

$$Q \ = \ Cp \ x \ \rho \ x \ q \ x \ \Delta T \ x \ 60 \qquad \textbf{(8)}$$

In **equation (7)**, P(W) represents the power in Watts and P(BTU/hr) represents the british thermal units per hour generated by the resistor. **Equation (8)** uses C_P (specific heat in BTU/lb ^{O}F), p (air density in lb/ft^3), q (measured airflow in CFM), and ΔT (change in temperature ^{O}F) to calculate Q (heat flow in BTU/hr). A quick manipulation of this equation allows us to calculate the CFM required for a specific change in temperature using **equation (9)**.

$$q \ = \ \frac{Q}{Cp \ x \ \rho \ \ x \ \Delta T \ x \ 60} \qquad \textbf{(9)}$$

For our system, we determined that a temperature increase of 10^{O}F was acceptable and appropriate for our design. Inserting this in for ΔT allows us to calculate a CFM of 56.83. For simplicity, we would have used a small fan of 60 CFM. This is very easy to achieve using small usb fans. These fans would be connected to the Raspberry Pi for power and control. Doing this will allow the fans to automatically be turned on when the system is in use. The electronic shelf located underneath the cart will also be well ventilated to ensure that any other sources of heat can be dispelled. One other source of heat was the charge controller. However, the charge controller power consumption is negligible. The charge controller also comes with its own heat sink.

Ultimately, we determined that the total heat generation for this semester was negligible. The main reason for this conclusion was that the battery was never going to be fully charged. Therefore, the dump load would never be dissipating any power into heat. While testing, we found that the motor drive controller generated a lot of heat while connected to the battery. The heat generation happened whether the controller was being used or not. Instead of adding fans to cool the controller, we opted to prevent the heat generation. To do this, we implemented a relay to control when the motor drive controller was connected to the battery. Doing so prevents power from being delivered and wasted by the motor drive. A simple addition to the code closes the relay connection immediately before a bump start command is issued. The connection is opened directly after the bump start is completed.

3.12. Brake System

To demonstrate a general turbine system, we implemented a braking system. Braking systems in wind turbines are necessary to prevent the generator from reaching dangerous rpm’s. While charging up a battery, the generator acts under a load. This requires a higher input torque. However, when the battery is full and no charge is flowing to it, this load is removed. A generator with no load is allowed to spin freely. This becomes dangerous as wind speeds increase. One method that we’re using to prevent this is a dump load. A dump load is a load that receives excess current (power) that cannot be delivered to the battery. When the battery becomes full, the charge controller diverts the excess current into the dump load. The dump load then dissipates this power into heat. This only works to prevent the turbine from moving freely.

The second method that we are implementing works along the same principle. The other way that we will be braking the generator is by shorting the generator output wires. By shorting the wires, the generator is put under an extremely large load. For some generators, this acts as an immediate brake that will not allow any more movement out of the generator. For others, such as our PMDC, this slows down the rpm significantly. With no input torque, such as that coming from the wind, the turbine will quickly come to a halt. Although this braking method is quite limited, we deemed it appropriate because we control the wind input. We used a 5V relay to control the shorting of the output leads. This relay is controlled by the Raspberry Pi using one of the 5V pins and a Run function. The relay was configured such that the short occurs in the Normally Closed port of the relay. In order for the braking system to not occur, the Pi must output high. When the Raspberry Pi outputs low, the leads will be shorted. This serves as an emergency braking system. If power to the system were removed, the turbine would automatically experience braking.

In an external environment, where wind speeds can reach dangerous levels, a turbine would require an external brake. These can be in the form of electromagnetic brakes or mechanical brakes. The idea of an electromagnetic brake was considered. However, the limited size of our turbine didn't allow for a bulky external brake. These brakes are also not widely sold to individual consumers by third party vendors. This means that we would have to manufacture the brake ourselves. The final reason for not building an electromagnetic brake was the weight. To improve efficiency of the system, it was desirable to design the turbine to be as lightweight as possible. An external brake would add a considerable amount of weight to the shaft due to the brake drum and magnets required. This would actually help the braking system to be more effective, but would decrease the power efficiency of the system. Building a small electromagnetic brake would be a large and unnecessary task.

3.13. Wire Sizing

The size of every wire in our system was determined by a worst case scenario. This was to prevent any damages or hazards in the case of unforeseen circumstances. Our wire sizing also took into consideration the extra modules that will be added to the system in the future. Currently, part selection and wire sizes were designed to allow up to five total modules. The additional modules will contain individual turbines and generators. Common wires that are shared by all modules have a total amperage rating greater than the maximum current output of one generator multiplied by five. However, if a total of five modules were implemented later, it is advisable to change the common wires to a larger gauge. We used 18 AWG wire for the entire electrical system. Mostly, this was due to the availability factor. The wire that we used can sustain a five module system, but the ampacity would be close to its limit. This could result in a voltage drop across the system. Individual modules have limited space due to the size restraints of the project creating short wire connections. Short wires can slightly exceed normal ampacity without experiencing a large voltage drop. Additional modules will require extended wire lengths which favors the use of larger wires.

We followed the CEAT IDD Color Schemes on the Interdisciplinary Canvas page. Our system is largely DC. The color scheme is as follows: red (DC +), black (DC -), misc. (Control).

3.14. Bump Start & Circuit Diagram

We used the Qunqi L298N Motor Drive Controller to act as an interface between the DC motors and microprocessor (Raspberry Pi 4), because the motor requires a high amount of current since the microprocessing works on low current signals. So, the function of motor drivers is to take a low-current control signal and then turn it into a higher-current signal that can drive the motor. In other words, the bump start will start the generator motor inorder to rotate the airfoils in the desired direction without the help from the fan. Where as the raspberry pi is used to control motor speeds, torques, and rotating direction of our motor generator while our battery acts as power supply and ground for both devices because the raspberry pi can not provide enough current to rotate the generator itself.

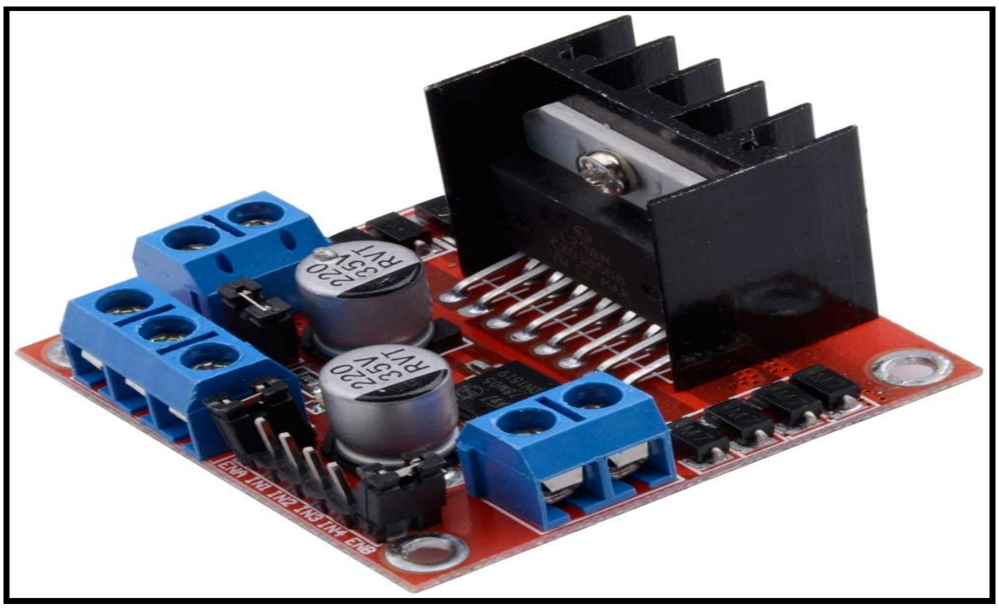


Figure 20: Motor Stepper

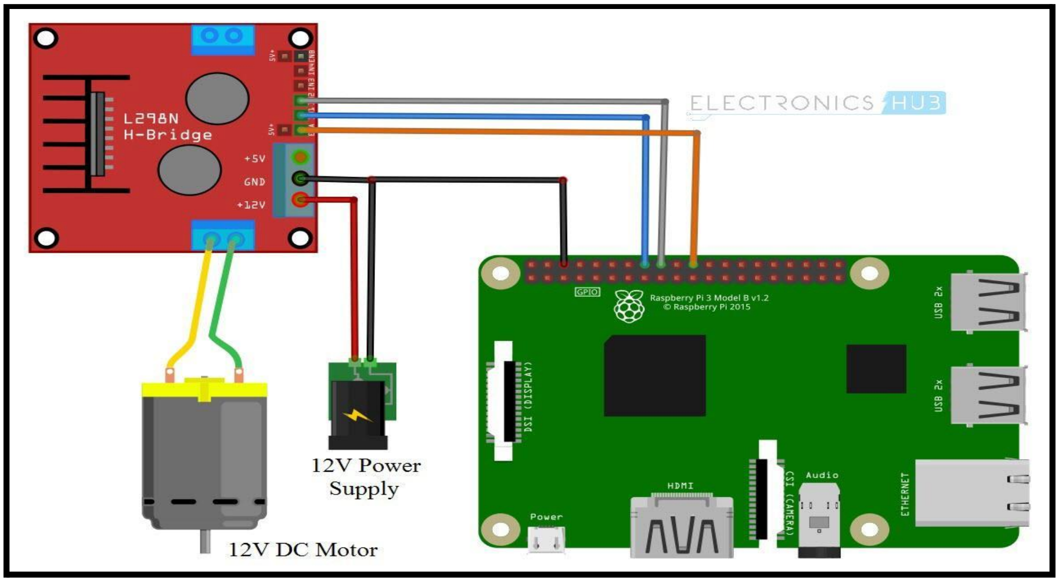
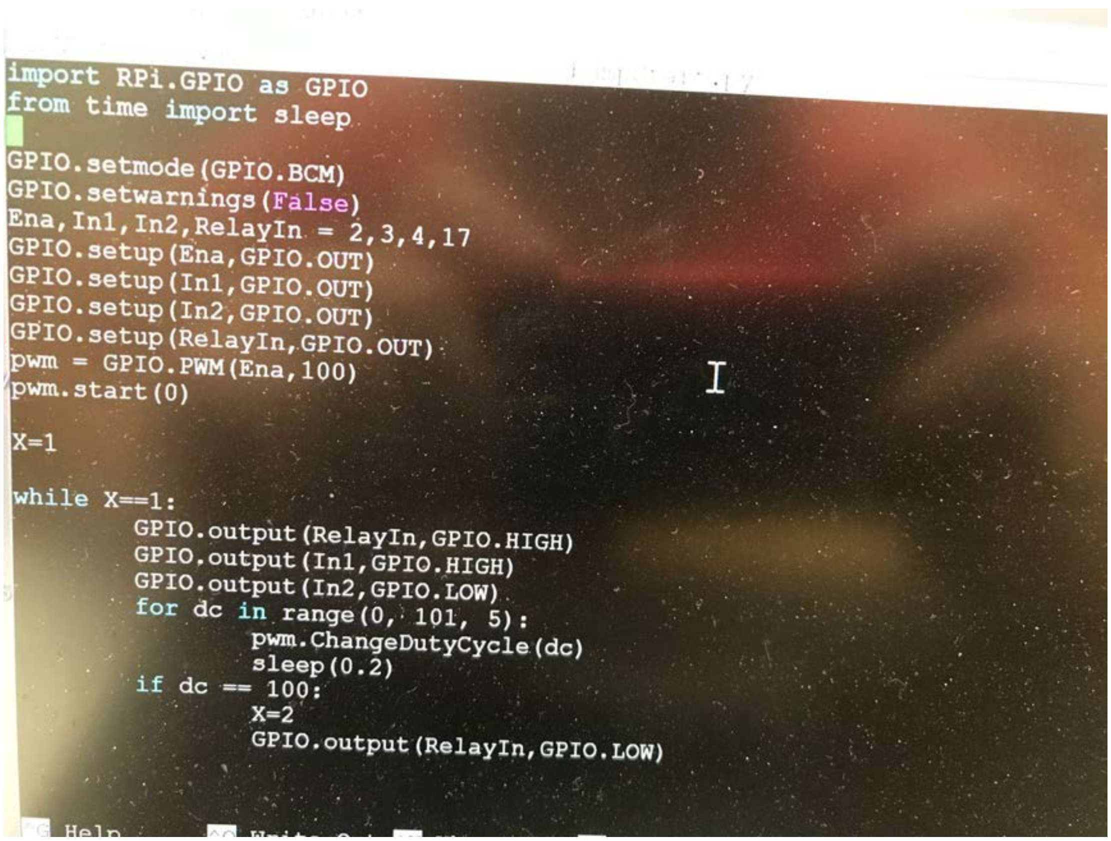


Figure 21: Bump Start Circuit Diagram



```
import RPi.GPIO as GPIO
from time import sleep

GPIO.setmode(GPIO.BCM)
GPIO.setwarnings(False)
Ena,In1,In2,RelayIn = 2,3,4,17
GPIO.setup(Ena,GPIO.OUT)
GPIO.setup(In1,GPIO.OUT)
GPIO.setup(In2,GPIO.OUT)
GPIO.setup(RelayIn,GPIO.OUT)
pwm = GPIO.PWM(Ena,100)
pwm.start(0)

X=1

while X==1:
        GPIO.output(RelayIn,GPIO.HIGH)
        GPIO.output(In1,GPIO.HIGH)
        GPIO.output(In2,GPIO.LOW)
        for dc in range(0, 101, 5):
                pwm.ChangeDutyCycle(dc)
                sleep(0.2)
        if dc == 100:
                X=2
                GPIO.output(RelayIn,GPIO.LOW)
```

Figure 22: Bump Start Python Code

3.15. Inverter

The inverter is one of the most important pieces in a renewal energy system because it changes direct current (DC) to alternating current (AC) to power electronic applications. Our Ampeak 1000W Pure Sine Wave Inverter has 2 AC outlets, ECO saving Mode, and comes with remote control. Additionally, it will be able to handle more than 5 turbines for future reference. We are going to use AGM Battery 12 Volt 100Ah as a power source and we used the Charge controller as a Communication Port to monitor the power consumption.

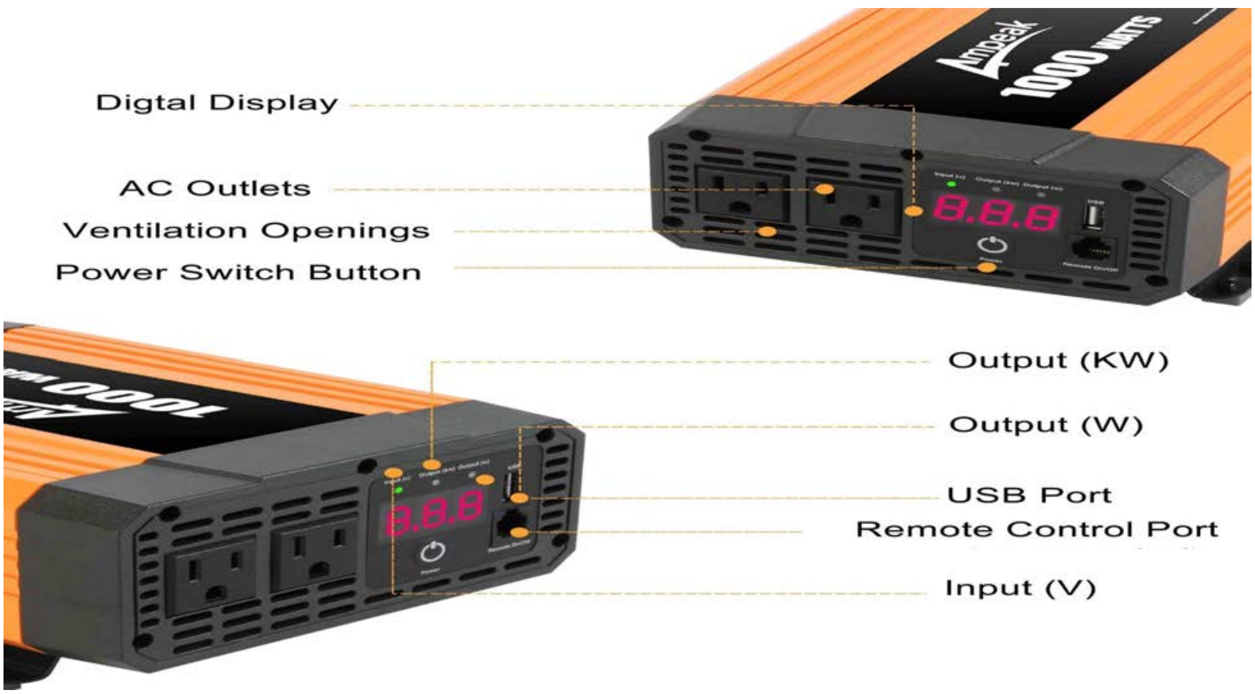


Figure 23: Inverter component diagram

3.16. Layout and Mounting

For Electrical components that don't come with mounts, custom 3D prints were designed. These prints were easily mounted to the cart using small bolts. Except for one instance, the custom mounts didn't require the component to be joined with the mount. The only component that required a permanent connection was the buck boost converter. In this instance, "feet" were printed for the converter and joined to the side of it using

JB-Weld.

Parts were positioned in such a way that no portion of the cart is under extreme stress. The battery was the only item with significant weight. However, the cart shelf proved to be strong enough to hold the battery anywhere along the length. If multiple batteries were placed on the same shelf, users would need to take special care to not overload the shelf. The parts were also positioned for ease of access. Part positioning was designed for easy maintenance as well as visibility. The electrical system was enclosed in clear plexiglass. This protects the system from the environment while maintaining visibility.

Parts were also placed in such a way that the system can be run by one operator. This was important to our project because of the safety factor. With our design, the entire system can be controlled from one corner of the cart. A simple switch can kill power to the entire system and activate the braking system. It was also desirable because of the education factor. This design allows one person to control, demonstrate and teach students about the system.

4. Engineering Principles

This project having an interdisciplinary team naturally leads to many different engineering principles being used as well as woven together. The first major principle involved in our project is the transfer of energy, this being from kinetic (wind), to mechanical energy to electricity. This can be seen in how turbines operate, as the wind forces the turbine shaft to rotate the shaft then rotates the generator. The second major principle is power systems analysis, including circuit design and analysis. A more detailed look at the electrical engineering principles includes: voltage regulation, control system, modbus coding, current flow operations. The rest of the principles are as follows: material science, data communications, and control system design.

5. Considering Constraints

5.1. Overall

Our main constraint when building the Test Bed was sizing. Everything for our design was generated from the ADA requirements for a standard classroom door. In general, the requirements are a minimum of 32” in width, and 80” in height. Our doors located in the Endeavor Building are 36” in width and 80” in height. This led to our table width of 30” and our height of ~76”. Our next constraint was the ordering and manufacturing of our parts. Trying to balance the long lead times and planning of our build process has been at the hands of our suppliers and is often inconsistent and hard to judge accurately.

5.2. E.E.

Our main constraint when building the Test Bed electronic system was picking devices that can handle up to 5 test turbines and fit in our 14”x72” table shelf. Another constraint that we had to work around was the communication between devices. It is necessary for all communication products to be hosted by the same device. This requires parts that use the same language, or a host that can speak to all devices. We also have constraints concerning some of our modular parts. They must be able to implement and handle the ability to step up or brake the generator, as well as the voltage and currents that come with it.

5.3. M.E.

The main constraints involving the Mechanical Design portion of the project were with the sizing of the airfoils, and getting the turbine to work with our generator via gearbox. The sizing of the airfoils were directly restricted by our size requirement as stated in the constraint overview. With this, we had to optimize the performance of our blades with equations and tables involving different blade heights and diameters that would produce the most amount of theoretical power based on the swept area at a constant high setting of our fan (7800 CFM). Our generator had to be chosen based on the theoretical power, and due to this the size of our generator is quite small. A smaller generator needs more RPM to achieve the rated power, which in this case is about 36W at around 2600RPM. There is no way for our size turbine to reach this rotational speed, therefore we had to create a gearbox. This gearbox turns our ~1RPS to about ~43RPS with a 42.9:1 gear ratio, therefore reaching our needed RPM to achieve the rated power.

6. Engineering Codes, Standards and Guidelines

The codes and standards were always in mind through the start and current status of this project. A major code that defined our project was the ADA requirement for door size, which was talked about in the previous section. Next was getting ourselves familiar with industry standards for vertical axis wind turbines (VAWTs), which we used the International Electrotechnical Commission (IEC) standards that were made for wind turbines. Through acquiring the IEC 61400-2 and 61400-12 standards we were able to get the professional standards for small wind turbines and their power performance measurements. With our project generating electricity we are also going to follow the National Electrical Code. Lastly, with our team manufacturing components for our project at the Oklahoma State University Endeavor and North Campus Labs locations, we will all follow the rules and requirements at both locations for safe operation.

7. Knowledge Acquisition

EE:

The electrical team has received advice from Dr. Hamid Nazaripouya and professor Nate Lannan throughout this project. Dr. Pouya is an expert in the power field and has been very helpful for choosing parts and designs. Professor Lannan has been extremely helpful in all aspects of our project.

ME:

The mechanical team has had the advice of OSU faculty Dr. Joe Conner, Dr. Dan Fisher, and Dr. Arvind Santhanakrishnan throughout this project. They have given us different topics of help ranging from material selection to overall design selection.

8. Concept Evaluation

The original concept was for a large standalone turbine with separate power generation system, so that multiple formations of turbines could be manufactured and used in the future with one power generation system bed. The scope was changed during week 3 to a much smaller turbine with attached power generation system and attached wind source. This was due to the sheer magnitude of the original turbine for a 4 person team, and so it could easily be carted throughout different rooms on campus and in the Endeavor Labs as needed. From there, our main concept design of a mobile cart was generated and has not been changed.

9. Engineering and other Analysis

Most of the engineering analysis was shown in the overall design in the forms of calculations and assumptions mentioned.

The way our final design deviated from our Critical design report was the strut bars and the strut-collar attachment that was made for the strut bars, shown in Figures 13 & 14. Also, we did not encase our turbine and fan in acrylic since we were unable

10. Testing performed to verify the design and Quality

- **Dump Load**
  - Due to the battery never being fully charged, the testing of the dump load was not completed.
  - When the battery is full and the turbine is spinning, the dump load should be generating heat.
  - A simple way to test this would be to connect the dump load to its own circuit. A power source can deliver power directly to the dump load. Testing would simply be determining if dump load dissipates the power.
- **Brake System**
  - The braking system was tested immediately. Because the braking system solely involves shorting the output leads, simple tests were run to make sure this actually functioned as expected.
  - When the leads were open, the generator was free to spin. It also delivered brief spurts of current (due to lack of continuous rotation) to the power converter. When the leads were shorted, we experienced much more resistance while trying to spin the shaft. There was also no power delivered while the leads were shorted.
- **Bump Start**
  - Once the circuit was complete, the bump start was tested on the unconnected generator.
  - Initial testing of the motor drive controller determined that the generator can spin in either direction based on applied forward voltage or reverse voltage. Applying a forward voltage bias generated a counterclockwise rotation (while looking down onto the shaft). Applying a reverse bias produced a rotation in the opposite direction.
  - After mechanical fabrication was completed, the bump start was tested again to ensure that the generator could spin while attached to the gears. This test proved successful. We were only able to test the attached generator-gearbox bump start with a forward bias. Applying a reverse bias would require a rewire of the system.
- **Airfoil/shaft speed**
  - Test the turbine, with different starting conditions. Was not able to fully get the turbine to spin without aid, needing to look into different fittings and manufacturing of airfoils.
  - Shaft came with certification of testing, which exceeded the safety factor wanted.
- **Battery**
  - The battery was first tested with a multimeter and the generator to ensure

proper charge capacity and voltage.
  - The battery was also tested with the inverter to ensure power delivery.
- **Charge controller**
  - The charge controller was tested to ensure the power analysis was functional.
  - A quick test of MSView revealed that the initial thought of using an ethernet cord was not possible without use of an additional part. The necessary serial-ethernet adapter was not purchased and left the only option for accessing data as a serial connection. Fortunately, our team was able to produce a serial-usb adapter. The serial adapter provided access to the power analysis. However, it wasn't in the desired format. To achieve a better format and easier access, the ethernet-serial adapter is necessary.
- **Inverter**
  - The inverter was scarcely tested by connecting it to a battery and charging a device from the output. The inverter behaved as expected.

11. Costs

Item Name	**Quantity**	**Cost unit excluding shipping [$]**	**Cost for all units [$]**	**Shipping cost [$]**	**Total cost [$]**
Pikasola Wind Turbine	1	269.99	269.99	0	269.99
BUBUQD Generator	1	42.99	42.99	0	42.99
Tornado Fan	1	129.99	129.99	0	129.99
Foam	2	34.17	68.34	0	68.34
Table Cart	1	350	350	160	510
Cart Casters	1	83	83	0	83

Aluminum shaft 1.5in x 48in	1	60.62	60.62	32.27	92.89
Epoxy Finishing Resin (12oz)	4	19.27	77.08	0	77.08
Fiberglass Cloth	1	59.95	59.95	0	59.95
Charge Controller (PWM 45A)	1	198	198	0	198
SLA Battery	1	273.74	273.74	0	273.74
DC DC Buck Boost	1	16.88	16.88	0	16.88
5V Relays	1	6.79	6.79	0	6.79
Ampeak 1000W Inverter	1	63.74	63.74	0	63.74
Ring Terminal Connector	1	11.29	11.29	0	11.29
uxcell Fixed Type 100W	1	11.40	11.40	0	11.40
Mounted Ball Bearing 1-1/2" Diameter	1	119.90	119.90	0	119.90
Medium-Strength Steel Serrated Flange Locknut 1/4"-20 Thread	1 Pack of 100	6.90	6.90	0	6.90
Zinc-Plated Alloy Steel 1/4"-20 Thread	1 Pack of 25	6.94	6.94	0	6.94

Flange-Mount Shaft Collar for 1-1/2" Diameter	2	84.42	168.84	0	168.84
Flush-Mount, 1/4"-20 Thread	1 Pack of 50	14.67	14.67	0	14.67
Phillips Thread-Locking Flat Head Screws 1/4"-20	1 Pack of 25	9.69	9.69	0	9.69
Pan Head Phillips Screws	2 Pack of 10	6.33	12.66	0	12.66
Rotary Shaft 2 mm Diameter	1	12.86	12.86	0	12.86
Rotary Shaft 4 mm Diameter	1	16.08	16.08	0	16.08
Rotary Shaft 8 mm Diameter	1	23	23	0	23
Ball Bearing Shielded, for 2 mm Shaft Diameter	2	7.03	14.06	0	14.06
Ball Bearing Shielded for 4 mm Shaft Diameter	2	7.17	14.34	0	14.34
Ball Bearing Shielded for 8 mm Shaft Diameter	1	14.39	14.39	0	14.39
Screw Shaft Collar for 2 mm Diameter	2	2.13	4.26	0	4.26

Clamping Two-Piece Shaft Collar for 4 mm Diameter	2	8.35	16.70	0	16.70
Clamping Two-Piece Shaft Collar for 8 mm Diameter	2	8.47	16.94	0	16.94
18-8 Stainless Steel Unthreaded Spacer 1/2" OD	4	7.63	30.52	0	30.52
Extra-Wide Truss Head Phillips Screws Passivated, 1/4"-20	1 Pack of 5	8.79	8.79	0	8.79
18-8 Stainless Steel Extra-Wide Truss Head Phillips 1/4"-20	1	7.01	7.01	0	7.01
Rotary Shaft 3 mm Diameter	1	16.08	16.08	0	16.08
Ball Bearing Shielded for 3 mm Shaft Diameter	2	8	16	0	16
Clamping Two-Piece Shaft Collar for 3 mm Diameter	2	9.20	18.40	0	18.40
Ball Bearing Shielded for 4 mm Shaft Diameter	1	7.29	7.29	0	7.29

Left-Hand Tap Bottoming Chamfer, M8 x 1.25 mm	1	8.89	8.89	0	8.89
High-Speed Steel Screw Thread Die 1" OD, M8 x 1.25 mm Left-Hand Thread	1	32.02	32.02	0	32.02
5/8-in ID x 10-ft PVC Clear Vinyl Tubing	1	10.48	10.48	0	10.48
1/2-in x 25-ft Ultratite Non-Metal	1	15.15	15.15	0	15.15
2-1/2-in Gloss Mortise Door Hinge (2-Pack)	1	3.28	3.28	0	3.28
0.118-in T x 36-in W x 72-in L Clear Sheet	5	103	309	0	515
3/4-in Zinc-plated Steel Two-hole Strap Conduit Fittings	1	6.28	6.28	0	6.28
0802.11a Wireless Router	1	49.99	49.99	0	49.99
Geeni USB Smart LED Strip Light 79.2-in Plug-in Smart Strip Under Cabinet Lights	1	19.38	19.38	0	19.38

Warner 2-in plastic putty	2	1.18	2.36	0	2.36
Sandblaster pro-9-inx11-in	2	6.48	12.96	0	12.96
3m rubber sanding block	1	5.48	5.48	0	5.48
55-gal garbage bag	1	17.48	17.48	0	17.48
Custom steel strut bars	6	150	150	0	150
				Total	**3340.74**

12. Project Plan

Our Project Planning/Management is being tracked through ClickUp.

Gantt Chart Link:
https://sharing.clickup.com/g/h/6-163133399-7/8e88afbf08d6bf1

ClickUp
Master Plan

COMPLETE

Task Name	Due Date
Media Publication Waiver	01/11/2022
NCL Level 1 and Endeavor Safety Trainings	01/13/2022
Workspace Tour	01/13/2022
Team Contract	01/14/2022
Syllabus and Course Handbook Quiz	01/14/2022
Begin Research	01/17/2022
Meeting with Dr. Nazaripouya	01/19/2022
Turbine & Generator purchasing research	01/21/2022
Meet with Dr.Santhanakrishnan	01/24/2022
Preliminary Design Review	01/27/2022
Scalability & Dimensionalization Complete	02/01/2022
Additive Manufacturing Training 1	02/01/2022
Additive Manufacturing Training 2	02/01/2022
Long Lead Items Purchased	02/03/2022
Completed CAD Design of Turbine	02/03/2022
Begin Electrical Diagrams & Drawings	02/04/2022
Additive Manufacturing Training 3	02/09/2022
SOP Review at Design Friday	02/11/2022
Submit Standard Operating Procedure (SOP)	02/11/2022
Complete Electrical Diagrams & Drawings	02/16/2022
Tentative Equipment Delivery	02/17/2022
Critical Design Review	03/03/2022

IN PROGRESS

Task Name	Due Date
Begin Electrical Assembly	02/21/2022
Purchase Request Spreadsheet	02/25/2022
Begin Manufacturing	02/28/2022
Critical Design Report	03/04/2022
Manufacturing Progress Check	03/07/2022
SRB Approval of SOP	03/11/2022

BACK LOG

Task Name	Due Date
Engineering Leadership Quiz	02/04/2022
Team Leader Meeting	02/08/2022
Mentor Meeting	02/10/2022
Peer Evaluation #1	03/04/2022
Turbine and Power System Coupling	03/21/2022
Running Prototype	03/24/2022
Mechanical Completion / Safety Inspection Passed	04/01/2022
Project Video	04/12/2022
Final Presentation (EXPO)	04/21/2022
Peer Evaluation #2 and Final Report	04/29/2022
Final Exam	05/05/2022
All Project Files Submitted	05/06/2022

Figure 24: Project master plan

13. Risk Management

Probability of Risk		Severity of Risk				
		A	B	C	D	E
		Negligible	Minor	Moderate	Significant	Severe
1	Very Likely	Low Med	Medium	Med High	High	High
2	Likely	Low	Low Med	Medium	Med High	High
3	Possible	Low	Low Med	Medium	Med High	Med High
4	Unlikely	Low	Low Med	Low Med	Medium	Med High
5	Very Unlikely	Low	Low	Low Med	Medium	Medium

Figure 25: Risk Management Rubric

Risk	Initial Priority	Mitigation
The turbines won't be ready for use in designing the electrical system at the beginning of the project	1D	Ordering a commercial turbine before February 3rd
Battery choice may require a cell equalizer to ensure safe charging and discharging of the battery	4A	Choose lead-acid batteries or design/purchase a cell equalizer
Turbine size and mobility may be required to fit through small doors	3B	Use modular designs to ensure ease of transportation

Parts choice may limit scalability of the entire project. Power specifications will limit turbine use to a maximum	2A	Ensure that the project system will not require more turbine modules. Purchase parts with power ratings at least 25% over specified power output
Damage to turbines and other components	4E	Follow all safety standards, building codes, and specifications when building/testing to ensure safe performance.
Gathering Parts (Delays)	3D	Purchase parts as soon as possible and find multiple suppliers
Exceed Budget	5D	Find cheaper alternatives to parts or request additional funds
Faulty Part	3C	Receive and test items as soon as possible. Reorder broken items immediately

14. Work Breakdown Overview

- **Nathan Johnson**
    - Engineering principles
    - Guidelines
    - Codes and standards
    - Airfoil and Shaft calculations
    - Gearbox and gear shaft calculations
    - Overall design
- **Marc Noto**
    - Overall Turbine CAD Drawing
    - Gearbox Design
    - Manufacturing processes and Fitting selection
    - Coupling mechanisms and designs
    - Project Management.
    - Overall design
- **Preston Johnson**
    - Electrical Component Drawings
    - Heat Calculations
    - Braking System
    - Control Diagram
    - Charge Controller
    - Raspberry Pi
    - Overall design
- **Ali Alnuwaysir**
    - Motor Stepper
    - Inverter
    - Modbus
    - Overall design

15. References

[1] https://www.youtube.com/watch?v=ZlQZFib8PiM&t=1s
[2] https://www.youtube.com/watch?v=SeNCDJwJO14
[3]
https://www.onlinemetals.com/en/buy/aluminum/1-5-aluminum-round-bar-6061-t6511-extruded/pid/1094
[4] https://www.mcmaster.com/