Vertical Axis Wind Turbine to Power a Well Pump

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Abstract

The group was tasked with finding a socially and environmentally sustainable way to power a well pump in a developing community. After research into a variety of vertical axis wind turbines, a combination of the Savonius and Darrieus designs was chosen. By utilizing the Penn State wind tunnel, the design can be tested for power output at specific wind speeds. A scale prototype was constructed so the design can fit in the wind tunnel. Although more work is needed before a full scale design is implemented, the test results will provide valuable details into improvements and future steps in the process.

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Introduction

A major issue facing many communities in the developing world is access to water. Water is a vital resource to not only health and survival, but also to agriculture and industry. Lack of such a necessary resource can hinder the development in these areas. Without a centralized infrastructure, these communities are forced to use other techniques, like rainwater collection, to attain water. Still others need to travel a long distance to a well. By making the process to acquire water easier and more efficient, the first steps to solving this problem can be realized.

Figure 1: COMET-ME Logo

The initial guidance for this project came from a joint Israeli-Palestinian organization, COMET-ME, which implements similar infrastructure solutions to underprivileged communities in West Bank. Examples of some of these projects include solar panels and wind turbines used to pump water from a well to a holding tank. The challenge that was posed by COMET and Penn State project advisor Andras Gordon was to create a vertical axis wind turbine that would be able to power a mechanical well pump. Additionally, the design should be easy to construct and maintain by these communities where it is applied. The goal for the project was to create a solution that is both environmentally and socially sustainable. Although the resources are available for a highly technical project, it would not be a maintainable solution in developing areas. By focusing on the people rather than the details of the system, the possible influence of the project could be seen on a global level, rather than a single application.

Figure 2: COMET-ME water holding tank

Research

As four undergraduate engineering students without any prior experience in the field of aerodynamics, we needed to spend a significant period of time researching these topics. We started our preliminary research on general principles of converting wind into energy and how an efficient wind turbine functions. Professor Andras Gordon gave us guidance as to which types of vertical axis wind turbine would generate enough power to run the water pump. He provided us with many resources about different types of vertical axis designs. For each type of design we conducted extensive research to decide which designs would be ideal for the conditions of the target area. Factors that we considered when evaluating each design were discussed and established with the guidance of Professor Gordon. In order to have guidelines to evaluate these designs by, we contacted COMET asking for any of their data and they sent their comprehensive report for their turbine for the past year. The report included key information about wind speeds and power produced versus the power needed to efficiently pump the water. A low cut-in wind speed (the speed at which the turbine starts to rotate) would be necessary for the turbine because the wind speeds were low and steady. Their pumping efficiency was reported to be around 1.5 cubic meters per day to a holding tank that is ten meters tall. We decided that our goal would be to generate enough power to pump 3 cubic meters of water per day in the same conditions of a 10 meter head and 3 m/s average wind speed. With these criteria, we were able to accurately evaluate the designs.

Figure 3: COMET-ME previous turbine design

Once we had a firm grasp on the general concepts of the project, we moved into research about specific aerodynamic principles. Specifically, we worked with the Bernoulli principle of lift and the properties of airfoils. We worked to design an airfoil that would maximize the power output of our turbine. Once we had a general shape in mind, we met with Dr. Susan Stewart to get an expert's opinion on our airfoil design. Dr. Stewart received her PhD in Mechanical Engineering from Georgia Tech in 2003 and has since been conducting research in the field of aerodynamics at the Pennsylvania State University. Dr. Stewart gave us valuable guidance in our design process of the airfoils and after meeting with her, we collaborated with Andras and decided on a final design of our airfoils.

Our Design

After careful individual evaluation of each vertical axis design, we collaborated within our group and with Professor Gordon on a final design. Our design can be broken down into two distinct parts: the Savonius and Darrieus designs. The inner portion of our turbine will house the Savonius aspect to the design. Flush to the central rod about which the turbine spins, two half-cylindrical shells propel the turbine in a circular rotation. On the outsides of the design are the two airfoils that make up the Darrieus aspect to the design. Each of the design aspects add specific advantages to our hybrid design. The two shells close to the central axis of rotation will help the turbine to have a low cut-in wind speed. This is because the Savonius turbine is designed specifically for areas in which the wind speed is not very high. The Savonius shells also ensure that the turbine will rotate regardless of the wind's direction due to the circular nature of the design. As the turbine spins with the initial push from the Savonius design, the airfoils on the outside of the perpendicular axis will generate a higher tip-speed ratio, propelling the turbine's rotation faster than the Savonius. A greater tip-speed ratio means that the blade will move faster in relation to the wind speed, generating more power along with it. The airfoils are modeled after the GOE 435 design. With slight modifications to the design, we made sure that the connection of the airfoils to the perpendicular axis would be strong to withstand a strong wind. We installed the airfoils in a way that allows us to change the pitch of the airfoils in order to experiment and find the most efficient angle of attack and direction of the lift force. This Darrieus design will help generate the higher power output that we require in our goals for the project.

Figure 4: CAD model of the design

Figure 5: Prototype Airfoil

In order to achieve the goal of 3 cubic meters of water pumped per day, the turbine will have to provide at least 7 Watts of power to the pump. By calculating the available power of the wind, assuming 8% efficiency of the turbine, the necessary dimensions of the full size design will be two meters tall by three meters in diameter of rotation. The calculation is shown below.

$$Wind\ Power = .5 \times Air\ Density \times Swept\ Area \times Wind\ Speed^3$$

$$Turbine\ Power = 7\ Watts = .08\ (efficiency) \times 1.1839\ \frac{kg}{m^3} \times \left(3.34\frac{m}{s}\right)^3 \times Swept\ Area$$

$$Swept\ Area \approx 6\ m^2$$

Prototype

Figure 6: Completed Prototype

Building our prototype based on our design was a tricky task to say the least. One of the factors that made it so difficult was the budget. Our job was to build the working prototype in the most inexpensive way possible because the targeted area is 3rd world areas. This goal led to us to multiple challenges in finding materials. Our biggest concern was the airfoils so that is where we started. At first we had the hopes to 3d print them, but this had 2 problems. First, this feature is inaccessible for 3rd world countries so it wouldn't help our end result, and second it is extremely expensive to 3d print the size airfoil we needed because it was too big for the school 3d printer and we would have to have it shipped in from a separate company. This led us to how we designed it in our final prototype. We carefully cut small sections of the airfoil and connected them all with a rod. We then wrapped them in a metal sheet to allow for it to be completely covered, and the inside being mainly hollow allowed for them to be lightweight.

From here we moved on to the Savonius part. We needed 2 half cylinders 12 inches in height and 8 inches in diameter. Finding these specific dimensions was not easy so we went with a different approach. We found a long empty cylindrical shaped piece of metal that was 8 inches in diameter. We then cut it into 2 pieces of 12 inches in length to give us our base of the Savonius. From here we cut 4 blocks of wood that would act as the top and bottom of each Savonius piece and nailed them together.

Figure 7: Airfoil connection

Finally, we took our connection pieces, which connect the airfoils to the center rod, and cut a hole in the middle that allows for the connecting pieces to slide onto the center rod. From here we had all the pieces built and ready to be assembled. To start the assembly we first put our ball bearing on one end of the rod and secured it using the screws that came in the bearing. From here we measured the distance from the bearing to where the start of the PVC fitting, that holds our Savonius and airfoils together, and we slid the fitting over the center rod and bolted it in place. From here we slide on the connecting pieces and then attached one end of our airfoils to the connecting piece using adjustable bolts. These adjustable bolts allow for us to easily tighten and loosen the airfoil in order to change the pitch without tearing through the wood. Next we attached the Savonius parts by overlapping them around the center rod and to hold it all together we put bolts through the bearing to the other side of the wood piece holding the Savonius part together. This allowed for all the pieces to be attached and move as one while holding it steady on the center rod.

We then repeated this process backwards for the second PVC fitting. The final ball bearing will be attached once we are ready to test in the wind tunnel and the extra length on the center rod is to allow for part of the rod to exit the wind tunnel. This part the exits the wind tunnel will have a small hole drilled into the end where we will insert cords of a DC motor. This will allow for us measure the volts generated from our turbine rotating. The ball bearings will be drilled directly into the walls of the wind tunnel to hold the design in place.

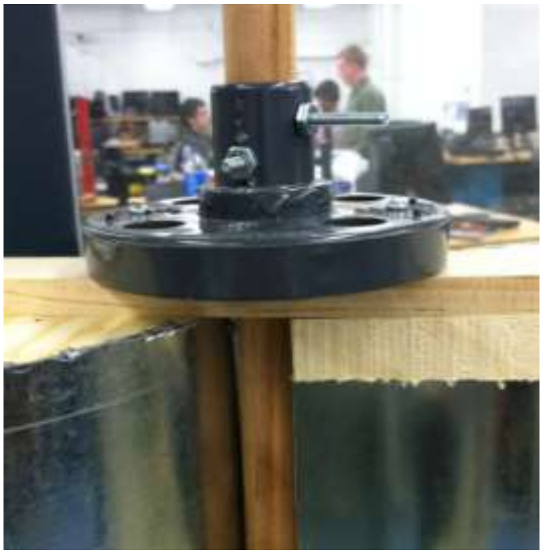

Figure 8: PVC fitting connection

Figure 9: Flange mount ball bearing

Figure 10: Full Prototype

Budget

The funding for this project was provided by Lockheed Martin. The goal for the prototype was to keep the price as low as possible using cheap, local materials. However, two of the pieces could not be made using the given resources. The two ball bearings and the two PVC fittings were ordered online from the manufacturer. These pieces accounted for around half of our budget. The other half of the budget consisted of the materials needed to build the prototype. However, many of the materials bought were only available in far greater quantities than we needed. Another prototype could likely have been constructed with the materials already bought, so the cost of construction for one prototype was less than the existing budget. Nonetheless, the budget for the project, including all of the purchases, is listed below.

Item	Quantity	Price
Grainger Flange Mount Ball Bearing	2	$54.36
9V Magnetic Cylindrical Mini DC Motor	1	$5.62
Spears 856 Series Flange PVC Pipe Fittings	2	$14.84
10 ft x 10 ft Aluminum Flashing	1	$8.78
Gorilla Glue Epoxy	1	$5.48
8-Pack #6 - 1.5 Inch Nuts and Bolts	1	$1.24
8” x 24” Round Metal Pipe	1	$5.20
Balsa wood sheets	2	$9.98
Wood circle	1	$2.49
Xacto knife	1	$4.49
Wooden rod	2	$5.56
Wooden block	1	$4.47
Wooden plank	1	$7.40
Carpet tacks	1	$1.30
Wood plank	1	$2.17
Wood Screws	6	$7.08
1.5 inch nails	2	$2.60
Wooden moulding	5	$4.65
Oak Dowel Rod	3	$8.70

Figure 11: Budget Table

Project Total: $160.07

Results

After testing the design in the wind tunnel, the results turned out to be largely inconclusive. This obscurity was caused by improper test conditions. The plan to test the power output of the turbine was a small, DC motor with a turn shaft connected directly to the central axis of the turbine. However, the DC motor, and electrical power, is only useful at large revolutions per minute values. Due to the size and orientation of the vertical axis turbine, it is very difficult to create the necessary RPM to output a noticeable voltage from the motor. The horizontal axis turbines are much more efficient for electrical power generation. For the application of a mechanical well pump, the best design is a vertical axis orientation because it generates the necessary torque. There was no way to test the torque of the machine, which is the most important value for the application. Regardless, some simple measurements were taken, and are shown in the table below.

Figure 12: Wind Tunnel Results

Volts	**Velocity (ft/s)**	**revolutions**	**sec**	**rpm**
0.73104	26.1	Starting Speed … Blockage slowed tunnel down.		
0.42644	20.0	22	20	66
0.54828	22.6	78	60	78
0.67012	25.0	28	20	84
0.9138	29.2	34	20	102

As seen in the table above, a small voltage was created by the motor as the wind speed increased. Another problem that arose from the motor was the load. Without a high enough RPM, the load attached to the motor, a resistor in this case, has little to no effect on the turbine. To obtain valuable results for COMET-ME, the design will need to be tested with a mechanical load to test for torque.

Additionally, the start-up wind speed of the turbine was larger than expected. The turbine did not begin to turn until the wind in the tunnel reached nearly 17 mph (8 m/s). With an average wind speed in the area of application for COMET-ME at just over 3 m/s, the full scale design should start at a very small wind speed. Even with the scale speeds in mind, the prototype should ideally start at a lower wind speed.

Lastly, after seeing the turbine in the tunnel and a more detailed analysis, tunnel operator Rick Auhl believed that our airfoils, that were meant to increase the tip speed ratio using the lift force, were not functioning as expected. The lift force of the airfoils did not provide any further rotational speed for the design. Instead, the only benefit the airfoils provided was a "deflector," pushing the wind toward the Savonius part of the design. Since the turbine rotates on its axis, the orientation of the airfoils is constantly changing. Ideally, the orientation and pitch of the airfoils would be constant in relation to the direction of the wind. With the airfoils constantly moving, it would only obtain the desired lift force at one instant over a whole rotation. While the expectation of the airfoil influence on the rotation was small to begin with, the lack of any sort of influence was unexpected and disappointing.

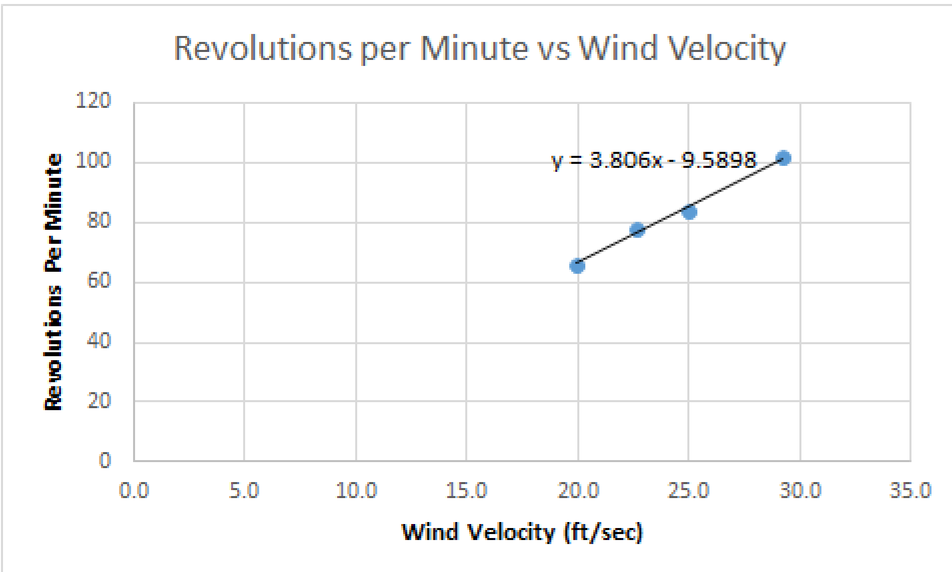

Figure 13: Graph of Wind Tunnel Results

Conclusions

In conclusion, we have been tasked with designing a wind powered water pump that is intended for use in rural areas. We chose the design after extensive research into different vertical axis wind turbine designs and combined two separate existing designs so as to make our design more efficient in both low and high winds. The design had to be simple and easy to construct as rural areas do not have many tools or good equipment. It must also be able to be constructed using cheap, local materials as the areas it is intended for will often not have stores where they can buy materials but will only have spare items or repurposed materials. We feel that our design is easy to construct with materials that can be found lying around anywhere like wood and sheet metal or plastic sheeting. We faced many challenges in choosing our design as we had to make sure that it met all of our criteria. We looked at many interesting designs but many of them were too complex and difficult to build. Our design is socially and environmentally sustainable because it can be built with cheap, local materials, uses only renewable energy with no emissions and can be easily built to help communities get water easily and effectively. We also tested our prototype in the wind tunnel and measured the voltage that the prototype produced as well as the RPMs at different speeds. Our start up speed was about the same for all of our tests and our results showed that our prototype had fairly linear RPMs with respect to wind speed which is good because it will be consistent and you will know what you are getting from it. Our design worked fairly well and we were very pleased with how it worked. However, there is room for improvement in our design as we did not have the time to fine tune our design to make it the best that it could be. We also did not have the time to do a detailed analysis of our design so we do not know if our design is as efficient as it can be.

Gantt Chart

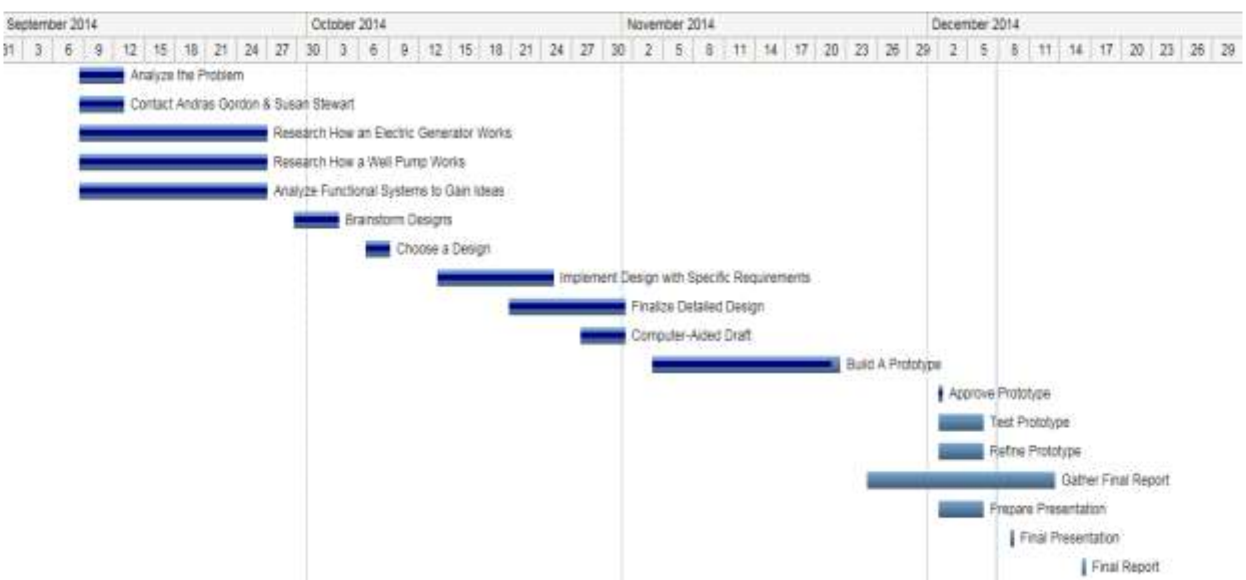

Figure 14: Team Progress Chart as of Deceber 6

Future Recommendations

Moving forward with this project, there are certain improvements that we would hope to implement. With respect to the design, certain changes to the Savonius design would increase the efficiency of the rotation. As our design stands now, the two shells are perfectly circular. This creates a force of the wind on the trailing shell when the wind is directed perpendicular to the shell. A solution to this would be making the shape of each shell more aerodynamic than a perfect semicircle. Another factor that this could help with would be to diffuse the wind off of the ends of the shell toward the airfoils, generating a stronger lift force and tip-speed ratio. Ropatec, an Italian wind turbine company, has perfected the shell diffuser in their designs of the hybrid Savonius-Darrieus turbine, the T-Vision.

The means of changing the pitch of the airfoils is fairly crude and imprecise on our prototype. A device that could automatically change the pitch would greatly increase the efficiency of the turbine. The device would have to have a means of measuring the wind's speed and direction and then automatically change the angle of attack of the airfoil. Airplanes have achieved this implementation with ring-like structures around their propellers. The dual airfoil design also changes the purpose of the airfoils to more of a wind deflector rather than generating lift. More lift could be generated if the angle of attack of the airfoils were more precise and aerodynamic. Much of the future work on the efficiency of the design should be focused on making the airfoils more aerodynamic.

Teams in the future could benefit from some insight into the testing process. As discussed in our results, the DC motor was not successful in calculating any of the generated power because it measures revolutions per second. After discussions with Rick and Professor Gordon, the solution decided upon is to use a torque measuring device. Because the force is directly applied to the mechanical pump, torque is more important than an electric power output. Since an automated torque measuring device is expensive, it is not practical without department approval to purchase one specifically for this purpose. Rick proposed the idea of a manual device that would measure the torque: something that would apply a resisting force to the axis of rotation and measure the time it takes for the rotation to stop. Makeshift ideas that were brainstormed included a brake pedal with a force sensor or making a Prony brake as a dynamometer. With these devices, an accurate measurement of how efficient the turbine is can be used to evaluate what aerodynamic properties need to be changed.

In the future, we would like to see this design implemented successfully by organizations like COMET-ME and implemented globally with many different applications. In order to successfully achieve this goal, we would plan to work with a lamination school in Maine to develop a way to easily construct certain parts of the turbine. The plan as of now is to package the each turbine into a kit that would make the assembly simple enough for a person without an engineering background to assemble with ease. The main parts of the turbine would come already assembled with the help of the lamination teams in Maine. Preliminary requirements for the lamination would include a very detailed 3-dimensional CAD drawing of the airfoils and the

Savonius shells. If these steps are taken, then we can certainly make a positive impact towards helping developing worlds thrive.

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