Executive Summary: Design of a Small-Scale Wind Turbine to Charge a Battery

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India is one of the most advanced and successful nations in the world. However, approximately 304 million people across the nation do not have access to a basic resource: electricity [1]. Many cities are struggling to provide electricity to many of their people. Chennai, India is a port city that has this issue. Despite a major influx of money from Chennai's tourism industry, according to The Borgen Project, almost 29% of the population live in slums [2]. For people who live in areas without access to electricity, it is important for them to have stored energy. Our team has been tasked to propose a solution to this problem using a small-scale wind turbine. We have designed a small-scale wind turbine that can charge a small battery pack for people in Chennai, India.

For our design, we based our specifications upon six different customer needs. The six needs are the production of electricity, durability during high speed winds, durability during constant applications of wind, portability by being lightweight, portability by being small, and to be aesthetic. These metrics allowed us to create various designs that can potentially serve as a viable wind turbine. After selecting the optimal design, we designed two alpha prototypes and a final beta prototype. The alpha prototypes allowed us to gain valuable insight in areas to improve upon our design. We were able to learn from the problems in our prototypes and produce an effective beta prototype that meets the needs of our customer. The next three sections will include the concept selection process for our design, the sequence of our prototypes, and the performance of our final design.

Concept Generation, Screening, and Selection (ME 297 Only)

After identifying our customer needs, accompanying metrics, and conducting a functional decomposition of the wind turbine system, we began our concept generation process. We broke down the wind turbine system into three different subsystems: wind capture, power transmission, and support structure. We had come up with six different designs that could potentially serve a solution to our problem.

Once we had completed designing different concepts, we conducted a concept screening process to reduce the number of designs. We had crossed out three poor concepts which left us with three plausible concepts.

Upon looking at our customer needs, we created an AHP matrix to help assist in our concept selection. After weighing our top three concepts in relation to our selection criteria, we were able to identify our most effective concept. We proceeded to calculate the efficiency of our design in order to validate our proposed design. Once validated, we began the production of our prototypes. The calculations that were conducted can be found in Appendix C.

Sequence of Prototypes

Prior to reaching our beta prototype, our team had to create two alpha prototypes to test our designs. The first alpha prototype, which can be seen in Figure 1a, had blades made out of acrylic, our transmission was a direct drive setup that included a wooden shaft and an aluminum machined coupler, and our support structure was built out of acrylic and PVC pipe. The testing of our first prototype provided us essential information about our design. We produced no power but had withstood the durability aspect of the testing. With this knowledge, we had to redesign our transmission and blades.

The second alpha prototype, which can be seen in Figure 1b, had blades made out of tin foil, an aluminum shaft and coupler, 3-D printed housing, and an aluminum support structure. Based on the testing of our second alpha prototype, we were able to successfully produce power. Additionally, our design passed the durability test. With this information, we decided to keep everything on our turbine the same expect the transmission. Since we didn't meet the minimum power output we expected through a direct drive setup, we decided add a gear drive.

The beta prototype, which can be seen in Figure 1c, had the same construction and design as the second alpha prototype. However, there was the addition of a housing cover made from tin foil and gearing. The gearing consisted of a 6:1 ratio that allowed us to increase our power output significantly. The assembly of our beta prototype can be found in Appendix B.

Figure 1. Sequence of prototypes for the model of the wind turbine: (a) alpha 1 prototype, (b) alpha 2 prototype, and (c) beta prototype.

Performance of Final Design

Our beta prototype was tested against the six metrics we had identified. The six needs are the production of electricity, durability during high speed winds, durability during constant applications of wind, portability by being lightweight, portability by being small, and to be aesthetic.

For the production of electricity, we expected a minimum of 0.2 Watts to a maximum of 1 Watt of power and this need was met. Based on the testing, we were able to produce 0.512 Watts of power. This was calculated by testing the voltage created across a resistor. Our team chose a resistor of 20 Ω and received a maximum voltage output of 3.2 Volts. Additionally, the rotor shaft spun at 478 RPM. After multiplying this by our 6:1 gear ratio, the motor shaft spun at approximately 2,868 RPM.

In terms of durability, we had two different metrics: withstanding high speed winds and withstanding constant applications of wind. The first metric was going to be measured by placing the turbine in front of leaf blower and making sure that there is no destruction of our turbine. This will imitate a high-speed gust. Our turbine did not meet this need as there was a slight rotation of the housing on the support structure during the test. However, our second metric was met. We tested the ability of our wind turbine to withstand a constant application of wind by placing it in front of a box fan and seeing if there is a constant production of power for more than 13 seconds.

The portability of our turbine was measured by two metrics: its weight and size. We wanted our turbine to be less than 20 lbs. and less than 2 feet tall. The weight of our turbine was met by being less than 20 pounds. However, the size of our turbine was not met as the height was approximately 2' 4". Our turbines aesthetics were also met by having very few visible bolts once the housing cover was attached.

While our turbine was fully functional and worked properly, there is still a lot of room for improvement. The different areas of improvement are discussed in Appendix A. However, all of our criteria were met and the performance of our final design proved exceptional. Our team was able to successfully produce a wind turbine that will effectively meet the needs of the people in Chennai, India.

Appendix A: How the Design Could Have Been Improved

While our design was effective in meeting the customer needs of the people in India, there are a lot of areas of improvement for our design. From the concept generation, we had three subsystems that we based our designs from: wind capture, power transmission, and support structure. Each of these areas could easily be improved.

Wind Capture

The wind capturing design of our blades and rotor could be designed to have a more effective way of being connected. Our beta prototype used a hose clamp to hold the blades to the rotor in order to make the assembly easier. However, this can be changed to a much better design where the entire rotor can be taken off along with the blades. This change will result in a more convenient way to disassemble the blades from the turbine. Additionally, this is will result in the much safer overall design.

Figure A-1. Hose clamp holding blades around rotor

Power Transmission

Since our transmission of power involved smaller gears and an ineffective way of being secured, we could easily improve the way the gears and shaft have been laid out. If we add in a bearing for the smaller shaft that holds the gear, it will reduce the effects of gravity weighing on the gears. Furthermore, we could also reconstruct the layout of our housing to potentially include even more gears to increase our power output.

Support Structure

Our support structure was a durable and portable design, yet there could be a better way to assemble the housing onto the support shaft. We inserted a set screw into the female connector to connect the housing to the support structure since we 3-D printed our housing. However, we could have used an aluminum housing design to create a more uniform looking turbine.

Overall Aesthetics

The overall appearance of our beta prototype could definitely have been improved. During the designing of our prototype, we had drilled holes in various places to test out different setups. These setups did not end up working and had to be removed. Furthermore, we had to work around prefixed pieces on the housing that could not be removed. These can all be improved if provided more time. The housing could have been reprinted to fit the exact specifications and appearance of our final beta prototype. Additionally, we could have printed the entire housing in a uniform color.

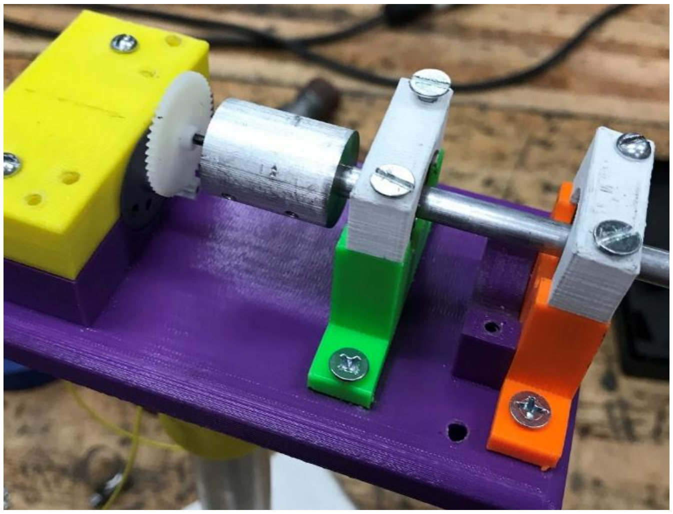

Figure A-2. Various holes and discolored housing

Appendix B: How to Assemble the Wind Turbine

Our small-scale wind turbine has been designed for easy assembly and operation. We have included everything required to have the turbine run effectively. Additionally, all necessary tools for assembly will be provided. The tools that are included are a flat and Philips screw driver, 4-40 hex key, four 4-40 set screws, a hose clamp, four ¾-8 screws, and a ¼-14 screw. The entire housing set up will be provided as shown in Figure B-1. The rest of the assembly will be shown as follows.

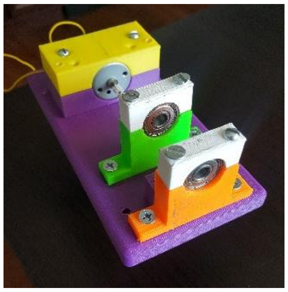

Figure B-1. Prebuilt housing set up

1. *Connect the base to the support shaft.* Locate the base, support shaft, flat screwdriver, and ¼-14 screw. Place the support shaft against the hole in the base and screw in the ¼-14 screw to connect the two pieces. For an illustration, see Figure B-2.

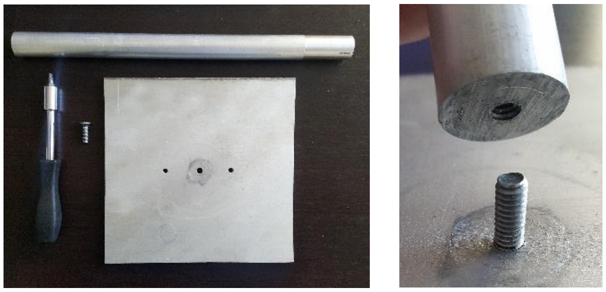

Figure B-2. Connection between base and support shaft

2. *Connect the housing to the support shaft.* Take the premade housing and place it on top of the support shaft. Locate a 4-40 set screw and use the 4-40 hex key to screw it in. For a second illustration, see Figure B-3.

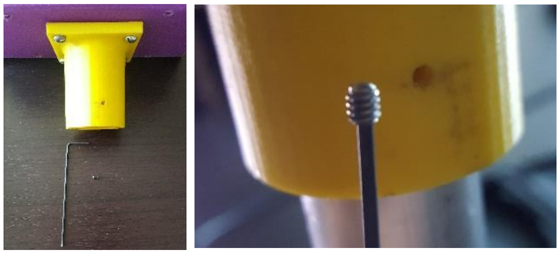

Figure B-3. Connection between housing and support shaft

3. *Assembly of blades to rotor and shaft.* Locate the rotor, blades, hose clamp, shaft, set screw, hex key, and flat screw driver. Take the rotor, place it on the one end of the shaft and tighten it using a set screw. Place the hose clamp around the rotor and slightly tighten it so it does not fall off. Place each of the three blades symmetrically in between the hose clamp and rotor and then tighten the clamp. For a third illustration, see Figure B-4.

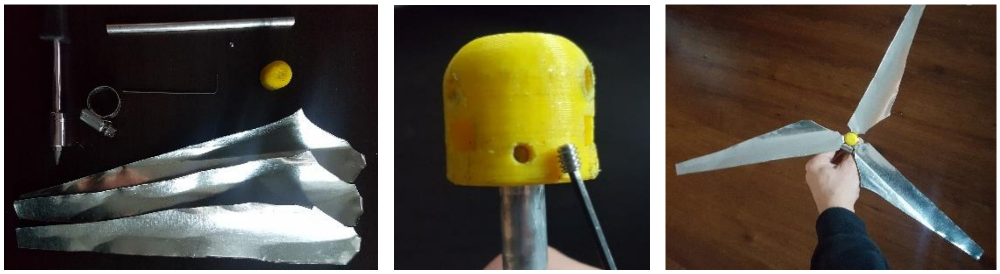

Figure B-4. How to assemble the blades, rotor, and shaft together

4. *Finalize the connection between the shaft and motor.* Place the shaft through the two bearings on the housing until a small portion of the shaft sticks out. Connect the coupler to the smaller shaft and attach large gear to the open end of the smaller shaft. Then, connect the coupler to the larger shaft. Tighten both shafts in with set screws using a hex key. For a fourth illustration, see Figure B-5.

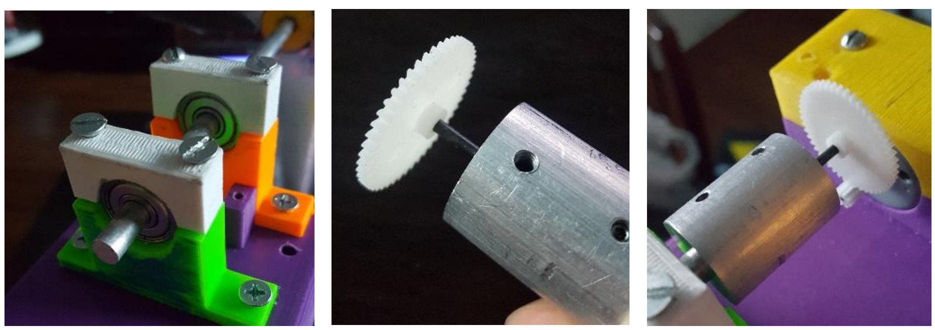

Figure B-5. How to assemble the rotor shaft to the motor

5. *Attach housing cover.* Locate four ¾-8 screws, a Philips screw driver, and the tin foil housing. Place the rim of the housing cover underneath the housing and screw in the four screws in the four locations. Once complete, the turbine assembly is complete and ready for use. For a fifth illustration, see Figure B-6.

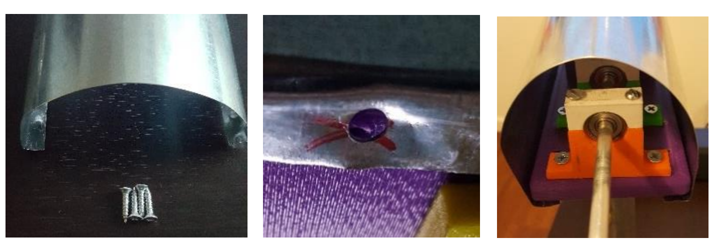

Figure B-6. Attaching the housing cover

Appendix C: Physical Principles to Make Design Choices

This appendix presents the relevant calculations that made the basis for our design decisions. To do this analysis, we began by calculating the average wind speed of a box fan. Once this was calculated, we were able to figure out the theoretical power output. Additionally, we were able to see the optimal angular velocity required to achieve maximum power output.

Average Wind Speed

Table C-1 shows nine wind speed measurements on different areas of a box fan. After taking the average of these measurements, we were able to see that the average speed of the box fan was 2.9 m/s.

Table C-1. Wind speed measurements in nine different areas of a box fan [m/s]

2.2	3.3	2.7
2.5	2.6	2.8
4.0	3.7	2.3

Theoretical Power Output

Based on the average wind speed of 2.9 m/s, we were able to calculate the average power available from the box fan using Equation 1:

$$P = \frac{1}{2}\rho A U^3 \quad (1)$$

where P is the power available (Watts), ρ is the air density (kg/m^3), A is the cross-sectional area of the blades (m^3), and U is the wind velocity (m/s).

$$P = \frac{1}{2}\rho A U^3 = \frac{1}{2}(1.2)\big(\pi(0.25^2)\big)(2.9)^3 = 2.873\ W$$

The total power available from the box fan is 2.873 Watts. Figure C-1 shows the relationship between the angular rotation of the rotor and generator and their optimal torque outputted. Since we expected a minimum of 0.2 Watts of power to be produced, our turbines design was effectively able to meet this requirement, as shown in Figure C-1. However, this is not the optimal operating point for the turbine.

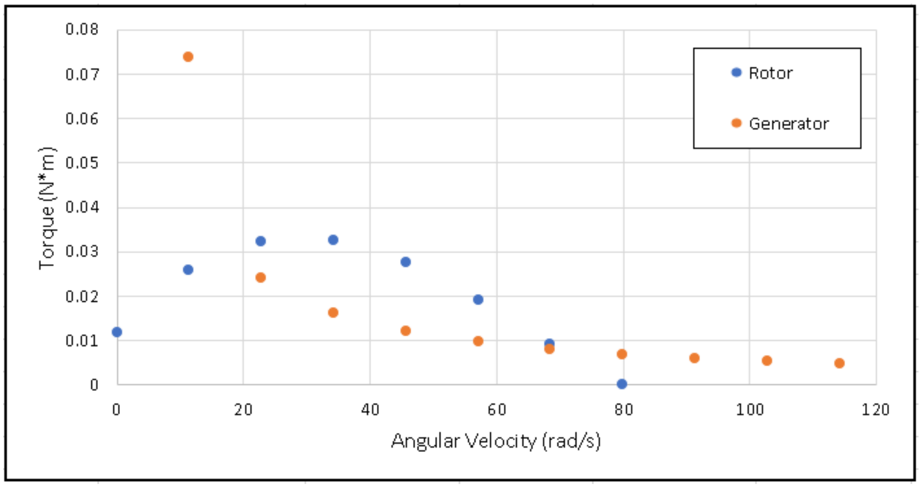

Figure C-1. Torque vs. Angular Velocity at a power output of 0.2 Watts

Comparison between Theoretical Power and Actual Power

The maximum power that we were able to produce from our beta prototype was 0.512 Watts at 478 RPM of the rotor. Based on this output, the RPM obtained of our rotor was extremely close to the theoretical RPM. Figure C-2 shows the optimal torque outputted at a power output of 0.512 Watts. Based on this Figure, it can be seen that the optimal angular velocity for the rotor is around 45 rad/s. The angular velocity is equivalent to 429.7 RPM. There is a 10% percentage error between the actual value and theoretical value. An error of this sort can be caused by various things such as the actual speed of the box fan, aliasing issues in the stroboscope, or the equation not taking into account the distance the box fan is from the turbine. Based on this data, our turbines optimal operating point is at 45 rad/s for a maximum power output of 0.512 Watts.

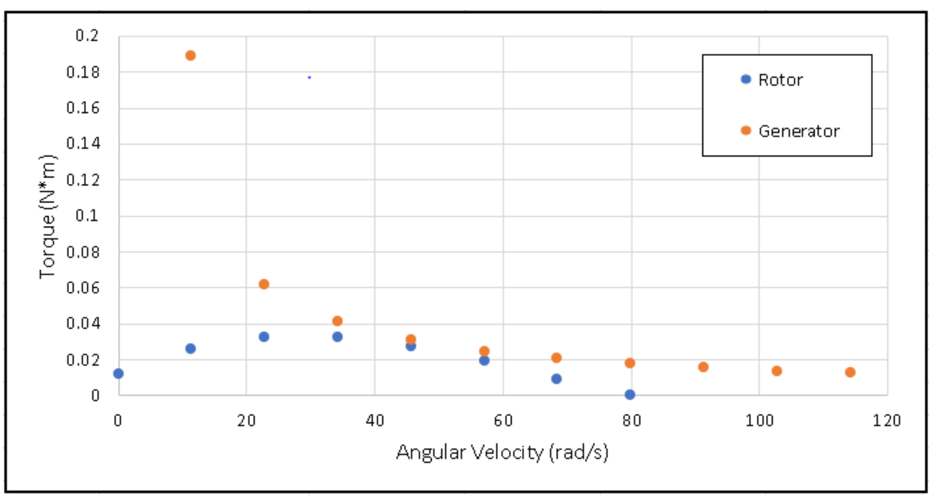

Figure C-2. Torque vs. Angular Velocity at a power output of 0.512 Watts

References

[1] "India's Poverty Profile." World Bank, 25 May 2016, www.worldbank.org/en/news/infographic/2016/05/27/india-spoverty-profile.

[2] Sewidan, Nada. "Poverty in Chennai, India." The Borgen Project, 16 Feb. 2016, borgenproject.org/poverty-chennai-india/.