Micro-Wind Turbine System

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Abstract

Residents of Least Developed Countries (LDC) can extend the useful portion of their day by gaining access to reliable electrical energy. Currently, some residents rely on 12- Volt automobile batteries to provide electricity to their households. Current charging sources include fossil fuel generators, micro hydroelectric systems, and photovoltaic systems. However, these options are problematic because fossil fuel systems are cost prohibitive, photovoltaic systems are difficult to produce, and micro hydroelectric generators require flowing water. The primary objective of this project was to produce a build manual for a micro wind turbine to charge 12-Volt batteries. For this project, the build manual details the fabrication process of a micro wind turbine utilizing readily available materials. A car alternator was reconfigured into a permanent magnet generator to charge a recycled marine or automobile 12-Volt battery. Acrylonitrile butadiene styrene (ABS) piping was cut to produce the turbine blades using the design specified in the build manual. A prototype was built to verify that this design will provide 200 watt-hours per day, which is the average household electricity demand for LDC's. The micro wind turbine produced using this build manual enables impoverished communities to extend their productivity via a low cost and sustainable solution.

Background

Problem

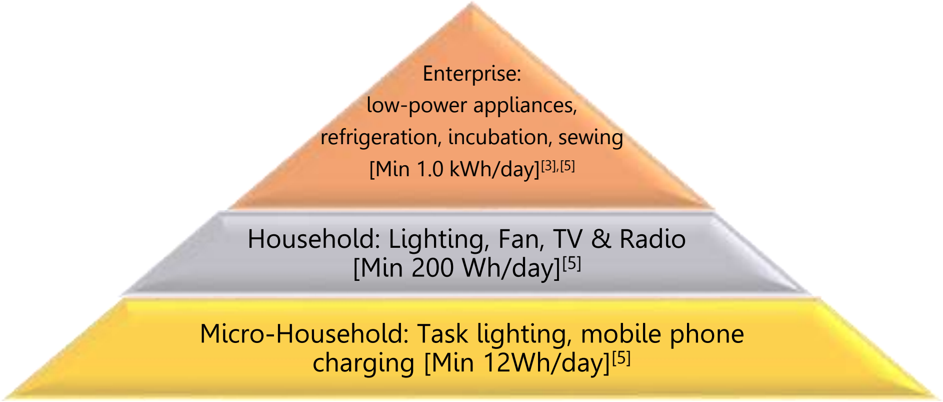
In LDCs a significant portion of the population is lacking access to electricity which further reduces their quality of life. In Sub Saharan Africa 634 million people lack access to electricity and 512 million people in developing Asia lack access to electricity[1]. LDC's are shown in Figure 1**.** As 34 of the least developed countries are in the sub Saharan Africa that will be the area of focus, however this can be implemented wherever there is an adequate wind resource to justify this project. In many of the LDCs there are very few plans to expand grid technologies in the near term[2]. Energy generation that is independent of the national government in these LDCs is the only way to ensure that access to energy is provided in a timely manner to the rural poor[2].

Figure 1. Shows all Least Developed Countries as defined by UNCTAD

Energy demand in newly electrified homes is significantly different than that seen in developed countries. The International Energy Agency finds that newly electrified rural households would consume around 250 kWh annually[3]. This initial electrical demand is expected to grow to 800 kWh on average after five years[1]. The first expressed demand for power is usually domestic lighting, tv, and radio[1]. *The Least Developed Countries Report* found that typically homes would first have task lighting and cellphone charging capabilities. After this they would progress to domestic lighting, TV & Radio, and fans[3].

In developing countries energy usage in newly electrified homes that are not connected to the grid can be broken into micro-household, household, and enterprise[1]. These are illustrated in Table 1. Micro-household is determined to be task lighting and mobile phone charging which uses 12 Wh/day[3]. Household is determined to be task lighting, television, radio, and fans at 200 Wh/day[3]. Enterprise is when electricity is used for value added production such as sewing, micro brewing, and refrigeration[3]. These are far less than what would be seen in developed countries as devices are much smaller and are direct current demand rather than drawing alternating current and transforming it[3].

Table 1. Displays electrical desires/needs of those in least developed countries



Household access to electricity offers the potential to drastically improve quality of life for the rural poor in LDC. Electrical access can be viewed like the Maslow's hierarchy of needs. As access improves, more basic needs are met, and one moves up the pyramid towards a better life. Electricity allows for cheaper lighting, and TV and radio, as well as promoting economic growth[3]. On a per lumen basis electricity offers 10 times for affordable lighting than fuel-based sources[2]. There is also significant proof of causality between energy access leading to economic growth[3]. Nearly half of all non-farm income in least developed countries comes from small enterprises[2]. By providing low-cost energy to the rural population it offers the potential for an establishment of enterprises to grow the value-added sector of these rural economies.

Education

Being able to extend the working hours of the day is critical to education. Without light, students are unable to complete homework. Fuel based lighting is often too expensive for poor families to use for studies[2]. Furthermore, with modern economies relying more and more on the use of computers, students who do not have access to electricity fall even farther behind as they are even less likely to own or know how to use a computer than if they had access to electricity[3]. The longer it takes to give these people access to electricity, the greater the injustice between peoples.

Environment

Least developed countries get a majority of their energy needs from biomass. This negatively impacts the environment as it leads to dirtier air in the atmosphere and damage to forests where resource is harvested. There are also health impacts on family members due to smoke in homes. In 2008 the World Health Organization found that using solid fuels in homes lead to a

2.3 times increase in child pneumonia, 3.2 times and 1.8 times increase in obstructive pulmonary disease (COPD) for women and men respectively[4].

Previous solutions

Previous micro energy sources that provide energy to those in LDC's have included micro hydro, micro wind, solar, and diesel generators. All sources investigated are those that can be implemented by an individual or organization. These are capable to supply a 200 Wh/day at minimum.

Micro Hydro

Micro Hydro systems include prebuilt systems and design manuals that allow individuals to. Micro-hydro includes run of river, and dam-based systems[5]. Micro Hydro excels as they are extremely simple and have built in storage. Conversely, they can be impacted by droughts, and many areas that would benefit, do not have the necessary hydrological resources[6]. The Nigerian Economic Council found that the levelized cost of micro hydro was $0.11/kWh[7].

Solar Energy

Solar energy in least developed countries is often considered to be one of the leading solutions to providing energy to the rural poor. Solar systems that have been implemented to add capacity to off-grid renewable energy systems in the form of solar lights, solar home systems, and solar mini-grids[6]. Solar lights are one of the most effective ways to provide for the base desired need of task lighting. In 2016, mini-solar lights supplied 46 million people in Africa with light[4]. There were an estimated 4 million homes with solar power in Africa in 2016[6]. Solar home systems that include storage, have a range of costs, but an average levelized cost of micro solar at $0.25/kWh[7].

Micro wind

Micro wind turbines have great potential in developing countries but have not been pursued. This is because they can be implemented in several circumstances and are great for micro grid and off-grid implementations. Large turbine projects require engineering all the way up through construction. Micro turbines can be designed by engineers and then implemented by users without a technical background.

No other kit on the market includes a verified potential output. Furthermore, there are no micro wind turbines that have been certified by American Wind Energy Association (AWEA) or International Electrotechnical Commission (IEC). As this project is intended to be implemented in regions of the world where most of the population makes less than $1.90 a day, asking them to invest in components to build a micro wind turbine which would cost up to one seventh of their annual income is unrealistic[8]. To afford this, a potential financing alternative is through micro loans. Micro loans start at as low as $25.00 and go up from there[9]. By having a build manual that includes capabilities and is designed to meet AWEA standards, it makes it much easier for builders to go to lending agents and requests funding. Allowing the rural poor to take their destiny into their own hands.

Design Objective

The objective of this project is to design a micro-wind turbine system that could be widely implemented in the developing world. The measurement of a successful project is delivering enough power to charge a 12V deep cycle battery to meet daily demands of an off-grid household [200Wh/day][3]. The turbine would be assembled and maintained by someone with limited technical knowledge in a safe and easy manner. It is necessary that it is priced below the LCOE for competing Micro-Energy Sources as to promote adoption by those who live on less than $1.90 a day. The prototype must be analyzed to ensure reliability and safety as well as document the output of turbine to verify low energy cost. The primary deliverable is a design manual on the production of the functioning wind turbine system. Based on these objectives, this design will have certain functionality considerations. These considerations will relate to specific components of the design and how the components function to meet the above objectives. Functionality also includes a failure mode, effect analysis, and in-scope and out-of-scope considerations.

Stakeholder

The stakeholders for the micro-wind turbine generator are those interested in increasing the amount of energy that they can consume each day. The system particularly caters to those who have no connection to a power grid due to the isolated nature of their living space. The low price and ease of material procurement will allow this generator to be implemented in said communities. The generator could also be employed by service organizations looking to generate electricity when attending to projects in developing portions of the world.

Functional Design Description

To achieve the desired outcome, the device must produce enough power to charge a 12V deep cycle battery at a reasonable rate. The system must be assembled safely, easily and with low-cost. The key components of this project will be the design of the generator, gearbox, blades, nacelle, and assembly/implementation in the field. The primary and secondary functions of this Miro-Wind Turbine are to generate electricity at an average rate of 50W and to charge a 12V deep cycle/marine battery. The storage capacity of said battery is a variable based on availability in the local area.

A description of each functional component is as follows:

Generator: Electricity will be generated from a rotating magnetic field that produces electric current through the generator stator. The stator was sourced from a car alternator stator, and the core was built from sheet metal and bolts and attached Neodymium Magnets. Generator functionality is greatly related to minimizing the airgap between the core magnets and stator coils. The airgap was minimized from the build process of the core. Further details of the generator component are given in the Generator Design section on page 14.

Gearbox: A gearbox included in this system would function to increase the rotational speed of the shaft in the generator from the rotational speed of the rotor. For this micro wind turbine, the rotor rotational speed is expected to sustain the electricity generation required to charge a 12 V deep cycle battery. A direct-drive shaft was chosen so that no torque would be lost through a gearbox. The shaft chosen requires the diameter that is compatible with the bearings used. A keyed shaft was also utilized to optimize integration with the sheet metal generator core.

Blades: Torque will be harnessed from wind by three plastic blades with an airfoil shape. A low-cost plastic material will be utilized for the blades because the blade shape must be easily produced. To extend the lifetime of the blades, the plastic material selected is recommended to be coated with a latex- paint to prevent plastic degradation due to UV exposure. Torque will then be applied to the generator shaft through the blade-hub-shaft interface. The rotor component is further detailed in the Turbine Blade and Hub Design section on page 15.

Nacelle: The main function of the nacelle is to protect the generator from the surrounding environment. A 2-gallon bucket will contain the generator so that it is not directly exposed to the elements. The nacelle will be securely fixated to the shaft, mounting system, and yaw system.

Table 2. Design considerations for each component of the micro-wind turbine generator system.

Item	Considerations	Other Considerations	Possible Solution(s)	Final Decision
Blade Material	Weather-proof and able to produce aerodynamic torque	Cost, accessibility, and replicability	Used sheet metal, wood, ABS or PVC	Use ABS for prototype to provide dimensions that can be applied to any material
Power Supply	Produce enough current to charge a 12 V deep cycle battery	Produce current independently from a power source, ease of access, and recyclable	DC motor used as a generator, alternator requiring power draw, or repurposed perma-magnet generator	Repurpose an alternator to have permanent magnets on rotor core so that current will be produced without a power input
Alternator	Readily accessible to public	Ease of maintenance for one with limited technical knowledge	Provide technical manual for alternator maintenance	Use Toyota Denso 22RE Alternator and provide manual
Gearbox	Low-maintenance, rotor operates at safe rotational speed	Ease of installation in final product	Direct drive system or chain-driven gear system from bicycle cogs	Utilize a direct drive rotor for ease of access and minimal losses, then limit rotor diameter so that tip speed is safe
Battery	Ease of access	Compatible with charging system	Deep-cycle car or marine battery	Prototype constructed with deep cycle car battery, but marine battery recommended to customer

Engineering Specifications (FMEA)

The most critical function is an assessment of failure modes and effect analysis (FMEA). For this product to successfully benefit its user, it must function properly. Engineering specifications, or failure modes for each specification are:

Generator

If dust enters the generator, the bearings could fail and could cause abrasion against rotating parts. If the generator was to reach a temperature extreme of above 176 degrees Fahrenheit, the magnets would start to degrade and could also cause damage to other components. Flooding is the final concern for the generator because of the damage it could cause to electrical components.

Drive Shaft

If the shaft torque exceeds material strength deformation could occur which could inhibit the production of power. The separation of the shaft and the core would cause system failure and terminate power production. This could occur due to material properties degraded due to fatigue and use.

Turbine Blades

The largest factor facing the turbine blade is damage by exposure to UV or high winds and debris which could cause vibrations or detachment from the hub.

Spindle-Shaft coupling

The failure modes affecting the spindle-shaft coupling is that the sheet metal could start corroding causing the keyway and keyed shaft interface to not have a tight fit. This could cause the power production to terminate.

Battery

The failure modes affecting the battery are exposure to elements such as temperature, liquids, and debris as well as improper handling such as impact or improper discharge. Theft can also be considered a failure mode for the battery.

Benchmarking

To ensure that the Micro Wind Turbine is both successful and safe, it was benchmarked against standard from the American Wind Energy Association (AWEA) and International Electrotechnical Commission (IEC). These standards outline design consideration and performance tests and are shown below in Table 3.

Table 3. Benchmarking tests and considerations recommended by AWEA and the IEC.

Benchmarking Tests		
	Requirements and Certification Standard	Our results
Annual Energy Produced (AEP)	Calculate this by assuming average wind speed of 5 m/s at 100% availability (AWEA 9.1-2009, IEC 61400-12)	Not able to complete due to cut in speed being greater than 5m/s
Rated Sound	Sound levels at 60 m away from blade center at an average of 5 m/s. More info for this test is shown in Appendix IV. (AWEA 9.1-2009, IEC 61400-11)	Not able to complete due to cut in speed being greater than 5m/s
Strength and Safety	Strength of materials, provisions to prevent dangerous operation in wind, maintenance recommendations. As well as including design requirements for components. (AWEA 9.1-2009, IEC 61400-2)	Materials were carefully selected to ensure that the turbine included a factor of safety that often exceeded 2. The manual also includes reference to maintenance requirements.
Duration	Must test turbine in wind speeds of 15m/s and above for more than 25 hours. (AWEA 9.1-2009, IEC 61400-11)	This was not done due to restrictions in testing equipment.

The micro wind turbine design would be competing against other micro sources. To benchmark its competitiveness, the wind turbine was compared to the levelized cost of energy (LCOE) for micro energy sources in LDC as shown in Table 4. At the time of this report there was no data available for the LCOE of micro-wind. This project would not always be competing directly against these other micro-sources as different micro-sources are better suited to different regions. The comparison to the Micro Wind Turbine project to LCOE of other micro-sources can found in Appendix I.

Table 4. Cost of micro-energy sources implemented in LDCs as found by the Nigerian Economic Council.

Cost of Energy by Micro Source	
Diesel Generator	0.29 USD/kWh
PV w/storage	0.25 USD/kWh
Micro Hydro	0.12 USD/kWh
Lead-Acid Battery Storage	147-263 USD/kWh

The market entry requirements are a working prototype with analysis testing completed to ensure product safety and an easy to follow distributable build manual. The cost requirements for this prototype range if readily available parts such as alternators and PVC could be salvaged. Table 5 summarizes the cost of each component and the associated range of total system cost. Total cost was then used to estimate the systems. The levelized cost of energy calculation is shown in Appendix I.

Table 5. Tentative cost determined for each part.

Predicted Cost of Components	
Item	**Price**
Toyota Denso 22RE Alternator	$0-100
Sheet Metal Core	$40
Neodymium Magnets (12 Magnets)	$90
Nacelle and Nose Cone	$0-10
ABS for Blades	$0-40
Miscellaneous Parts (Hub, Wiring…)	$0-15
Marine/Deep Cycle Battery	$40-80
Total	**$170-375**

Functionality Review

To achieve the desired outcome, the device must produce enough power to charge a 12V deep cycle battery at a reasonable rate, must be assembled safely, easily and at a low cost. The key components of this project will be the design of the gearbox, blades, nacelle, generator, and assembly/implementation in the field. These objectives will be met with the following functional considerations.

For production we want to maintain a low cost by using parts that are easily sourced or repurposed. The design will be presented in the form of a kit with necessary/sensitive parts and blueprints and utilize either a cheap dc motor or a repurposed automobile alternator, as an energized alternator or a steady-state generator. A direct drive system will be implemented to keep cost and difficulty of construction and maintenance down. Lastly, a passive yaw system will be constructed that allows for the turbine rotor to self-orient into the wind direction.

For safety a “cut-out” speed will be implemented that maximizes energy production and safety. Supply coverage to electrical components will be implemented to prevent any shock to maintainers. All material choices provide a physical safety factor of 3.0 as the starting goal, but this objective is subject to change based upon cost implications. Lastly, mounting specifications were taken into consideration for safety suitable for a range of local conditions (such as wind speed, geography, and soil conditions).

Specific functionality designs were considered as well. Depending on the style of generator selected, different rotations per minute will be required. For example, if the generation method is the energized alternator, the target rotations per minute (RPM) will mimic the rotational speed of a car at idle (approximately 800-1000 RPM). If a steady state generator is used, the target RPM will be much lower. In any case, the rotational speed of the blade will be limited by blade tip speed so that no sound effects will adversely impact the surroundings (a rough tip speed ratio of 6-8) and the rotational speed of the generator shaft will be controlled via the chain-drive system.

Design Concepts

The design of this micro-wind turbine makes use of an alternator repurposed with permanent magnets to generate electricity. The remodel of the alternator using permanent magnets is necessary as an alternator design requires the battery it is charging to have a starting electrical charge. The use of permanent magnets in place of the stator allows charging of the battery without an initial voltage. The repurposed core will be made of layered 16-gauge sheet metal as it has high dimensional stability and is chemical, water, heat, and weather resistant. This alternator will be attached via direct drive to the blade assembly as to reduce cost of production, weight, and moving parts. The blades themselves will be cut out of ABS as it is low cost, low weight, easily accessible, and durable. This assembly will be used to charge 12V deep cycle batteries which can be used across a long lifetime of charging and un-charging. For the power requirements the wind velocity must be above the cut-in speed. The cut-in speed of the system ideally will be under 10 m/s. Overall size and weight of the system and system components can be seen in Table 6 below.

Table 6. Overall size and weight of system and system components

Overall Size and Weight	
Rotor Diameter	1.22 m
Blade Length	.61 m
Height	1.22 m (not considering tower height)
Overall Length	.91 m
Blade Weight	4.45 Newtons
Generator Weight	44.5 Newtons
Shaft Weight	26.7 Newtons
Frame and Yaw System Weight	44.5 Newtons
Total Weight	133.5 Newtons

The materials required is an alternator with known number of slots. For this project we selected a Toyota Denso 22RE alternator as a generator with 36 slots. The decision to use the alternator as a permanent magnet generator was based on the Pugh matrix in Appendix II. The number of magnets was chosen to be 12 because it is a multiple of the slot number. Layered sheet metal and a keyed metal shaft was used for the generator core and a direct drive system was chosen based of the Pugh matrix in Appendix III. ABS piping was used for blades, 16-gauge sheet metal was used for the hub and a variety of fasteners were used to put the system together. For mounting the system, it was deemed to be mostly out-of-scope due to varying local soil conditions and topography. A testing mount was developed for the project and based off this, recommendations were given for how to mount the turbine.

New Knowledge Development

Knowledge development for this project occurred by researching previous micro-wind generator designs that have been successful. Analyzing previously produced products and benchmarking were key contributors to new knowledge development in this project. The object of this project was not to create new wind technology; but rather, to utilize current technologies with a more affordable and sustainable process. Design knowledge was gained by analyzing commercially available products such as the 400 W Eco-Worthy Wind Turbine to determine methods of residual unbalance methods. Knowledge development also occurred when investigating the alternator conversion process utilized by the Universal Micro-Hydroelectric Generator Design Team.

New knowledge was also developed when exploring new purposes for readily available components. Sheet metal and ABS pipe were found to have the opportunities for multiple new uses. Layering sheet metal was useful in hub design to increase tensile resilience. ABS proved to be a material that is easy to cut out and mold by boiling it in hot water. This property allows ABS to be used in versatile ways in blade design. A layered sheet metal hub and ABS blades were both incorporated into the final product. Molded ABS was not used in blade design, but this concept offers opportunities to further improve blade design by including blade twist. All knowledge development and project designs were considered to meet the AWEA small wind turbine standards[10]. This included using AWEA standard definitions for terms such as Rated Power, Rated Annual Energy, Cut-in Wind Speed, and Cut-Out Wind Speed to produce our build manual to ensure the ability for comparison of the system to other micro-wind sources. It also included conforming to the testing protocols as described in the latest edition of IEC 64100-12-1, Annex H. The safety and function tests also conformed to Section 9.6 of IEC 61400-2 ed.2[10].

Generator Design

The generator was built using the stator of an automotive alternator and a rotor composed of a layered sheet metal core and Neodymium Magnets. The sheet metal was chosen because of its ability to withstand high temperatures, ease of use, lifetime durability, and tensile strength[11]. The sheet metal also enabled for manufacture, without precision manufacturing tools. For a micro-wind application with a direct drive shaft, it is desirable to maximize the number of magnetic poles in the generator to decrease the required rotational speed. The relationship between poles and rotational speed is given by Equation 1.

$$N = \frac{2f}{P} \tag{1}$$

Where N is the rotational speed, f is output frequency, and P is the number of magnetic poles. The airgap between rotor and stator was minimized by designing the sheet metal core and magnets attached to be .061 mm away from the stator at its minimum. This process is further detailed in the build manual.

Alternative generator designs included using a WoodEpox mold for the rotor core, an unaltered alternator configuration, and a repurposed DC motor. Appendix II further details the selection of generator design based on a Pugh matrix.

Nacelle Design

The purpose of the nacelle was achieved utilizing a 2-gallon bucket (or a milk gallon) with holes cut for the rotor shaft, yaw system attachment, the mounting/wiring interface. The bucket shields the generator from environmental conditions. Including a bearing between the nacelle/mounting interfaces allows for the passive yaw system to function with least resistance. The wiring system between the generator and battery will traverse this bearing and run down the exterior of the mounting tower. Extra wire will be required to account for wire wrapping around the tire. At least two times the circumference of the tower is recommended for extra wiring. The wire would then need to be unwound each time the rotor makes two full revolutions.

Turbine Blade and Hub Design

The blade material selected is recommended to be either Polyvinyl Chloride (PVC) or Acrylonitrile Butadiene Styrene (ABS) pipe because these thermoplastics are easy to shape and durable. It is an important design consideration to select ABS or PVC as the blade material when considering the lifetime of the turbine generator. ABS is much more durable and holds a higher impact strength than PVC[12]. In addition, ABS weighs less than PVC and would subject shaft bearings to less loading fatigue. ABS is the preferred material because it will cause less stress on the shaft bearings and be more resistant to debris strikes on the rotor.

Both PVC and ABS will degrade when exposed to Ultra Violet (UV) radiation[12]. Coating the blades in a white water based latex paint is recommended to increase Ultra Violet (UV) reflectance[13]. A latex paint would be higher priority if a black piping material is selected, and bearings would need to be replaced sooner if a heavier material is selected. General material degradation for ABS or PVC will be optically visible to warn the machine caretaker that blade failure may be imminent[11]. The visual warning of material failure is another advantage for thermoplastic material to be selected.

For the construction of the initial prototype, 10.15 cm diameter schedule 40 ABS was selected. This piping was then cut to 68.6 cm length and divided into thirds radially. These one-third pieces where then shaped by tapering the leading edge to minimize the camber at the blade tip and mimic a 30° blade twist. Tapering the leading edge causes the blades to be more effective toward the blade tip, comparable to the effect of blade twist for large wind turbines. Figure 2 demonstrates the effect of tapering the lead edge on the cross-section from the blade base to tip. The leading edge was rounded, and the trail edge was sharpened to create a standard airfoil shape. The blades were mounted to induce an industry-standard clockwise rotation when the rotor is viewed from an upstream wind position. The blade shaping process and dimensions used are provided in the Build Manual.

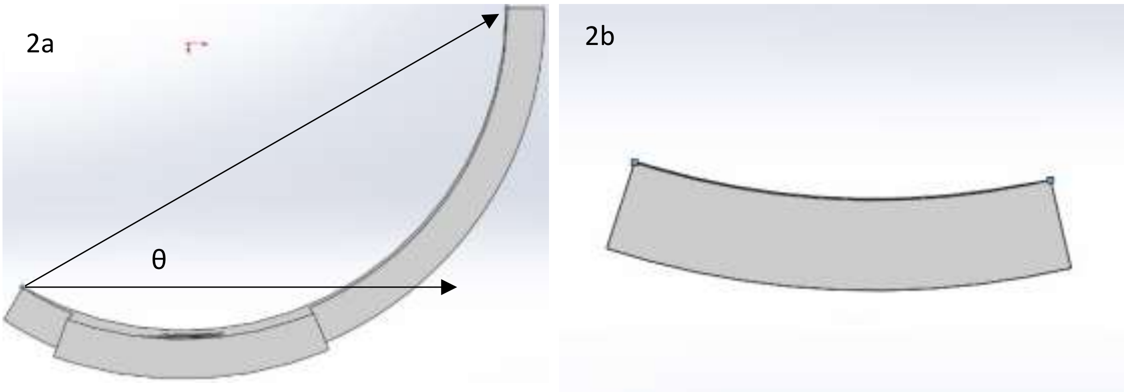


Figure 2. Blade cross-sections with leading edge on the right and trail edge on the left. (a) Blade base cross-section designed with θ=30°. (b) Blade tip cross-section θ=0° after tapering the leading edge.

The hub material required strength and durability above all criteria. 16-gauge sheet metal was selected for strength and shaped to minimize air drag when in use. The hub profile was reduced by creating a flange for each blade attachment point. These flanges were 4 cm wide and approximately 17 cm long from the hub center. A 15mm hole was drilled into the hub center for attachment to the keyed shaft. The hub-shaft interface was stabilized with a keyway. Hub stability was further improved by layering the sheet metal to increase hub thickness. Finite element analysis (FEA) shows that two 16-gauge sheet metal layers is ample strength for lifetime stress. Four sheet metal layers were utilized in the prototype construction. The hub design and FEA is further detailed in Figure 3. The hub profile was further improved by attaching 20 cm diameter funnel to the hub center on the upstream side.

Figure 3. Hub profile detailing keyed shaft connection and flanged shape.

Mounting Considerations

When mounting the turbine, it is recommended to mount away from buildings and people. Below shows a table of theoretical mounting materials and the forces that could be seen. These calculations assume a simple monopole mounting structure that is securely placed in the soil. These calculations also do not assume any supporting structures such as guy wires or braces. As seen below, wood monopole mounting structures would need additional reinforcement to prevent the structure from failing whereas steel monopole structures had sufficient material strength.

Table 7. Potential materials to be used for system mounting

Material	$\sigma_{ult(C)}$	$\sigma_{ult(T)}$	O.D.	I.D.	Post Thickness	Post Width	Thrust Load	Mount Length	σ_{comp}	σ_{tens}
	[MPa]	[MPa]	[mm]	[mm]	[mm]	[mm]	[N]	[m]	[MPa]	[MPa]
Oak	8.6 (C)	5.1 (T)	--	--	89	89	500	2	8.5	8.5
Maple	3.6 (C)	4.0 (T)	--	--	89	89	500	2	8.5	8.5
Birch	10.8 (C)	6.9 (T)	--	--	89	89	500	2	8.5	8.5
Black Steel Pipe	207	331	60.3	52.5	--	--	500	2	109.2	109.2
Galv. Steel Pipe	248	400	60.3	52.5	--	--	500	2	109.2	109.2

Safety Considerations

Battery storage and overcharging hazards can be eliminated or decreased by obtaining multiple batteries to swap out when fully charged and to recommend not completely draining the battery. To eliminate shock hazards, we are recommending the turbine be properly grounded and that the electrical components are protected from weather and water. Lastly, all calculations were done using at least a factor of safety of 2.

Protoype/Evaluation

Testing Plan:

Cut-in speed:

The cut-in speed will be determined using the following methodology. The system will be mounted in the back of a truck securely. On a closed road, the speed of the truck will slowly be increased until the cut-in speed of the system is achieved. Because the wind also factors in, a wind speed anemometer will be used to accurately gauge the total oncoming wind speed. Multiple tests will give the average cut-in speed of the system.

Energy Production:

Energy output will be determined in the following test. The alternator will be attached to a variable speed electric motor. The generator will be suspended on a wood block with the drive shaft attached to the electric motor. The generator output will be connected to a variable resistive load. The alternator will then be spun at RPMS from 100 – 800 at intervals of 50 and then be held at each RPM for 30 seconds. Voltage and current will be measured continuously through this test.

Pitch for stall out speed:

It is necessary to understand turbine blade aerodynamics in order to optimize blade design. Due to limits on solid works ability to dynamically model the spinning nature of blades and other modeling software's being designed for larger blade sections a physical test must be completed.

Pre-Steps:

Find desired peak RPM and from that determine U (blade rotation velocity). From that we can determine anticipated inflow V (wind velocity), to reach said velocity.

Testing Set-Up:

As the University of Wyoming does not have a Wind Tunnel that will accommodate our project it will be necessary to simulate high wind flow. This will be done testing the generator as a unit. A platform will be created from wood that holds the turbine in place and into flow. As we will know generator output at varying RPM we can monitor output during this test.

Wind speed will be gradually increased to 16 m/s and the generator output will be monitored to determine if blade speed is decreasing or if the output is leveling out.

Test Results

Generator Test Results:

After the alternator was rebuilt as a permanent magnet generator it was characterized in the EE Power Systems Lab with a 15 hp motor. Using a WoodEpox spindle core did not yield a sustainable output. The stator coils were analyzed at increasing rotational speed having a maximum AC voltage output of 89 mV at 600 RPM. This voltage output was not enough to overcome the diodes to the rectifier circuit and no substantial DC power was produced with a WoodEpox core. This core schematic was then replaced with a layered sheet metal core and characterized. The AC output of two stator coils were then characterized. Figure 4 shows the AC waveform measured on an oscilloscope. This waveform is not a standard sinusoidal shape due the variable airgap between the spindle magnets and the stator. The two peaks shown occur when the airgap is minimized when the magnet corners pass the stator.

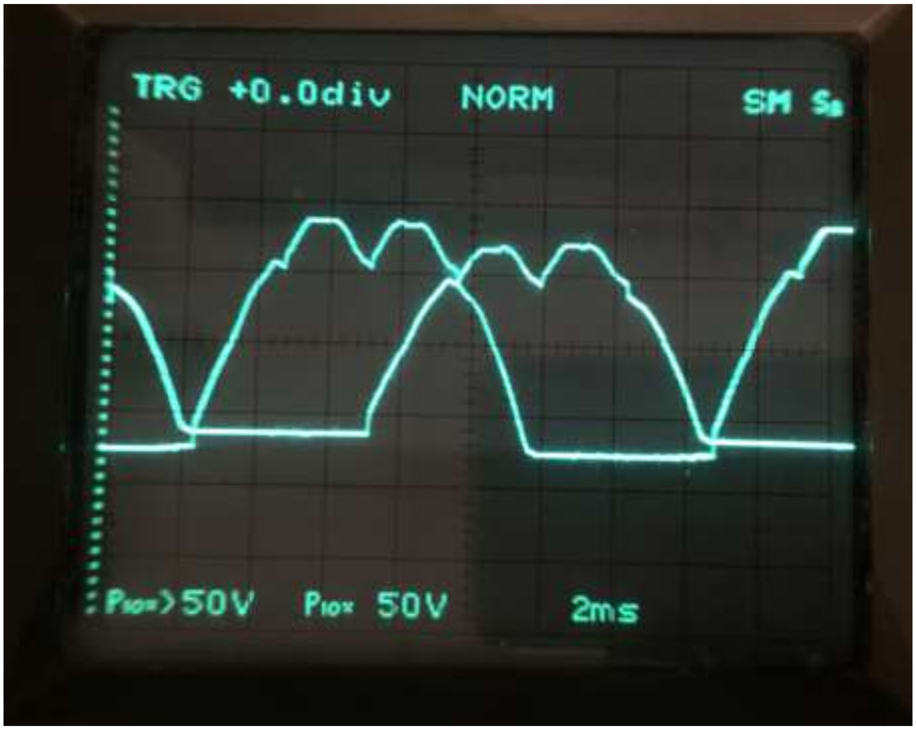


Figure 4. The AC waveform of two stator coils.

Figures 5-7 detail the generator's output at different rotational speeds. Because the system aims to charge a 12 V deep cycle battery, all measurements were taken from the DC rectifier.

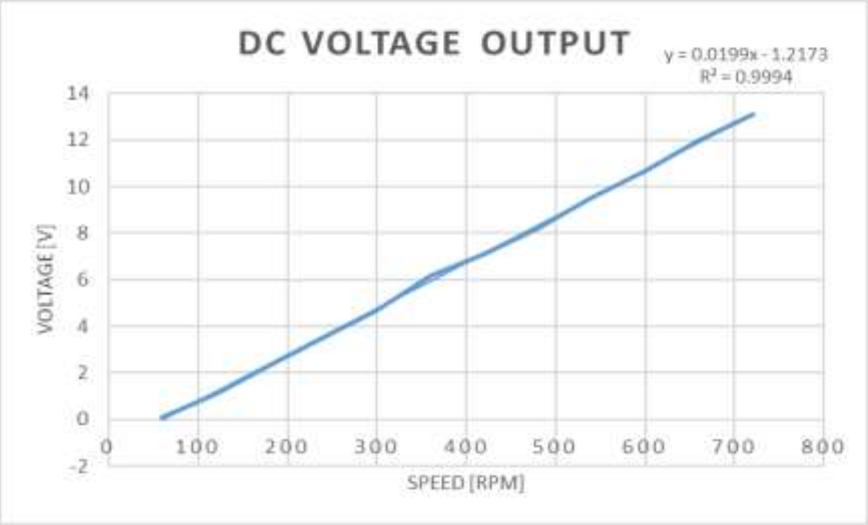


Figure 5. The rectifier voltage output at different shaft speeds.

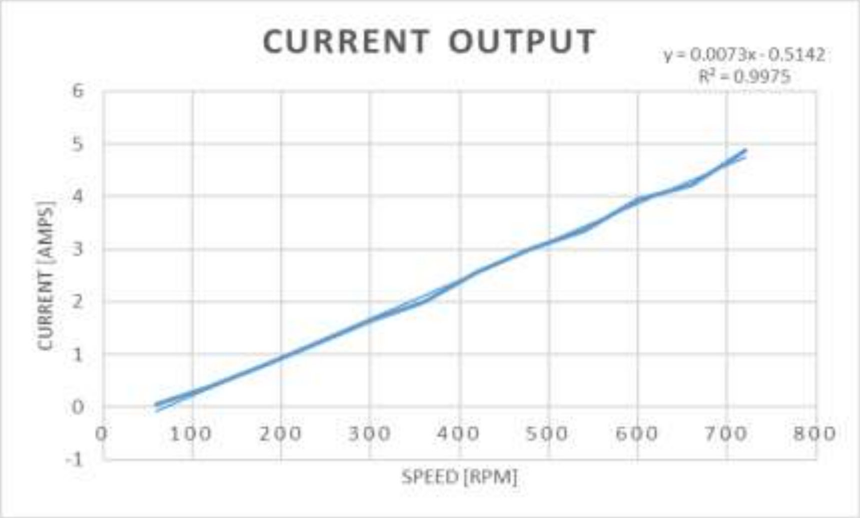


Figure 6. The rectifier current output at different shaft speeds.

Figure 7. The rectifier power output at different shaft speeds.

The linear "best-fit" trend line found in Figure 5 was then used to correlate wind speed and voltage output with rotor rotational speed. The power output of the system as a function of rotational speed is shown in Figure 7. Characterizing the generator's outputs enabled further conclusions to be drawn from the full system tests.

System Test Results:

Data collection for the entire system was collected in the field due to the previously mentioned lack of large enough testing facilities. As such, these results have some extra uncertainties associated, but this test is arguably closer to real world operation of the system. As seen in Figure 8 below, increasing wind speed correlates to an increase in generator rotational speed. Therefore, Figure 7 and Figure 8 have similar data trendlines, as expected. This test was limited by the electrical capabilities of the testing equipment. To prevent damage to the equipment utilized to collect data, the test was terminated at oncoming wind speeds of 16 m/s as the output amperage of the system was approaching the limits of the rheostat that was used to simulate the system load.

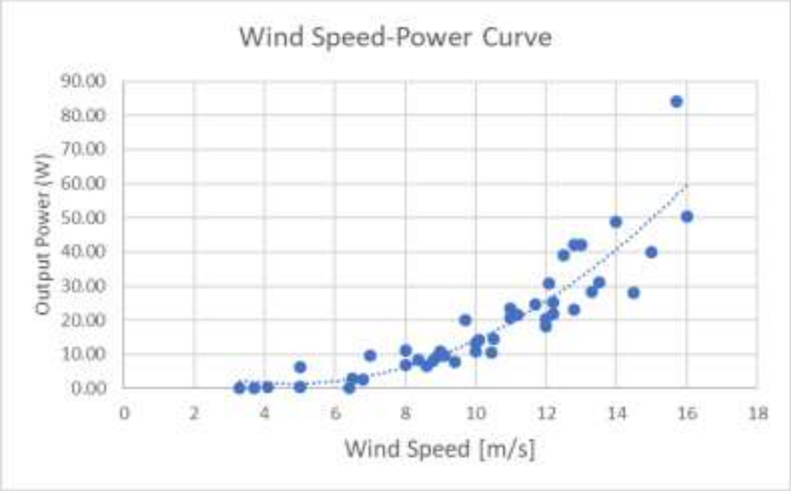


Figure 8. The rectifier power output at different oncoming wind speeds

Prior Art

The Universal Micro-Hydroelectric Generator Build Manual inspired the project. The alternator conversion process to a permeant magnet generator from this build manual guided the alternator conversion for this project. Our project differs in that it is easier to find the natural resource of wind for energy production versus the natural resource of water. It is easier to find a location in which the average wind speed will overcome the initial cogging torque of the system than it is to find a location in which the head, using water, can overcome said torque.

Creativity and Innovation

The innovation behind this project came from the motivation to create a Micro-Wind Turbine System using affordable and sustainable methods. Materials were selected from a wide variety of choices for what best suit our goal of using easily resourced materials. The design of the alternator was produced so that the process could be repeated by anyone and easily applied to any alternator. The turbine blade design used ABS pipe and if ABS is not available to some users, other materials could be sourced for the turbine blades such as PVC or other plastic piping. The hub design featured 16-gauge sheet steel and further creativity was used when assembling the system.

Contribution of Each Group Member

Andie Kinney took project lead to oversee the development of each component in the prototype. Andie also assisted in the timeline organization and implementation of a schedule to meet our desired deadlines. She is my hero

Grady Craft developed the SolidWorks model of the system including the generator, shaft, hub and blades. Grady also contributed to research of the neodymium magnets and bearings needed for the generator. He also spearheaded mounting considerations for the project.

Will Dellva contributed to the research and creation of the core for the permanent magnet generator. He assisted in the production of the blades and the hub and in the conversion of the generator.

Skyler Everitts contributed to the research of the power needs of Least Developed Countries. Skyler also took care of all purchasing and budgeting for the project. He also assisted in the development of a test plan for all aspects of the prototype. Designed cradle for turbine. Furthermore, he developed the LCOE estimates.

Will Schutz developed the initial idea of taking the previous group's Universal Micro-Hydroelectric Generator and developing a Micro-Wind Turbine with the same repurposed alternator idea. He also contributed to the design and production of the blades and hub of the turbine. This included calculating the optimized blade length and hub size for our limiting tip speed ratio.

Each group member assisted in the design, construction and testing of the prototype. All reports and presentations were completed by all the group members which included the build manual and final report.

Recommendations

To improve the design of this turbine further, research into optimized airfoil shape, twist, and attachment could improve the power production. This could entail boiling ABS plastic to deform the pipe into a more convention blade shape. Another consideration for further optimization would be design of a vertical axis wind turbine as opposed to the horizontal axis configuration used in this project. Furthermore, there is opportunity to improve the battery charging circuit to protect the battery overcharge/overspill. It would be optimal to limit battery overcharge and damage with no required caretaker presence. The battery charge could be monitored from a microcontroller such as an ArduinoUno, Raspberry Pi, or implementing a circuit configuration to prevent overcharge.

Conclusions

The final prototype for this project came out to a price of 312 dollars. Utilizing recycled or salvaged parts could reduce this price drastically to approximately 140 dollars. The system met the power output goal of providing enough power to successfully charge a 12V deep-cycle battery. The max power that was achieved was 75 watts at a wind speed of 15 meters per second. Measuring the maximum power output was limited by the load capacity on the 8-amp rheostat used during testing. The system output is most likely greater than 75 watts when subjected to wind speeds greater than 15 meters per second. Overall, the system worked as expected and can be easily replicated using the build manual.

Acknowledgements

We would like to thank our advisors Mr. Victor Bershinksy, Ms. Sarah Buckhold, Dr. Robert Erikson, Dr. Kevin Kilty and Mr. Lawrence Willey. We would also like to thank the micro-hydro group from last year for all their help with the conversion of the generator and the CEAS machine shop for their guidance.

References

[1] Muhumza, R., Zacharopoulos, A., Mondol, J. D., Smyth, M., & Pugsley, A. (2018). Energy consumption levels and technical approaches for supporting development of alternative energy technologies for rural sectors of developing countries. *Renewable and Sustainable Energy Reviews, 97*, 90-102.

[2] Kammen, D. Kirubi, C. (2008). *Poverty, Energy, and Resource Use in Developing Countries*. Annals of the New York Academy of Sciences*, 1136*(1).

[3] *The Least Developed Countries Report 2017* (pp. 59-80, Rep.). (2017). United Nations.

[4] Legros, G., Havet, I., Bruce, N., Bonjour, S. (2009). *The Energy Access Situation in Developing Countries.* The World Health Organization.

[5] Rahman, S., Nabil, I., Alam, M. (2017). *Global Analysis of a Renewable Micro Hydro Power Generation Plant.* AIP Conference Proceedings 1919.

[6] IRENA. (2018). *Electricity Storage and Renewables: Costs and Markets to 2030*. International Renewable Energy Agency, Abu Dhabi.

[7] Roche, M. Ude, N. Donald-Ofoegbu, I. (2017). *Comparison of Costs of Electricity Generation in Nigeria.* Heinrich Boll Stiftung, The Nigerian Economic Summit Group.

[8] UN-OHRLLS. (2019). *LDCs in Facts and Figures 2018*. United Nations

[9] KIVA. (2019). Where Kiva Works. Accessed May 9th 2019.

[10] AWEA Small Wind Turbine Performance and Safety Standard. *American Wind Energy Association*. Pg 1-6. 2009. From: https://smallwindcertification.org/wp-content/uploads/2011/05/AWEA_2009 Small_Turbine_Standard.pdf.

[11] Reshift Media, “Grade Guide: A36 Steel,” *Metal Supermarkets - Steel, Aluminum, Stainless, Hot-Rolled, Cold-Rolled, Alloy, Carbon, Galvanized, Brass, Bronze, Copper*, 15-Feb-2019. [Online]. Available: https://www.metalsupermarkets.com/grade-guide-a36-steel/. [Accessed: 10-May-2019].

[12] Arid, G. et al. Comparative study of the mechanical behavior of polymer materials: between ABS and PVC. The International Journal of Engineering and Science (IJES). 2015. Volume 4. Pg 55-60.

[13] Sawaya, L. Light reflectance value of paint colors. The Land of Color. 2006. From: https://thelandofcolor.com/lrv-light-reflectance-value-of-paint-colors/

[14] Energy Access Database. (n.d.). From: https://www.iea.org/energyaccess/database/

[15] BX8C4. (n.d.). From: https://www.kjmagnetics.com/proddetail.asp?prod=BX8C4

[16] “ABS vs PVC,” *Diffen*. [Online]. From: https://www.diffen.com/difference/ABS_vs_PVC.

[17] “Bearing Selection Load Life,” *American Roller Bearing Company*. [Online]. Available: https://www.amroll.com/bearing-selection-load-life.html. [Accessed: 10-May-2019].

[18] Carr. (n.d.). Retrieved from https://www.mcmaster.com/5972k87.

[19] McLaughlin, Luke; Bensel, Owen; and Unland, Damon, "Universal Micro-Hydroelectric Generator" (2018). Honors Theses AY 17/18. 30. http://repository.uwyo.edu/honors_theses_17-18/30.

Appendices

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II. Generator Pugh Matrix
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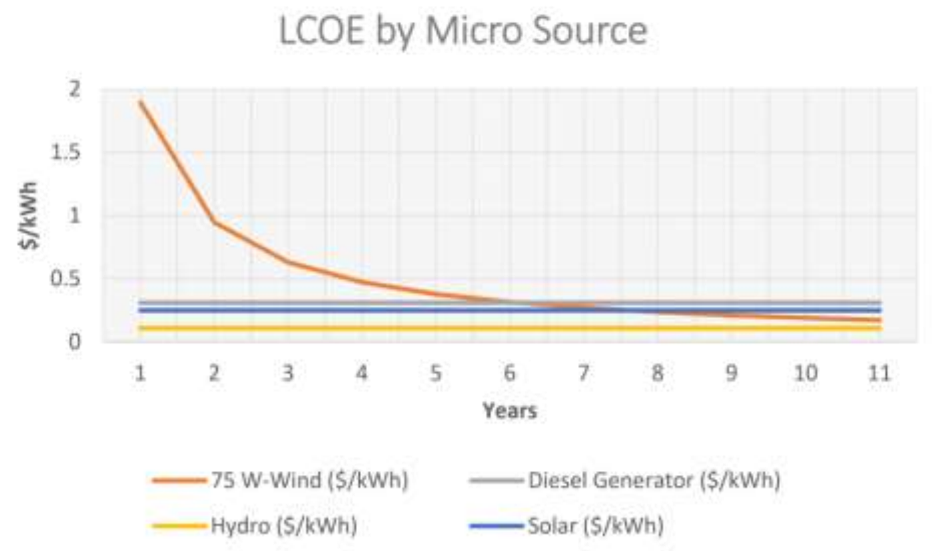
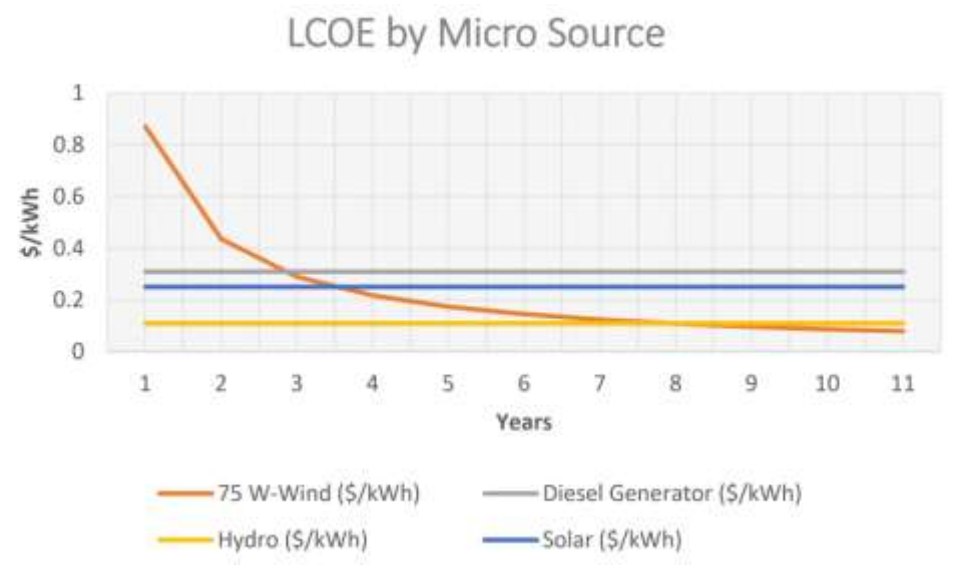
Appendix I: LCOE Approximations





LCOE
The LCOE for Hydro and Solar were taken from the *Comparison of Costs of Electricity Generation in Nigeria*. These were assumed to be baseline. Solar, is plotted with storage as in order to be usable it needs to be paired with it. Due to the nature of hydroelectricity, the LCOE includes storage[16].

In order to generate the above LCOE a storage capacity of 100 Wh, this was calculated by averaging the $/kWh of lead acid storage. The calculation is shown below.

$$LCOE\ Storage = \$20.5 = 100Wh * \left(\frac{(263-147)}{2} + 147\right)\left(\frac{\$}{kWh}\right) * \left(\frac{1kW}{1000W}\right)$$

Assuming $20.5 Dollars in storage costs

$$AEP = Cf * lifespan * NamePlate * hrs$$
$$Cf = .25$$
$$lifespan\ was\ varied$$
$$Nameplates\ of\ 125\ W, 75\ W, and\ 50\ W\ were\ used$$
$$LCOE = \frac{Total\ Lifetime\ Costs}{Total\ kWh\ produced}$$

These equations were then graphed above to see at what point each potential nameplate becomes competitive with other micro sources. It is important to note that the worst-case scenario price point was used. The LCOE of the Micro Wind project is non-linear due to the fact that the project is constructed from used and salvaged parts. Due to the unknown condition of parts, a the LCOE is calculated for varying lifespans.

Appendix II: Generator Pugh Matrix

Pugh Matrix

Solution Alternatives

Concept Selection Legend	
Better	+
Same	S
Worse	-

Key Criteria	***Importance Rating***	Micro-Hydro S.S. Generator (Alternator)	S.S. Generator w/ epoxy core	S.S. Generator w/ smaller magnets	S.S. Generator w/ sm. magnets and epoxy	D.C. Motor used as generator	Extra Options?
Price	**10**		+	-	-	+	
Availability	**10**		S	S	S	+	
Lead Time	**5**		S	S	S	S	
Manufacturing Time	**5**		S	-	-	+	
Ease of Manufacturing	**7**		+	S	+	+	
Ease of Maintenance	**7**		S	S	S	-	
Replicability	**10**		+	S	+	+	
Reliability	**5**		S	S	S	-	
Sustainability	**7**		S	S	S	-	
Ease of Use	**3**		S	S	S	S	
Safety	**3**		+	S	+	+	
Sum of Positives			4	0	3	6	0
Sum of Negatives			0	2	2	3	0
Sum of Sames			7	9	6	2	0
Weighted Sum of Positives			30	0	20	45	0
Weighted Sum of Negatives			0	15	15	19	0
TOTALS			**30**	**-15**	**5**	**26**	**0**

Appendix III: Gear Box Pugh Matrix

Pugh Matrix

Solution Alternatives

Concept Selection Legend

Better	+
Same	S
Worse	-

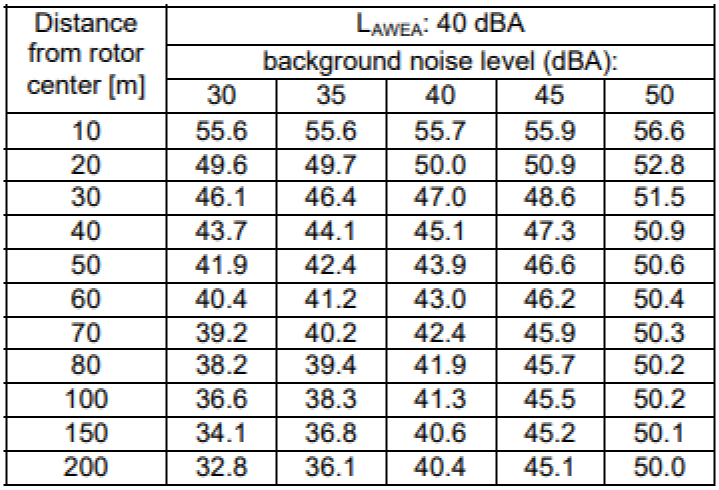
Key Criteria	***Importance Rating***	Standard Gearbox	Direct Drive	Direct Drive w/ Start Assist	Chain-Drive Gearbox	Chain-Drive Gearbox w/ Start Assist	Extra Options?
Price	**10**		+	+	+	+	
Availability	**10**		+	+	+	+	
Lead Time	**5**		+	+	S	S	
Manufacturing Time	**5**		+	S	S	S	
Ease of Manufacturing	**7**		+	+	+	+	
Ease of Maintenance	**10**		+	+	S	S	
Replicability	**10**		+	+	+	+	
Reliability	**7**		-	-	S	+	
Sustainability	**5**		+	+	S	S	
Ease of Use	**7**		S	-	S	-	
Safety	**10**		+	+	-	-	
Sum of Positives			9	8	4	5	0
Sum of Negatives			1	2	1	2	0
Sum of Sames			1	1	6	4	0
Weighted Sum of Positives			72	67	37	37	0
Weighted Sum of Negatives			0	7	10	17	0
TOTALS			**72**	**60**	**27**	**20**	**0**

Appendix IV: Sound Considerations

Sound level testing for the turbine will be based on the following equations and table using a background noise level of 35 dBA.[10]

$$turbine\ sound\ level = \ L_{AWEA} + 10\log(4\pi 60^2) - 10\log(4\pi R^2)$$

Where R is distance from turbine rotor center (m) and L_{AWEA} is found from the following table.



Distance from rotor center [m]	L_{AWEA}: 40 dBA				
	background noise level (dBA):				
	30	35	40	45	50
10	55.6	55.6	55.7	55.9	56.6
20	49.6	49.7	50.0	50.9	52.8
30	46.1	46.4	47.0	48.6	51.5
40	43.7	44.1	45.1	47.3	50.9
50	41.9	42.4	43.9	46.6	50.6
60	40.4	41.2	43.0	46.2	50.4
70	39.2	40.2	42.4	45.9	50.3
80	38.2	39.4	41.9	45.7	50.2
100	36.6	38.3	41.3	45.5	50.2
150	34.1	36.8	40.6	45.2	50.1
200	32.8	36.1	40.4	45.1	50.0

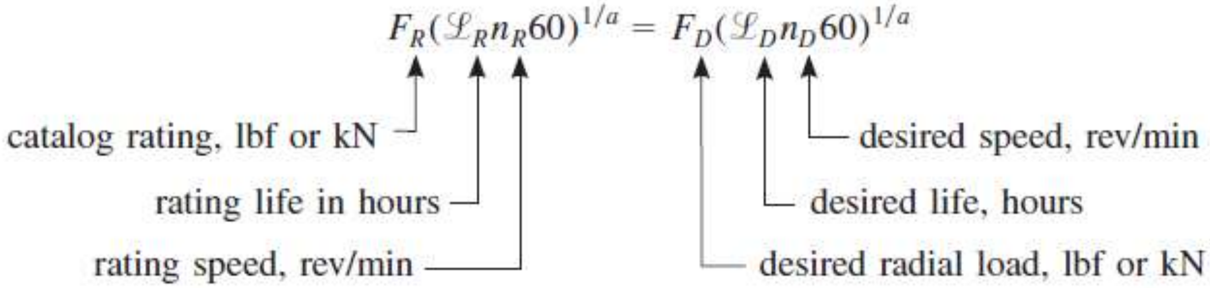
$$overall\ sound\ level = 10\log(10^{\frac{turbine\ level}{10}} + 10^{\frac{background\ level}{10}})$$

Appendix V: Scope Diagram

In-Scope/Out-of-Scope assignments for each task.

In-Scope	Out-of-Scope
Generator Design • Air gap minimization • Core Design • Number of poles/Magnets	Storage • Having an automatic shut-off • Preventing “over-spill” • Wind does not have built in storage
Housing for generator • Protection from environment	Mounting • How to mount • Where to mount
“Gear Box” • Must overcome cogging torque • If needed start assist is an option	Pitch system • Blades mounted at ideal angle of attack
Turbine Blades Design • Sizing and Balancing of the blades • Hub to attach blades	Optimization
Safety	Commercial Production
Build Manual	Grid connection

Appendix VI: Bearing Calculations


$$F_R(\mathcal{L}_R n_R 60)^{1/a} = F_D(\mathcal{L}_D n_D 60)^{1/a}$$

- $a = 3$ for ball bearings

Small Bearing[17,18]:

OD = 35mm, ID = 15mm, Fr = 1750lbf = 7784

Rating life in hours = 8000 hrs, Rating speed = 1400 RPM

Large Bearing[19,20]:

OD = 48mm, ID = 15mm, Fr = 2550lbf = 10000 N

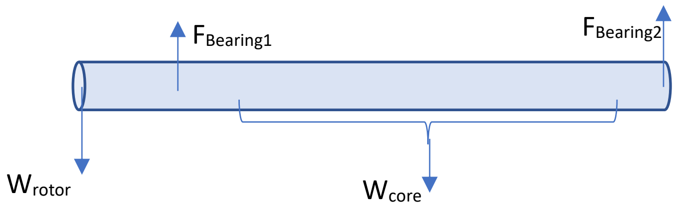
Rating life in hours = 8000 hrs, Rating speed = 1200 RPM

Calculated Values:

- Desired Life Small Bearing = 13832168 hrs
- Desired Life Large Bearing = 17770000 hrs

Appendix VII: Shaft Calculations

Theoretical forces on shaft



Rotor→Critical Distance→Bearing 1→ 10 mm→ Core for 51 mm→ 10 mm→Bearing 2

If each force on the bearing is equal.

$$F_{Bearing1\&2}=\frac{W_{core}+W_{rotor}}{2}$$

$$\sum M_{Bearing1}=W_{rotor}d_{critical}-W_{core}d_{core}+F_{Bearing2}d_{Bearing2}=0$$

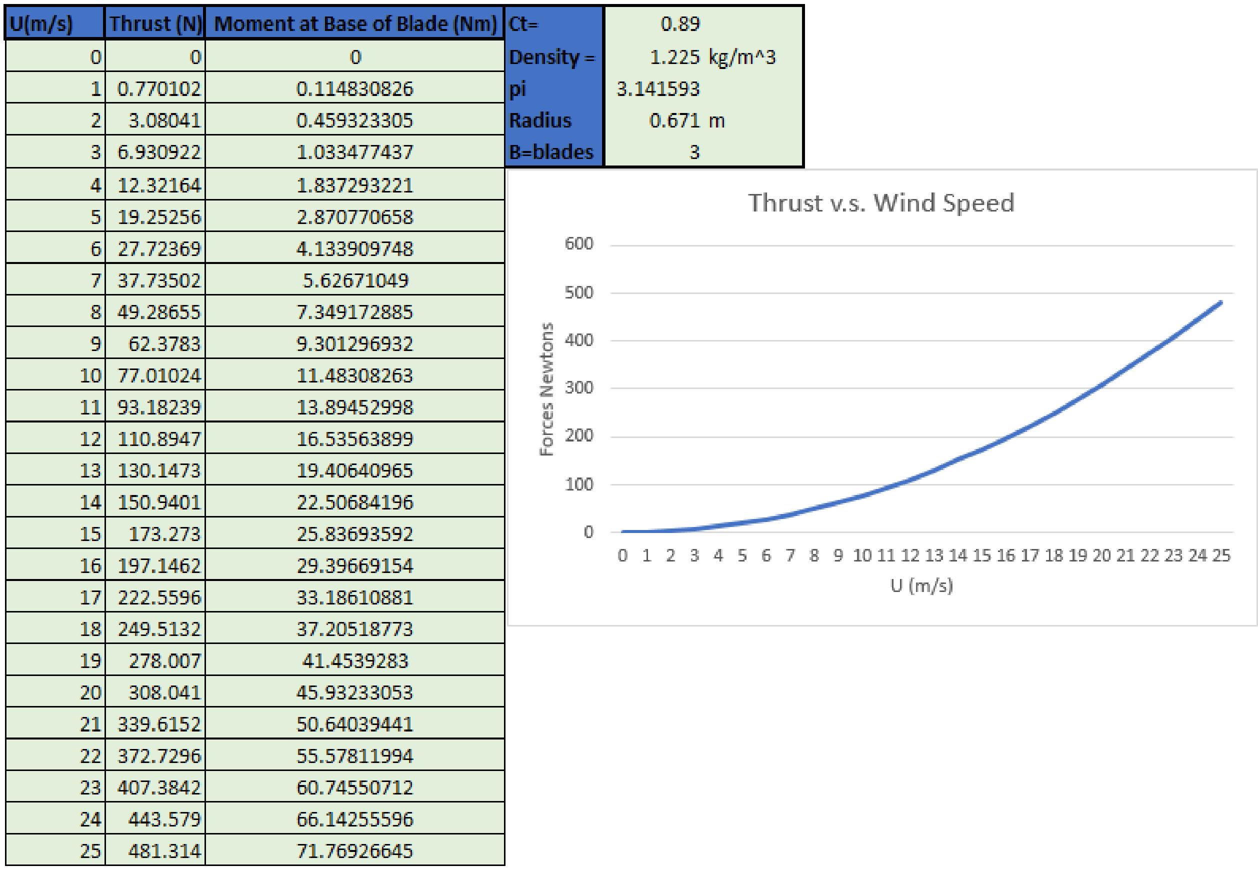
$$d_{critical}=\frac{W_{core}d_{core}-F_{Bearing2}d_{Bearing2}}{W_{rotor}}$$

Cogging torque:

- Required torque to overcome in generator to provide desired power output[19]

$$\mathrm{T= P\omega=50W400*2\pi*60rads=3.32*10-4Nm}$$

Appendix VIII: Thrust Calculation Spreadsheet



U(m/s)	Thrust (N)	Moment at Base of Blade (Nm)
0	0	0
1	0.770102	0.114830826
2	3.08041	0.459323305
3	6.930922	1.033477437
4	12.32164	1.837293221
5	19.25256	2.870770658
6	27.72369	4.133909748
7	37.73502	5.62671049
8	49.28655	7.349172885
9	62.3783	9.301296932
10	77.01024	11.48308263
11	93.18239	13.89452998
12	110.8947	16.53563899
13	130.1473	19.40640965
14	150.9401	22.50684196
15	173.273	25.83693592
16	197.1462	29.39669154
17	222.5596	33.18610881
18	249.5132	37.20518773
19	278.007	41.4539283
20	308.041	45.93233053
21	339.6152	50.64039441
22	372.7296	55.57811994
23	407.3842	60.74550712
24	443.579	66.14255596
25	481.314	71.76926645

Ct=	0.89
Density =	1.225 kg/m^3
pi	3.141593
Radius	0.671 m
B=blades	3

The equation below was used to calculate the "Thrust" column and was sourced from *Wind Energy Explained*

$$T = C_T \frac{1}{2} \rho R^2 U^2$$

The equation below was used to calculate the "Moment at Base of Blade" column and was sourced from *Wind Energy Explained*

$$M_\beta = \frac{T}{B} \frac{2}{3} R$$

Appendix IX: Blade and Hub Calculations

Assumptions: Wind cut-in speed of 2.5 m/s, 226 RPM=23.736 Hz, Tip-Speed Ratio=8

$$r = TSR\frac{WS}{\Omega} = 8\frac{2.5\,{}^{m}/_{s}}{23.736\,{}^{1}/_{s}} = 0.843\,m = 2.76\,ft$$

If the blade radius is limited to 2 ft the approximate rotational speed would be 313 RPM.

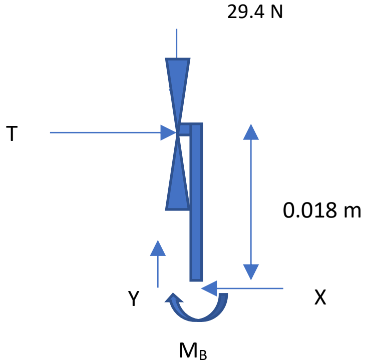
Turbine speed:

- The rotational speed needed to produce power with generator (synchronous speed) is shown in the equation below.

$$\text{ns}= 60\text{fP}/2= 60\text{s}{-}118/2*60\ \text{sec}/\text{min}=400\ \text{RPM}$$

Appendix X: Cradle Calculations

Using the spreadsheet in the Thrust calculation spreadsheet a Thrust at 20 m/s was found to be $T_{20m/s}$=308 N.

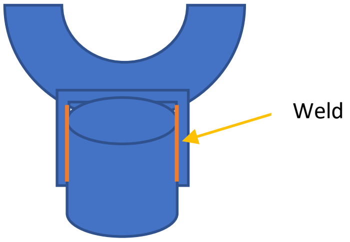


$\sum_{FX:}$ 0= T-X → T = X

$\sum_{FY:}$ 0= -29.4 N + Y = 0→ Y = 29.4 N

$\sum_{MB:}$ 0= -T(.018m) + B → B= 5.54 Nm↻

Analyzing the Joint:



F= .707 •h•l•τ_{Allow}

$$l = \frac{F}{.707 * h * \tau}$$

h= 5mm, Using E60xx Electrode S_{ut}*= 480 Mpa*

Tension in bending from table 9-4 Shirley states .66 s factor

τ_{Allow}*= .66**S_{ut} *= .66*480 MPa = 316 MPa*

F= 600 N to simulate worst case of 40 m/s gust

Solving for required length of weld

$$l = \frac{600\ N}{.707 * 5E-3\ m * 316E6\ MPa} = 53mm$$

Machining process lead to 100 mm of weld, meaning that 2 x required length was used.

Double Check

$$F = .707 * 5E - 3m * 100E - 3\ m * 316\ E6\ MPa = 111.7\ kN$$

Appendix XI: Governing Wind Theory

Power produced wind is proportional to V^3 and is limited to 59.3% of power available in the kinetic energy from wind. Current capacity factors in LDC are around 32%.

Pwind= 12pairAsweptV3wind

$$P_{wind} = \frac{1}{2}\rho_{air}A_{swept}V_{wind}^{3}$$

Betz Limit=0.593=59.3%

Cf= .32=32%

Appendix XII: Power Calculations

Expected watt hours per day:

$$Daily\ Power\ Produced = NP(Hrs)(CF) = 75\,W\ (24\,hrs)(0.3) = \frac{540Wh}{day}$$

Battery Capacity

$$Battery\ Capacity = (Volts)(AmpHr)(DischargeCap) = 12\,V(20Ah)(0.80) = \frac{240Wh}{charge}$$

Charge Time (capacity factor included)

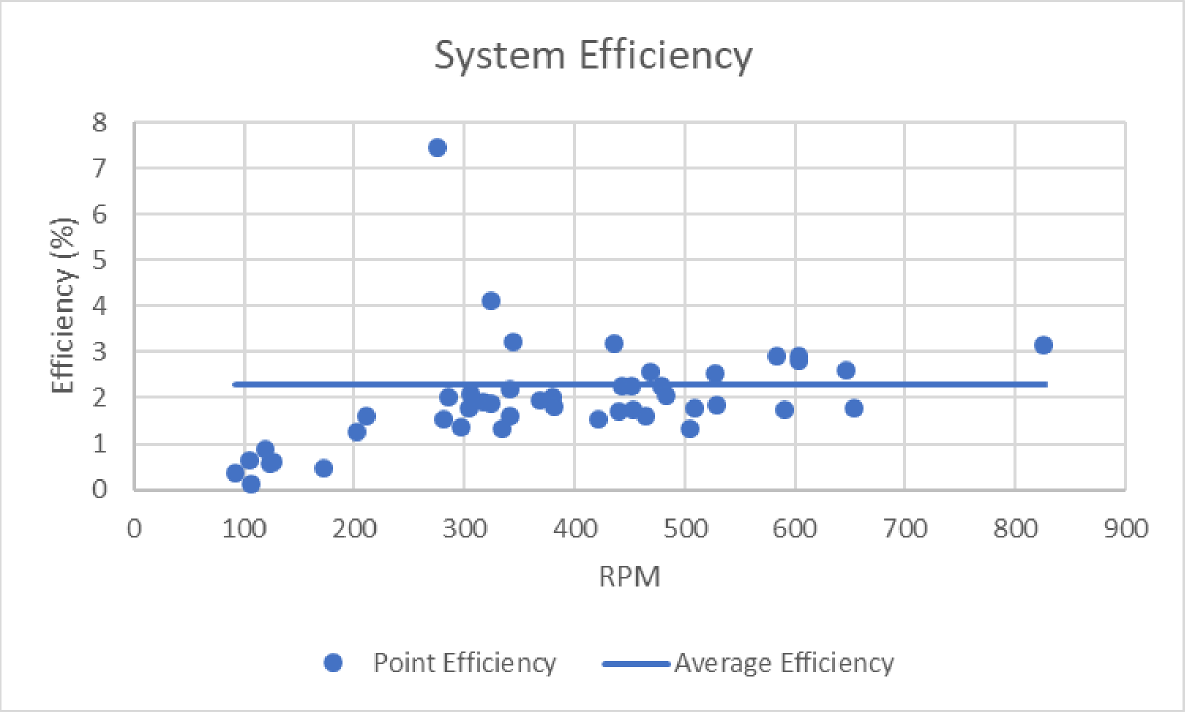
$$CT = \frac{BC}{DPP} = \frac{240\,\frac{Wh}{charge}}{540\,\frac{Wh}{day}} = 0.44\,\frac{day}{charge}\left(24\,\frac{hrs}{day}\right) = 10.6\,\frac{hrs}{charge}$$

Peak Demand: Generally, 2hrs in morning and 2hrs at night with a peak of 50 W

Appendix XIII: Efficiency Calculation

$$Power\ Available = \frac{1}{2}\rho A V^3$$

Average Efficiency from Wind Curve Data: 2.29%



Appendix IV: Build Manual

To read the build manual, please refer to attached document.