Wind EnGen:
Portable Vertical Axis Wind Turbine

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Abstract

Energy scarcity is an increasingly prevalent issue. Gas prices are higher than ever, temperatures are exponentially rising, and geopolitical conflicts have never been more impacted by energy sources as they are today. Efficient and reliable sources of renewable energy are a major key to solving many issues faced by the world today. Team Wind EnGen has sought to contribute to the advancement of renewable energy by developing an inexpensive, sustainable, and reliable energy source: a 3-D printed portable vertical-axis wind turbine (VAWT) made out of recyclable material. The team selected a Savonius turbine configuration as the best candidate as a result of its scalability, safety, and low cost, as well as its distinct ability to accept wind from all directions. The prototyped models were experimentally tested by measuring voltage and RPM once connected to a circuit with varying load against an existing portable, horizontal axis wind turbine (HAWT) produced by the company TexEnergy. The results of testing show promise: while the team's turbine's power output was lower than the existing model (~1 [W] versus a promoted 7.5-10 [W]), the product has laid a foundational basis for further development of low-cost vertical axis wind turbines made with sustainable materials. The turbine also showed the ability to increase its angular velocity substantially with a few small changes, leaving plenty of room for blade improvement and possible development as a commercially scalable product. Overall, the team met its goal of creating a proof-of-concept portable VAWT that has the potential to be competitive in the market.

Introduction

With the advent of mobile technology, society began to experience a perpetual deficiency of electrical energy as people constantly worry about the remaining charge in their pockets. Furthermore, with high urbanization rates characterizing modern enterprise, the search for escaping the polluted spires of the city has become omnipresent in the backs of people's minds. In line with the general increase in social mobility, there is a positive trend in the off-grid demand for electricity as the need to charge one's phone travels accordingly. However, while power banks and other transportable charge carriers present a short-term solution to such issues, they do not solve the problem at hand in the long run. With charge depreciating in line with consumption and the device generally adding considerable weight to equipment sets, such utensils are a contentious choice for longer excursions off the grid. In light of such developments, the Wind EnGen was developed to help remedy such issues and provide passionate travelers with a sustainable means of generating power on the road.

A portable vertical axis wind turbine (VAWT), the Wind EnGen, generates charge by capturing power from gusts of wind over 8 mph through its three concave, leaf blades. In doing so, it is designed to sustain small devices like mobile phones or Bluetooth headphones under circumstances that do not allow grid connectivity. As the turbine was designed as a travel accessory, its fully removable blades and compact nature enable the whole device to easily fit into a backpack. Furthermore, with components printed out of recyclable PLA, the material's strong integrity guarantees durability without sacrificing the appeal to sustainability. In doing so, Wind EnGen aims to provide backpackers and store-owners alike with a constant and renewable source of energy under night in any circumstances.

Technical Design

Concept

The original inspiration for the Wind EnGen was derived from the idea of a roadside VAWT intended to capture waste energy from passing vehicles (see Figure 1 below). A vertical axis configuration proved to be more appealing in comparison to a more typical horizontal axis because it is more space effective and thus more suitable for smaller scale applications, which is crucial to urban areas. But, rather than attempting to design a stationary generator that is completely dependent on the presence of vehicles, scaling down further seemed appropriate. Therefore, the team decided to combine the idea of a VAWT intended to capture waste energy and a smaller scale, more popular application: a mobile phone.

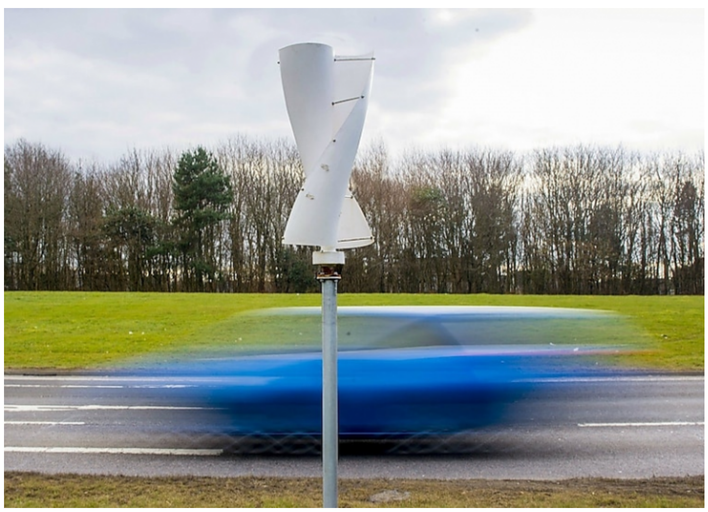

Figure 1. Roadside Vertical Axis Wind Turbine

As a result, the team's inspired concept of a compact, portable, and thus user-friendly VAWT for capturing unused energy allows for greater applicational breadth and opportunity while minimizing cost. In order to meet these desired features, the turbine's blades and main shaft were 3D printed such that the blades could be easily inserted/removed and stored.

Furthermore, in order to initially select the blade configuration of the VAWT, a Pugh scoring matrix was utilized to select one of four models against six design criteria (see Table 1 below).

Table 1. Pugh Scoring Matrix for Turbine Blade Configuration Selection

	Resource Requirement (hrs)	**Power Output (kW)**	**Capital Cost (≤ $)**	**Durability**	**Scalability**	**Safety**	**Total**
(weight)	*0.2*	*0.2*	*0.15*	*0.1*	*0.15*	*0.2*	*1*
Savonius	7	3	8	6	7	8	6.45
Helix	3	8	5	7	7	8	6.30
Darrieus	6	5	6	7	7	6	6.05
Horizontal	2	8	3	6	4	5	4.65

The Savonius configuration was ultimately selected due to its ease-of-use, widespread application, and cost. The less complex blade shape allows for intuitive construction, self-starting ability, and ease of spin (can accept wind from any direction). The Savonius design also boasts a lower predisposition to wear-and-tear and thus a decreased chance of harm. An anemometer-style configuration was considered for a time but ultimately discarded due to its more fragile blades/arms. Specifically, a three-blade Savonius geometry was chosen over the common two-blade version in the hopes of maximizing efficiency and power output, since previous research suggests that overall, it performs better and experiences a higher tip speed ratio than the two-blade structure (Hamzah, 2018). Despite the drawbacks posed by the drag-based Savonius configuration – such as lower average efficiency and power levels – it appears to be appropriate for the anticipated application of charging a mobile phone off the grid because it is both reliable and not dependent upon high levels of wind power.

Description of Approach

The team's approach consisted of designing a vertical blade and shaft system that could be used to replace TexEnergy's horizontal blade system while maintaining use of its other components – such as its motor, electric power output system, and tripod. The TexEnergy motor and electric system were ideal since there was a female USB port that can deliver a maximum power output of 10 [W] at 5 [V] or 2 [A] – the necessary specifications for a typical cell phone, like an iPhone. Also, the TexEnergy product came with an adjustable tripod that allows for conversion to a low-friction vertical configuration, which would ultimately allow for consistency in testing between models.

Once adjusting the TexEnergy tripod, the next step was choosing the method of prototype construction. Due to the extensive 3-D printing resources available to the team on Duke University's campus, its ability to facilitate an extremely iterative design process, and its relative inexpensiveness and ease of use compared to other options, 3-D printing was decided to be the construction method of choice.

A low fidelity, digital prototype was designed through SolidWorks, a 3-D Computer-Aided Design (CAD) software. This first prototype (Figure 2) did not include a method for attaching the blades to the rotation shaft, which would be attached to the motor. However, completing this digital model was an important step for visualizing what the end product should resemble.

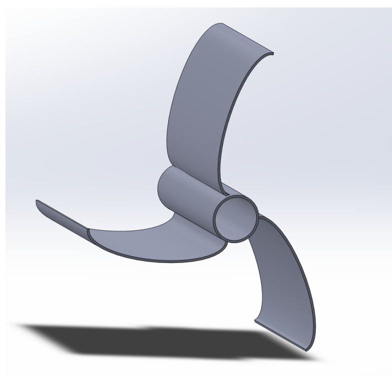

Figure 2. First Digital Low-Fidelity Prototype (SolidWorks)

After ordering and receiving the TexEnergy Infinite Air 5 Turbine, measurements were taken, and the model was altered to possess the necessary dimensions for the team's prototype. Brainstorming sessions for how to attach the blades to the shaft culminated in a T-shaped slit system on the shaft (Figure 3) with the corresponding T-shape on the end of each blade (Figure 4), as well. 3-D printing allowed for quick reprinting until dimensions were reached such that the shaft could easily attach onto the motor and the blades easily slide into the shaft.

Figure 3. Iterations of VAWT shaft

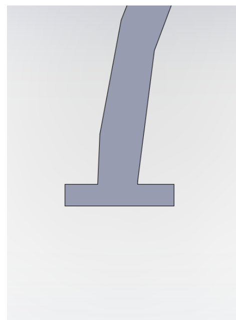

Figure 4. T-Shape on Blade End (SolidWorks)

Once the final shaft and three detachable blades were all printed, the blades and shaft were attached to the TexEnergy motor and set up so that the VAWT was functional and ready for testing and evaluation (Figure 5).

Figure 5. Final PLA Prototype ready for testing

Quantitative Evidence & Analysis

In order to theoretically determine the energy use and power output of the Wind EnGen, the following information and assumptions were necessary:

1. Dimensions: height $h = 0.5\ [ft]$, diameter $d = 1\ [ft]$

$$\Rightarrow A_{sweep} = hd = 0.5\ [ft^2]$$

2. Air density $\rho = 1.225\ [kg/m^3]$
3. Using TexEnergy's product specs, $v_{wind} = 15\ [mph]$ is necessary to create the 5[V] potential difference necessary to begin charging a mobile phone (TexEnergy, 2022)
4. Applied wind acts orthogonal to the blade plane

Therefore, the available wind power using the above conditions (and any necessary unit conversion factors) is as follows:

$P_{wind} = \frac{1}{2}\rho A_{sweep} v_{wind}^3$ **(1)**

$P_{wind} = 0.5 * 1.225[kg/m^3] * (0.5[ft^2] * 0.3048^2[m^2/ft^2]) * (15[mph] * 0.44704[m/s])^3$

$P_{wind} \approx 8.58\ [W]$

After substituting in values, the available wind power for the Wind EnGen under the stated conditions is predicted to be 8.58 [W]. However, this is not a realistic, expected power output. For all wind turbines, the Betz Limit η dictates the maximum possible efficiency given the available wind power. This limit is η = 0.593, which means the possible extractable energy by the Wind EnGen is calculated as:

$P = \frac{1}{2}\eta\rho A_{sweep} v_{wind}^3$ **(2)**

$P_{wind} = 0.5 \times 0.593 * 1.225[kg/m^3] \times (0.5[ft^2] \times 0.3048^2[m^2/ft^2])$
$\times (15[mph] \times 0.44704[m/s])^3$

$P_{wind} \approx 5.09\ [W]$

According to Savonius himself, the maximum efficiency *C* he observed in his turbines was 31%, thus making the average about 15.5% (Zemamo, Aggour, Toumi, 2017). Taking into account this configuration-specific efficiency, the team expected the Wind EnGen to likely produce power with the following average:

$$P_{wind, avg} = \frac{1}{2} C\rho A_{sweep} v^{3}_{wind} \quad \textbf{(3)}$$

$$P_{wind, avg} = 0.5 \times 0.155 \times 1.225[kg/m^{3}] \times (0.5[ft^{2}] \times 0.3048^{2}[m^{2}/ft^{2}]) \times (15[mph] \times 0.44704[m/s])^{3}$$

$$P_{wind, avg} \approx 1.33\ [W]$$

Evidently, the predicted extracted power of 1.33 [W] does not exceed the theoretical maximum of 5.09 [W] and thus energy conservation is not breached.

TexEnergy claims its product has an expected power output range of 7.5 - 10 [W], which is greater than Wind EnGen's prediction of 1.33 [W] (TexEnergy, 2022). However, this comes as no surprise given that TexEnergy utilizes a HAWT rather than a VAWT, and the horizontal structure is known to have a greater overall efficiency (Papiewski, 2022). Because the team constructed the turbine blades and shaft out of a more sustainable and thus lighter material than that which is typically used (metal), it was predicted that the output power would likely be observed as lower than 1.33 [W] once tested empirically.

Lastly, structural analysis, stress distribution, and failure analysis play an important role in any engineering design, particularly in this case due to the possibility of a stress concentration forming at the blade-to-shaft attachment. However, because applied wind speeds are taken to be fairly low and the turbine itself is not very large in size, the team expects no serious issues to arise in terms of blade failure. Furthermore, material choice proved to be another significant factor. Given that the team began with using PLA and has plans for use of the more sustainable PET in the future, rigidity/flexibility of the blades plays a role in terms of safety and efficiency. But, once again, the relatively low wind speeds at which the turbine will be tested and used allow for the estimate that the failure points of each of these materials will not be reached.

Testing & Evaluation

The focus of the testing process was developing a relationship between wind speeds and voltage and/or power output of the turbine. Though use of a wind tunnel for testing would have been preferred, a high power, industrial fan (example shown below in Figure 6) acted as a suitable wind source.

Figure 6. Testing Setup Demonstrated with TexEnergy Turbine

To begin testing, wind was measured with an anemometer in a grid-like position pattern in front of the fan in order to determine where wind tended to be most consistent. Once this location was found, the wind speed was recorded and the distance between the fan and location of known wind speed was noted for reproducibility; this is where the turbines were placed and centered about in each trial. Next, the turbine generator was connected to a breadboard, which was in turn connected to resistors in various configurations, all with single conducting wire. At the onset of testing, a multimeter was connected to the positive and negative terminals of one or more 1 Ohm 250-Watt rated resistor(s) as different turbine models were swapped out. Varying resistances included 0 Ohm, 0.5 Ohm, 1 Ohm, 2 Ohm, 3 Ohm, and short circuiting. Important to note is that the TexEnergy model has an ideal current of 1.5-2.0 [A] and thus an ideal resistance range of 2.5-3.33 [Ohms]. All of these tests were performed at the three available wind speed settings. See the Appendix for collected data. All data was processed using MATLAB.

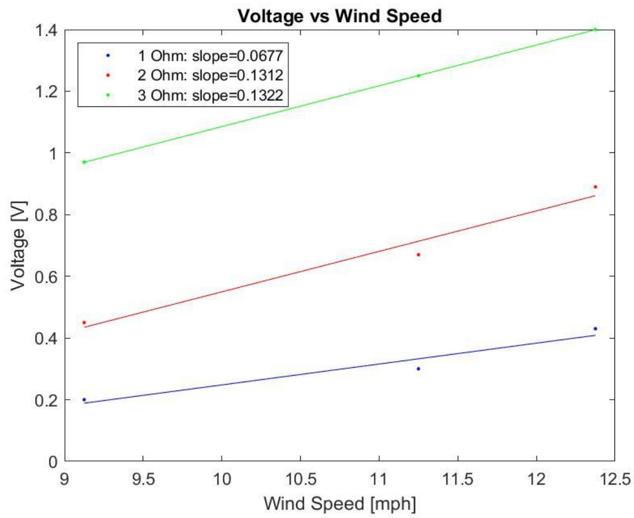

Figure 7. Voltage Versus Wind Speed with Varying Resistance for TexEnergy Model

As shown in Figure 7, the TexEnergy turbine specs hold to be true: with a resistance of 3 [Ohms] (in the ideal range of 2.5-3.33 [Ohms]), voltage output was greatest at all three tested and fitted wind speeds.

However, only the TexEnergy HAWT produced a voltage large enough for the multimeter to consistently read. The Wind EnGen model did not produce a usable voltage measurement with zero resistance at the maximum produced wind speed, 12 [mph]. So, the team made two decisions: 1) to measure RPM rather than voltage so that data could be recorded for all models at all conditions, and 2) to create a second model with less wide blades and blade shrouds in order to produce greater RPM and better capture wind. The former was conducted similarly to the original plan but instead of a multimeter, a laser tachometer with reflective tape was used. The latter was completed by simply adjusting the CAD model and reprinting; the updated PLA model is shown below in Figure 8.

Figure 8. Testing Setup with Updated PLA Model of Reduced Swept Area & Added Blade Shrouds

As a result, three models were tested for RPM versus wind speed data: the TexEnergy HAWT, the original PLA model, and the updated PLA model. Each was tested with the aforementioned varying resistances at a set wind speed of 12 [mph], the fastest setting on the industrial fan (experimental fan seen in Figure 8). Three separate measurements were taken for RPM and then averaged for greater accuracy. See the Appendix for collected data.

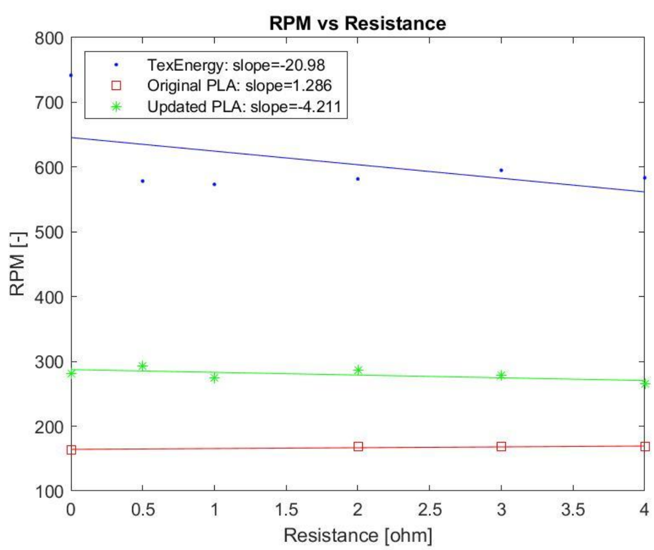

Figure 9. RPM Versus Resistance for All Models Tested (Resistance of 4 represent short circuiting)

While the lines of best fit do not seem to truly capture the data in Figure 9, it is clear that the updated PLA model obtained greater RPM in comparison to the original model, overall achieving about 54% of the TexEnergy RPM. The team speculates that perhaps the updated model has an ideal load near 0.5 Ohm since that data point peaks above the rest, but more testing is required to make a definitive conclusion. It is also difficult to comment on the original model's ideal load since the data tended to remain stagnant as resistance was changed.

Then, utilizing Equation (4) below – an equivalent form of Equation (3), the data were plotted such that RPM was converted into angular velocity, which could then be used to calculate the empirical power output.

$$P_{original} = T \times \omega = (F_{wind} \times R) \times \omega = (\tfrac{1}{2} C\rho A_{sweep} v^{2}_{wind}) \times R \times \omega \quad \textbf{(4)}$$

where T is torque in [N/m] and ω is angular velocity in [rad/s], F_{wind} is the force applied by the wind in [N], and R is the corresponding moment arm in [m].

For a wind speed of 12 [mph] at an assumed efficiency of 15.5%, the power outputs for both PLA models were plotted below in Figure 10.

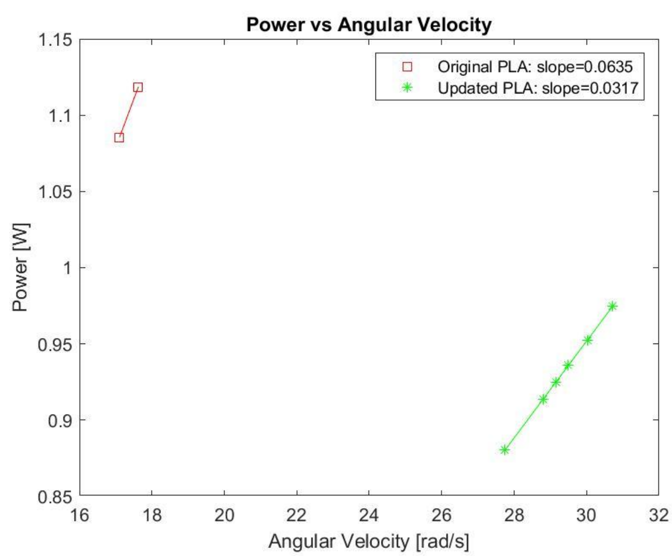

Figure 10. Power Versus Angular Velocity for All VAWT Models Tested

Evidently, the original PLA model's power output tended to stagnate around two points, similar to its RPM data. However, the updated PLA model increasingly produced power as its angular velocity increased. This leads the team to believe that perhaps the updated model has a higher efficiency than the original one and thus has greater potential for use. More testing is needed in order to determine the exact efficiency considering the power output data had to be plotted with an estimated efficiency since it was not possible to gather isolated power output data.

While greater power output was hoped for, it bodes well that both models were in the realm of 1 [W]. But, in order for this data to have more meaning for a potential user that cares more about power output than portability, the size of the turbine can be increased such that the blade height is 3 [ft] and width is 1.5 [ft]. This change in dimensions translates to a power output of 12 [W] at 15 [mph] wind speeds with an estimated efficiency of 15.5%.

With these results in mind, future research would be best followed in the direction of the team's latest Wind EnGen iteration: less wide blades with shrouds. The question now becomes an optimization problem: to what extent should blade width be decreased such that RPM is increased enough to maximize power output? There is also the question of the shrouds: what material allows for the shrouds to be thin but also durable such that their added weight is minimized? While the team wishes to answer all of these new questions, the purpose of this project has been achieved: to create an inexpensive, durable, proof-of-concept, portable VAWT that produces power renewably with the potential to charge a mobile phone for off-grid users. If this project were extended, the immediate next steps would be answering the above questions, further testing, and developing an optimized PET prototype.

Environmental Benefit Analysis

While the 48.7% share of North Carolina's power generation from fossil fuels stands well below the national average of 58%, this level still ensures a significant carbon footprint (Motive Power, 2021). As shown by the calculations below, such a load distribution generates 3.84gCO_2 each time one charges their iPhone. Furthermore, with the state's national reputation for natural reserves, tourism, and migrating energy demand, circumstances leave consumers to rely on charging their devices from disposable power banks or, even worse, disposable batteries and car chargers. This section aims to explicate how the Wind EnGen can help mitigate such environmental hazards and will present a quantitative analysis of this potential offset. To do so, it will first introduce calculations on the device's relative carbon footprint and thus elaborate on its improved environmental outcome in contrast to conventional generation. Second, it will discuss the advantages of relying on PET filaments as opposed to traditional PLA.

In practice, the Wind EnGen actively displaces the need to draw power from the grid to charge a device, thus effectively offsetting the carbon footprint for electricity generation. To quantify the environmental impact the turbine has, the team needed to ascertain the emission rate for local power generation. In the state of North Carolina, electricity generation from fossil fuels is 33.7% natural gas, 14.9% coal, and 0.1% oil (EIA, 2021). Discounting the environmental cost of developing the infrastructure for generation, one can assume that the remaining proportion of electricity production from renewables has a negligible carbon footprint. In this sense, it belongs to the lower third of US states in terms of carbon emission rates, which is 282.1 gCO_2/kWh (US EPA, 2020). Assuming the new iPhone 13 has a battery capacity of 3227 [mAh] and charges up to 4.2 [V], the power needed for a full charge and thus the carbon footprint of the charge can be calculated (Apple, 2022).

$$P = A \times V$$
$$P = 3.227\,Ah \times 4.2\,V$$
$$P = 13.56\,Wh = 0.0136\,kWh$$
$$ER\,per\,charge = P \times 282\,gCO2/kWh$$
$$ER\,per\,charge = 0.0136\,kWh \times 282.1\,gCO2/kWh$$
$$ER\,per\,charge = 3.84\,gCO2$$

While seemingly marginal, this emission rate quickly scales up once it is considered that there are 330 million Americans charging their phones every single day. Furthermore, this level accounts for charging an iPhone in North Carolina. In states like Wyoming or West Virginia where emission rates are more than triple at around 750 gCO_2/kWh, a full battery will produce over 10 gCO_2 (US EPA, 2020).

A further consideration about the relative environmental impact of the Wind EnGen relates to the negated need for car chargers or external charging devices, like power banks or disposable batteries. The environmental impact offset for the latter would be nigh on impossible to calculate, as one would have to quantify the manufacturing footprint, as well as the relative longevity and efficiency impact. However, car chargers rely on drawing power from the vehicle's engine, which translates to generation from the given fuel. As cars will mostly rely on either diesel or gasoline, a simplified carbon offset can be calculated (disregarding efficiency losses). As Table 2 shows, relying on car chargers ensures a higher carbon footprint and thus makes the Wind EnGen the perfect alternative as a travel charger.

Table 2. CO_2 Emission rate for vehicles

Fuel	**Emission Rate gCO_2/kWh**	**Emission Rate per Charge gCO_2/kWh**
Diesel	249.6	33.95
Gasoline	243.3	33.04

Another environmental advantage and vital component of the Wind EnGen is the material of which it is composed. While the electrical components of the device were designed and manufactured by TexEnergy and give limited insight into the materials used, their commitment to sustainability set a positive precedent. In order to further the product in the most environmentally friendly manner possible, the team considered the three most commonly used 3D printing filaments: polylactic acid (PLA), thermoplastic polyurethane (TPU) and polyethylene terephthalate (PET).

Table 3. Decision Matrix for 3D printing filaments

Material	**Printability**	**Flexibility**	**Durability**	**Weight**	**Recyclability**	**Cost**	**Total**
	0.2	*0.1*	*0.1*	*0.2*	*0.3*	*0.1*	*1*
PLA	8	2	4	6	8	8	6.6
TPU	5	9	8	5	1	3	4.3
PET	8	7	7	5	9	7	7.6

Out of the materials considered, it was PET and PLA which came out on top in this regard, while TPU fell back due to its limited recyclability for most low-cost applications (Table 3). Unlike PET, which is composed of a chemical cocktail of different hydrocarbons, PLA is made from biomaterials like corn or sugarcane starch. However, while this origin implies considerable recyclability potential, the material only breaks down under controlled composting conditions (over 140 degrees Fahrenheit and submerged in digestive microbes) and must be disposed of properly (Scientific American, 2008). Herein lies the advantage of PET filament, which, while inorganic in nature, can be continuously recycled or disposed of safely (Pakkanen *et al.*, 2017). Furthermore, with PET being the most commonly used plastic worldwide, the infrastructure required by the recycling industry is well developed and accessible. Since there are few facilities that have the capacity to work with PLA, the final emphasis was placed on PET (3Dnatives, 2019). While the availability of printers that accept such filament was limited, future plans to use PET will be critical to the further sustainable development of this product.

Social Benefit Analysis

Encapsulating extra charge capacity in portable devices enables man to venture farther away from the grid without losing contact with the outside world. However, while power banks and car chargers allow one to sustain a phone or headphones when sockets are unavailable, they still offer limited capacity as well as a significant decrease in energy efficiency. The Wind EnGen enables consumers to mitigate such defects, allowing for a constant supply of energy at no marginal cost. This section will further elaborate on the turbine's social benefits. First, it will introduce the wind turbine in the context of traveling, illustrating the foundational context for the project's initial idea. Second, it will aim to expand on potential future applications, speculating on how a long-lasting, mobile source of energy could supply disconnected communities with energy. Lastly, this section will discuss the urban applications of the Wind EnGen, highlighting some potential applications of the turbine that go beyond individual utilization.

In the Information Age, people rely on their mobile phones for everything from contacting third persons to determining their whereabouts in unfamiliar locations. However, once cut off, they are left vulnerable with limited options for calling help, a reality that might pose a significant threat when traveling at a distance from health services. This is the main advantage of the Wind EnGen, which enables one to generate the charge needed to sustain one's device in any circumstances. Under wind conditions over 8 mph, the turbine can deliver a steady flow of electricity, thus allowing travelers to venture farther from the grid without worrying about losing contact with the outside world. Additionally, it minimizes weight and maximizes the storage capacity as the whole device weighs around 400 grams, approximately the same weight as an average power bank but offering unlimited generation.

As highlighted in the following Target Market section, the benefits of the Wind EnGen can be utilized not only by the average backpacker but also by individuals and communities living disconnected from the grid. From terrain researchers to fishermen, the turbine would solve the need to charge one's appliance when access to regular infrastructure is curtailed. As discussed above, this proves especially beneficial for long-term ventures, which would otherwise rely on diesel generators that have exceedingly high emission rates. While the turbine might also prove highly beneficial to those from disadvantaged backgrounds to help remedy the cost of power, the higher price of the product would likely prevent most falling into this category from purchasing it.

Furthermore, this power offset provides benefits not only in terms of individual utilization but also on a more comprehensive social spectrum. While seemingly negligible, the 3.84 gCO_2 emission rate per charge scales up to impressive numbers when one considers how every person charges their phone at least once a day. The turbine's offset potential could thus have positive health repercussions since the decreased demand for grid power entails fewer emissions. However, such benefits are nigh on impossible to quantify accurately. One would have to measure the relative impact of a gram of CO_2 emitted and then apply for the scale of turbines in use. Such calculations thus go beyond the current capacity of this analysis given that the market outreach of the turbine is unknown, making scalability merely a matter of speculative assumption.

Lastly, the Wind EnGen can also be used in urban settings simply as a means to charge household appliances. Specifically, potential applications range from garden or advertisement illumination to sustaining digital billboards. Under the right conditions, connecting the turbine to a low voltage appliance would ensure continuous power delivery without connecting the device to the grid or relying on price-volatile energy. Potential applications would be most useful in windy or roadside conditions, where open areas and the drag of passing cars would help turn the turbine. Places like gas stations or small shops could thus benefit from demonstrating their commitment to sustainable practices while reaping the benefits of cheap energy.

Target Market Analysis

Determining the suitable parameters of a given target group is critical for designing a product that maximizes a consumer's utility. The report will draw on existing data to determine these vital parameters by categorizing potential customers into separate categories. In this sense, the Wind EnGen is meant to cater to two specific groups: travelers and the off-grid populace. In the former group, there is a further distinction between tech-savvy backpackers and so-called ecotourists – a label given to those traveling with an agenda to contribute to the "conservation of the ecosystem while respecting the integrity of host communities," (Wight, 1996). The off-grid populace is recognized as communities or individuals who venture away from conventional power distribution infrastructure for extended periods of time and are thus forced to rely on alternative means of electricity generation. This section will elaborate further on the attributes of both groups and will therefore aim to define the Wind EnGen's design parameters in terms of its target consumer group.

Looking first at travelers, the key features to consider are socioeconomic background, age, and environmental awareness. These parameters were selected as each represents attributes that influence a potential customer's willingness to buy. Socioeconomic background determines an individual's capacity to travel, ability to purchase the team’s product, and highest achieved educational background. Age provides information about the time when a person grew up, which hints about one's affinity to technology and provides insight into the completed educational potential (high school, higher education, etc.). Finally, as the Wind EnGen was designed to generate electricity in the most sustainable manner possible, an individual's environmental awareness is a crucial factor that might affect one's willingness to purchase the product.

In this context, Wight (1996) finds that ecotourists are generally better educated, with over a third achieving or in the process of achieving a degree in higher education. As the author points out, this directly correlates with environmental awareness as the higher levels of attained education provide an individual with a broader knowledge of natural processes and increase the likelihood of reading about such matters in the media. While gender seems to be a slight discrepancy, Carvajal and Alejandra (2013) find that ecotourists are most likely to be found between the ages of 24 and 54. This is because traveling requires considerable resources to enable one to cover expenses and be able to meet the extra cost of environmentally friendly travel. Simultaneously, older individuals display lower tendencies to travel and are less likely to consider environmentalism as a factor in their decision-making. This ties into another reason why ecotourists were chosen as part of the Wind EnGen target group: financial capacity. As Wight (1996) points out and adjusted for inflation, about 45% of ecotourists are willing to spend over $2,800 on their journey, and 25% would go as far as $3,800. This capacity to expend considerable resources is critical because it implies a willingness to procure equipment to achieve one's end.

Backpackers have a tendency to follow similar trends and thus represent the second key target group. With about 33.5% aged 20-24 and 37.1% aged 25-29, they are more likely to follow current events and thus be informed about the ongoing climate crisis (Møller Jensen and Hjalager, 2019). Furthermore, this age range significantly increases their affinity to technology and gadgets given that they grew up in a world colonized by technological prowess. While falling on the lower end of the financial capacity spectrum, they also display a heightened emphasis on environmentalism, especially those with a European heritage. This feature is further emphasized by their educational background: 86.4% are found to have achieved or are in the process of earning degrees in higher education (ibid).

While for different reasons, the off-grid populace Wind EnGen is another important target group. In the United States, 100% of the population has access to electricity (CIA World Factbook, 2022). However, individuals with constrained access to charging their devices from the grid, such as terrain researchers, fishermen, or loggers, are more likely to use alternate means of fueling their devices. This is true especially for those disconnected for extended periods of time, as their need for power generation, which requires no fuel, is exacerbated. In this sense, the omni-directionality and simplicity of the Wind EnGen potentially outweigh the efficiency deficit relative to HAWTs or photovoltaics. This is because the low maintenance and continuous power delivery, as well as durability, offer a more stable source over a wider spectrum of weather events. The Wind EnGen is thus the perfect backup to other means of generating electricity, providing a reliable alternative during unfavorable conditions.

Basic Business Plan

Based on the findings of the target market, it can reasonably be inferred that while durability and portability are the core marketable elements of the Wind EnGen, the focus on students and individuals between the ages of 21 and 29 generally makes final price the critical component. Additionally, while the current market is dominated by HAWTs, this vertical axis alternative similarly provides power output for significantly less maintenance. This is because, as opposed to the former which requires constant adjustments to ensure delivery, VAWTs are able to generate power with wind blowing from any direction. That being said, the market success of the Wind EnGen still depends on lowering the turbine's manufacturing costs from the most recent estimate of $155. Therefore, this section will first deliberate on the viable approaches to minimizing the key price components of the device, as broken down in Table 4. Next, it will calculate the projected costs for a commercial unit before highlighting some key marketing strategies and potential revenue streams.

Table 4. Manufacturing costs of prototype

Part	***Cost***
TexEnergy engine	*$135*
3D-printing filament	*$8.5*
Wiring	*$2*
Teflon tape	*$0.5*
Safety pouch	*$9*

Table 5. Projected wholesale production costs

Part	**Estimated cost**
Generator	$35
Drive Shaft	$2
Capacitor	$1
Alternator	$15
PET filament	$5
Wiring	$0.5
Safety pouch	$3.5
Total	$62

Tables 4 and 5 highlight that the price component breakdown differs significantly between prototype and wholesale production. This is mainly due to the initial reliance on the TexEnergy model, which served to demonstrate proof of concept. With evidence about the Wind EnGen's viability in hand, wholesale manufacturing would entail the development of the team's engine, which will significantly reduce production costs. Furthermore, pursuing the development of a trademark Wind EnGen generator will enable the team to further its commitment to sustainability, as even the body encasement could be manufactured from recyclable PET filament. However, as 3-D printing takes a disproportionate amount of time and resources, wholesale production would require moving to other means of manufacturing the blades and body parts. By purchasing said components in bulk, filament costs in line with the growing need for larger shipments of the material would be reduced.

Once the design and engineering targets have been attained, and the final product is ready, the next step is to develop business partnerships for distribution. To this end, it is vital to develop a network of established brand resellers, which could distribute the Wind EnGen to and beyond the target market. As the turbine is functionally a travel accessory, the team would reach out to companies like *REI, Camping World,* or *Dick's*

Sporting Goods and attempt to establish a distribution contract. Also, since the Wind EnGen is a gadget, the second line of commerce would be through tech and general stores like *Walmart, Target* or *BestBuy*. In doing so, the team would be able to reach out with its product to most of the target market through these stores that represent some of the most widely visited and notoriously inexpensive distributors.

Lastly, Wind EnGen's foundational appeal to sustainability would allow for marketing the turbine through numerous renewable energy fairs and conferences. By displaying the product at such events, the team would hope to promote the turbine as a green alternative to portable chargers and thus further establish itself on the market. Moreover, by participating in startup and innovation competitions, the team would potentially be able to accumulate capital to enhance the turbine and thus appeal to a broader audience. Finally, as such competitions and events would also help establish the brand, the team would be able to apply for sustainability government grants for research and development, allowing the Wind EnGen to develop even further.

Conclusion

In performing this experimental research, the goal of the project was shifted on numerous occasions, and the trajectory was modified accordingly. Research on the original idea of creating a roadside VAWT led to the discovery that affordable VAWTs were few and far between— not to mention made with unsustainable materials. The culmination was a project geared towards producing a proof-of-concept prototype for a low-cost wind turbine made with recyclable materials.

After extensive deliberation over the design of the turbine, the final decision was made to use the stand of the TexEnergy product due to its low-friction rotational abilities, while designing a completely original blade and central axis — the core components of any wind turbine. Additionally, the original parts were printed with the most sustainable filament reasonably available: PLA. The end result was a physical design capable of being tested in largely the same way as the TexEnergy prototype, using revolutions per minute and relating values to power output. While the results of the testing process were lower than anticipated, the design remains promising as an alternative to more typical turbine designs that differ in axis orientation, cost, and sustainability. The ability of the turbine to increase its angular velocity by more than 50% with a few mechanical changes also speaks volumes to its potential for growth in producing power. The original turbine parts created in this project were not only low-cost and capable of being printed with only a few dollars worth of 3-D printer filament but were also largely sustainable, given PLA's ability to be recycled (but improvements can be made in the future with use of PET filament).

The refinement of the physical design will come with further testing, and research on the shape and structure of the blades that achieve higher efficiencies and power will inform these changes. With the many blade parameters that can be modified, from infill density to curvature radius to height, there is abundant opportunity for improvement in the mechanics of this design. Thanks to this research, such a design can be built on a foundation of low-cost sustainability.

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Appendix

Table 1. Experimental Data

	A	B	C	D	E	F	G	H	I	J	K	L
1			**TexEnergy: 1 Ohm**	**PLA1: 1 Ohm**		**TexEnergy: 2 Ohm**	**PLA2: 2 Ohm**		**TexEnergy: 3 Ohm**	**PLA2: 3 Ohm**		
2		**low1**	0.2V +- 0.02V	0V		0.45 +- 0.02V			0.97 +- 0.03V			**fan1=original**
3		**medium1**	0.3V +- 0.01V	0V		0.67 +- 0.01V			1.25 +- 0.025V			**fan2=new**
4		**high1**	0.43V +-0.025	0V		0.89 +- 0.01V			1.4 +- 0.02V			**PLA1=original**
5												**PLA2=updated**
6												
7		**low1**	9 pmh	10 mph	9 mph	8.5 mph	8-10 pmh					
8		**medium1**	10 mph	12 mph	11.5 mph	11.5 mph	10-12 mph					
9		**high1**	12.5 mph	13 mph	13 mph	11 mph	11-13 mph					
10												
11					**PLA2: 0 Ohm**							
12		**high2**	12 mph		0.2-0.3 mV							
13												
14												
15												
16	**Turbine**	**Resistance**	**RPM**									
17	**PLA 2.0**	**0 Ohm**	290	280	275							
18		**1 Ohm**	260	285	280							
19		**2 Ohm**	285	290	285							
20		**3 Ohm**	270	290	275							
21		**0.5 Ohm**	310	290	280							
22		**short circuit**	260	265	270							
23												
24	**PLA 1.0**	**0 Ohm**	160	170	160							
25		**1 Ohm**										
26		**2 Ohm**	170	170	165							
27		**3 Ohm**	165	170	170							
28		**0.5 Ohm**										
29		**short circuit**	160	175	170							
30												
31	**TexEnergy**	**0 Ohm**	700	725	800							
32		**1 Ohm**	570	590	560							
33		**2 Ohm**	575	580	590							
34		**3 Ohm**	595	595	595							
35		**0.5 Ohm**	575	580	580							
36		**short circuit**	585	585	580							
37												