"Got Resilience?"

Hydroturbine and Catchment System for Clean Power Generation During and Before Large Storm Events

Energy and the Environment: Design and Innovation

FINAL DESIGN REPORT

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Executive Summary

Due to the intensity and growing frequency of large storm events, energy security is a growing concern. Our project goal is to create an in-home, renewable energy system from a storm event to mitigate concurrent power losses. Our design aims to gather energy through a rooftop rainwater catchment system and gutter-guided rainwater turbine. The turbine is a pelton wheel mounted to a permanent magnet commutator motor that acts a generator. The catchment system is a wall-mounted tank that meters water using a floating flapper that releases the water when it reaches a height that will create the maximum voltage. After design, the system was tested to find the ideal resistance-height relationship. The tests found that a water head of 1 meter can charge a standard car battery by producing 9 watts per hour of water flow. The testing also revealed that lower resistance values had higher power generation outputs. Therefore, it is proposed that the catchment system holds 1 meter of water before releasing to the turbine and that the motor's circuit has a resistance value of about 0.3333 Ω or lower.

The major benefit of the turbine is it will increase safety during large storm events by providing electricity to power phones and light. This will be useful to areas of the United States and the world that have less reliable power and less access to portable chargers. The design also has environmental benefits as it offsets carbon emissions that occur from using either portable gas generators or potentially a car to get a quick charge. A survey of Duke parents who own their homes showed that 92% were interested and 75% were willing to mount a system. To market the turbine, it was found that 61% of parents would be interested if the costs were under $50. The target market includes both individuals in rural areas with less electricity reliability and families in developing countries as an alternative to solar as this system is less complicated and costly, leading to a lower barrier of entry.

Introduction

The Earth's changing climate is likely to lead to increasing numbers of storm events that will have wide ranging impacts on society. The past few decades have seen increases in the frequency and intensity of weather-related storm events, as hurricanes and tropical storms have hit the United States harder and more often than in previous years (Zhang). In 2017, Hurricane Harvey dumped nearly 50 inches of rain on Houston in a matter of days, the highest rainfall total on the mainland America in history ("Weather..."). Additionally in 2018, Hurricane Florence left hundreds of thousands of people without power (Rice).

Given that hurricanes in the mid-Atlantic are expected to continue to increase in severity, there will be a growing need to offset future power losses that accompany storms and improve energy security and resilience. Our Bass Connections team aims to mitigate this problem by creating a system that will harness the energy and rainfall from storms to ensure that when electricity from the grid is interrupted, users will still have the ability to access electricity to meet some basic needs. This will increase safety through enhanced communication, resilience, and comfort of people who have been affected by natural disasters.

Multiple technologies could potentially replace lost electricity in the event of power outages. One possible system would rely on public infrastructure, such as storm drains. A turbine would be placed in the drain, and used to generate electricity during storm events that produce significant rainfall. This electricity would be transmitted to a local designated distribution center (such as a school or community center), allowing members of the community to tap into the energy should they lose power in their homes. A similar system has been implemented in Portland, Oregon in their clean water supply. A turbine collects energy through the gravity-powered, flowing water and places this water back into the grid. As the pipes already exist, this is a form of renewable hydropower without the negative environmental effects of dams (Peters).

Another product to provide support during power losses is a house-specific, microgrid system that harnesses rainfall to power small in-home appliances. This system would include a water catchment system attached to a house's existing gutter collection infrastructure and a retrofitted downspout. At the bottom, turbine and battery would produce and store energy. An invention similar to this called Pluvia also uses the idea of gathering energy from a downspout with a turbine and combines this with activated charcoal filter to produce very clean greywater. However, a pumping mechanism is used to start up the turbine meaning initial power is needed and this start-up power is actually more than the turbine itself produces (Brownell). Therefore, in a large storm event, it would be difficult to start the system, limiting its utility. For this reason, our prototype uses a catchment system to store the energy to start the system. Finally, Pluvia is not currently on the market meaning it was unable to find a viable cost and audience.

Ultimately, it was determined that a microgrid solution was more practical, feasible, and useful to consumers who lose power for short periods of time. While a larger public works system would be able to create more energy, it would require significant collaboration between government and private interests, as well as significant upfront capital investments. The microgrid system is a preferred method as it allows individuals access to clean energy in their homes in at a low cost.

Technical Design

Description of Approach (Turbine)

There are currently several common water turbine designs, and choosing the correct one for this project depended on evaluating each with respect to the five main criteria prioritized by our team. The five main criteria were cost, technological feasibility, constructability, innovation, and power generation goal. The cost of each turbine was estimated based on costs of materials needed to fabricate. The technological feasibility, constructability, and ability for the turbine to meet the desired power generation for our system were all determined based on technical information on each turbine design (see Table 1).

Table 1: Water head pressure for different turbine types

Water Turbine Type	Head Water Pressure		
	High →	Medium →	Low
Impulse Type Water Turbine Design	Multi-jet Pelton, Turgo	Pelton, Turgo, Cross flow	Cross flow
Reaction Type Water Turbine Design	Francis	Francis, Kaplan	Kaplan

Water turbines can either be axial flow or radial flow; for axial flow turbines, water flow is parallel to the turbine's axis of rotation and for radial flow turbines, water flow is perpendicular to the axis of rotation. Due to the general concept of our project in which a stream water would be falling vertically to hit a turbine situated horizontally, the team believed radial flow turbines would better suit our project. Turbines are also either reaction turbines, in which blades are submerged in water or impulse turbines, in which jets of water hit the turbine and the turbine is not encased. The team determined that a water turbine would be difficult to fit into a gutter downspout with enough clearance, and that a radial flow turbine would be especially difficult to be encased. Therefore, the impulse turbine was preferred. After research on water turbine designs, pelton turbines appeared to be the most promising option because the turbine has the highest estimated efficiency due to its classification as an impulse turbine.

The decision matrix (see Table 2 below) was used to rank the chosen criteria using a weighted ranking system, where 5 represents the most desirable and 1 represents the least desirable. Based on the research done on the various turbines, each turbine was ranked and the weighted averages were compared. The Pelton turbine was the clear winner, so it was chosen as the general turbine design.

Table 2: Decision matrix for turbine design

Turbine Decision	Cost	Technological Feasibility	Constructability	Innovation	Power Generation Goal	FINAL WEIGHTS
Spherical Turbine	5	5	1	1	3	3.4
Propeller Turbine	5	3	5	5	2	4.0
Francis Turbine	3	5	3	5	2	3.4
Pelton Turbine	4	4	4	5	5	**4.3**
Weights	0.3	0.2	0.2	0.1	0.2	

Turbine Design

The design of the turbine was chosen by looking at various .sldwrks pelton turbines online. A small inner diameter relative to the outside of the turbine was desired as well as two cups on the outsides of the turbine. The original turbine design was chosen below as shown in Figure 3 after adjusting the dimensions. This turbine design was quickly replaced because after 3D printing, it was noted that the designs on the outside of the turbine made it an unnecessarily rough surface and added extra material, which would increase the cost if the turbine were later made with a more expensive material.

A new turbine Solidworks file was found online (see Figure 1) and the file was edited to make the inner hole of the turbine significantly smaller and scale the turbine down by about ⅕ of its original dimensions. It can be seen that original Solidworks part had a significantly smoother and cleaner design. The final 3D-printed turbine (see Figure 2) was sturdier and better suited for prototype testing than the original turbine.

Figure 1: Solidworks file of chosen turbine design

Figure 2: 3D printed final prototype turbine used for testing

Motor Selection and Mounting

This project required a motor to be connected to the turbine that would act as a generator after being mounted onto the turbine. Many different motors exist in the market, but this project required one that was small enough to be encased and could be used at various different rotations per minute (RPM). A permanent magnet commutator motor was chosen because it can operate at various different rotational speeds, it has much more torque than standard "synchronous" motors, is relatively light, and can be inexpensive. The team specifically worked with the AMETEK Pittman 8224S006 servo motor with a power rating of 16W. This specific motor was used because it was made available in the lab; other more inexpensive motors can be used for the same purpose.

Perhaps one of the most unexpectedly challenging parts of this project was mounting the 3D-printed pelton turbine to the AMETEK motor as shown in Figure 3. It was known that some sort of coupling was necessary to connect these two pieces; however, getting the dimensions correct and ensuring a perfect fit was difficult.

After trying multiple different couplings, it was decided that a spacer or small rod designed to separate two parts, machined to the correct size, would be fit on the outside of the motor shaft and inside of the open hole in the turbine. A spacer made out of PEEK, a hard and very chemically resistant plastic, was ordered with inner diameter (ID) of 0.192", slightly smaller than the motor and outer diameter (OD) of 0.375", slightly smaller than the central turbine hole. Drill bits of sizes 0.22" and 0.23" were ordered to bore a just barely smaller than the motor shaft (0.25") in the spacer. The central hole of the turbine was machined to fit the OD of the spacer snugly. The spacer was pushed onto the motor shaft while the plastic was heated after machining, essentially shrink fitting the piece on. The turbine was pressed onto the spacer simply with human force, while the turbine plastic was heated. The full system of the turbine and motor can be seen in Figure 4.

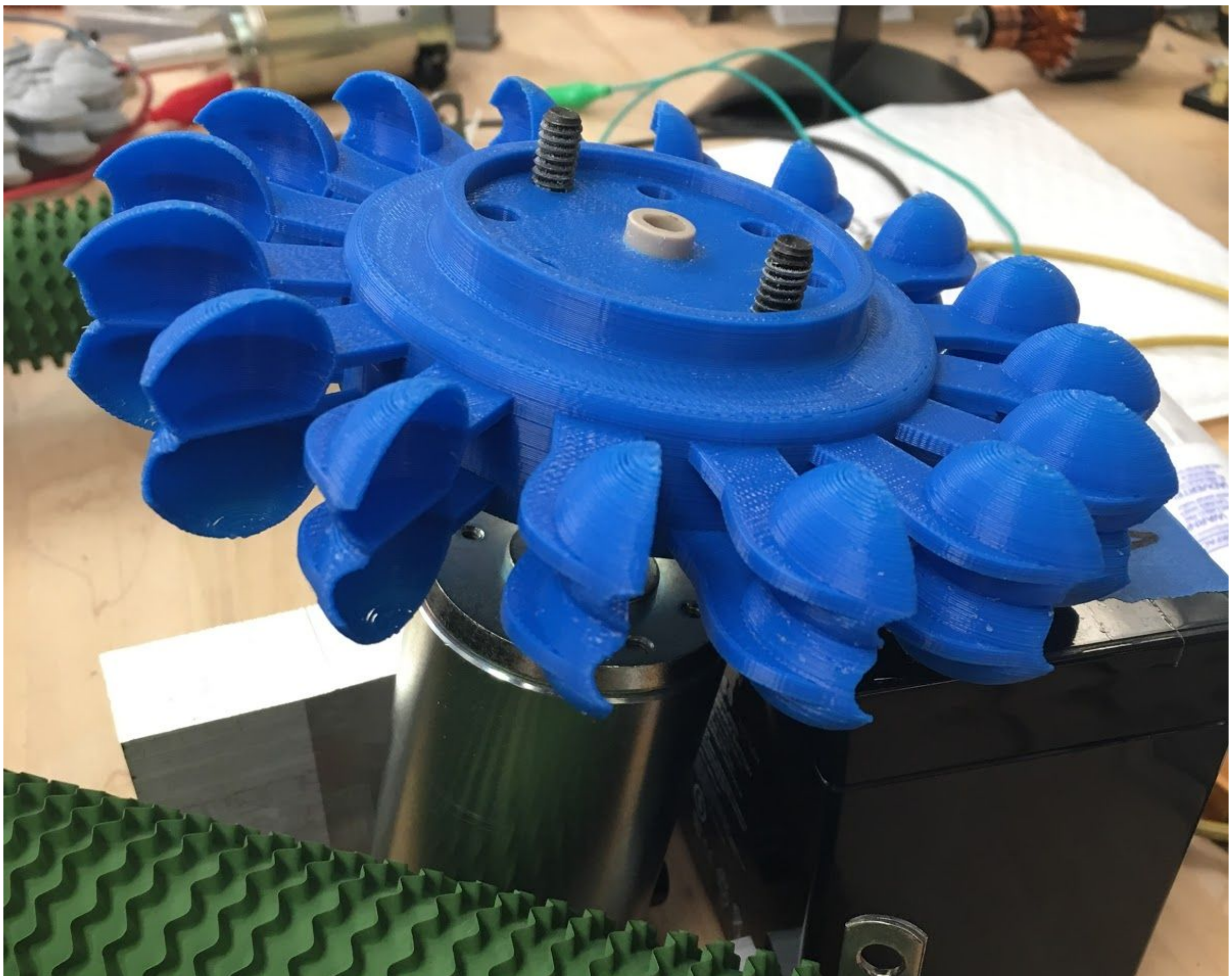

Figure 3: Turbine (top) mounted onto motor (bottom)

Motor and Fluid Performance Analysis

This project dealt with electrical power that could be delivered to the permanent magnet commutator motor from the turbine and power that could be generated from the fluid mechanics of the water hitting the turbine. The majority of the theoretical analysis was split into these two sections, with the two coming together at the end to predict the performance of the entire system as a power generating source.

Motor Performance Analysis:

Permanent magnet commutator motors can be used at various RPMs, and there is an positive relationship between the angular velocity of the shaft and the current through the ends of the motor, which is directly related to torque. Since torque is directly related to power, this relationships helps relate angular velocity to power. Therefore, the first step was to generate a relationship between current and angular velocity from the following equation

$$v = k\omega - i\,\mathrm{R_A}$$

v = voltage between terminals of motor
k = constant found through testing
ω = angular velocity
I = current through terminals
R_A = armature resistance (constant found through testing)

The values of the constants k and R_A had to be found for the above equation. This was done by connecting two motors through a plastic coupling as shown in Figure 4. The RPM of the motor shaft was measured when there was no current running through the circuit using a laser tachometer and this was later converted to angular velocity by multiplying by $2\pi/60$. The voltage between the terminals of one of the motors was also measured using a voltmeter and these measurements were used to find k. The different values of k were averaged and found k = 0.065 V-s. Next, a resistor was connected so that current could run through the circuit and the armature resistance R_A was found to be $0.825\,\Omega$ using the above equation, the calculated value of k, the laser tachometer for angular velocity, and the voltage and current through the voltmeter. These constant values led to a relationship between current and angular velocity that depended only on the resistance of the circuit as shown in Figure 5.

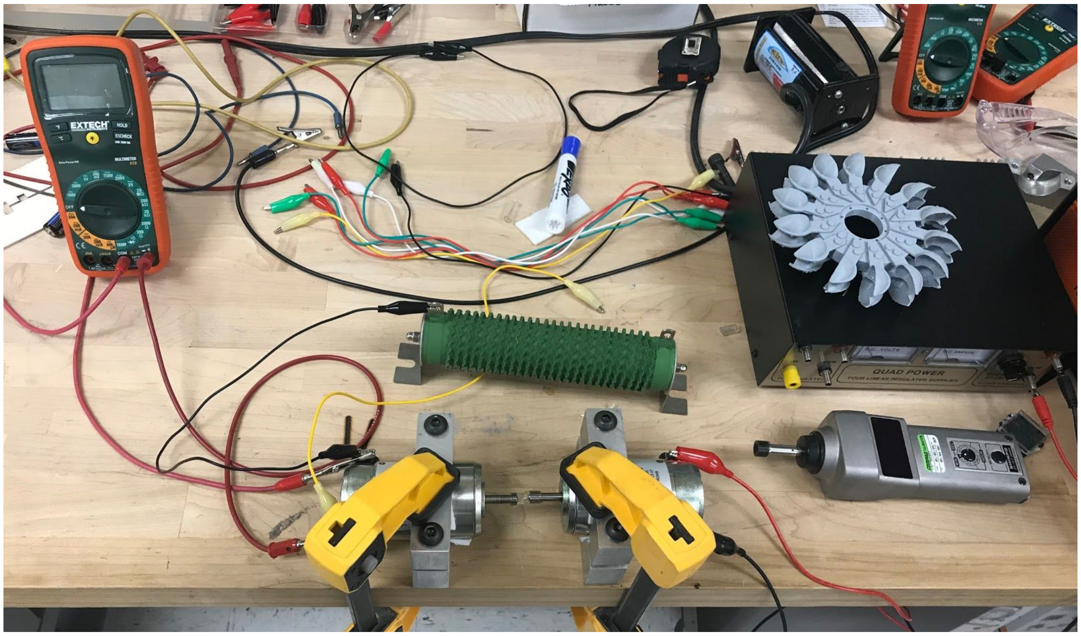

Figure 4. Experimental setup to determine motor characteristics used to develop current vs. rotational speed parameters as shown in Figure 7

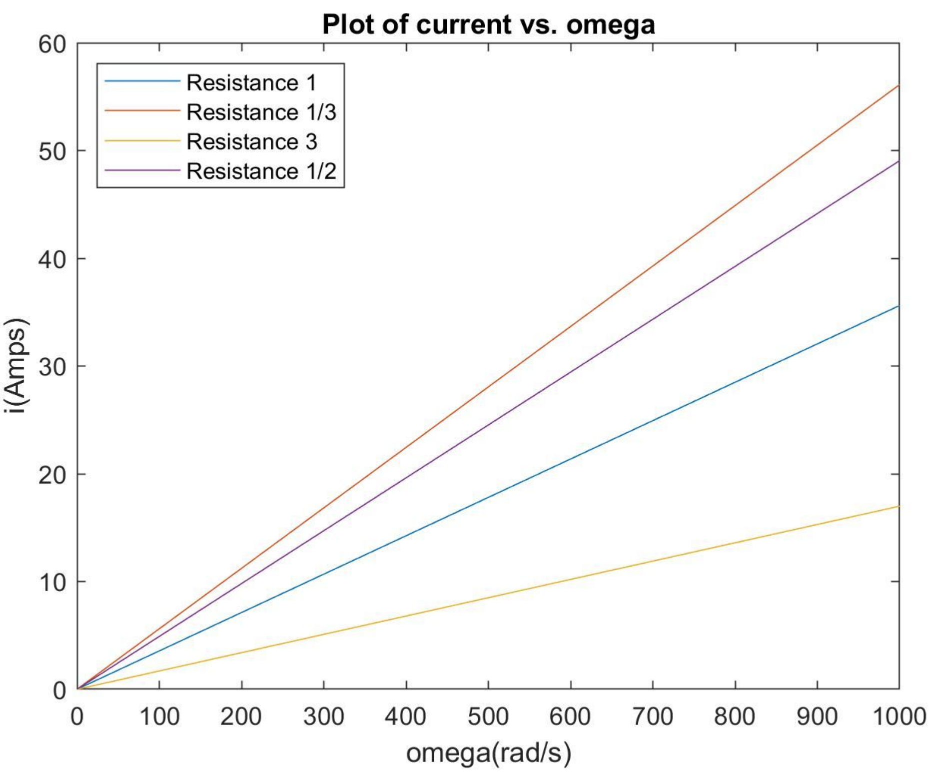

Figure 5: Rotational speed versus current for the permanent magnet commutator motor at various resistance values

Fluid Performance Analysis:

The torque on the pelton wheel has been derived as a standard equation. The torque on the pelton wheel is

$$T = \rho Q D(V_i - u)$$

Where ρ = density of water

$Q = V*A$

V = velocity of water

A = area of outer circle of wheel

$V_i = V$

$u = \omega * r$

r = radius of wheel

ω = rotational speed

Note that torque is directly related to power through the following equation, where P is power. The optimal power output should occur when the ratio of u to v is 0.5.

$$P = T * \omega$$

The parameters of the system were plugged into this equation and a number of values for torque were generated for various omega values at different heads, or heights of water falling. This was done using MATLAB (see Appendix A). The velocity of the water was found using basic kinematic equations from physics. Combining the graphs of both electrical torque and fluid torque versus rotational speed led to the graph shown in Figure 6. Electrical torque lines are those with positive slopes and the fluid torque lines have negative slopes. The points where these lines intersect represent the optimal angular velocities of the wheel which will generate the most power at various heights and resistances. This can be directly related to the speed of the water by the following equation.

$$V = 2\,\omega\, r$$

There are various intersections between each height and each resistance, representing multiple ideal angular velocities for the system. During prototype testing, the team aimed to use velocities for lower heights because a large head of about 5 meters or more would not be physically feasible for a house, especially given that the catchment system will be mounted to the side.

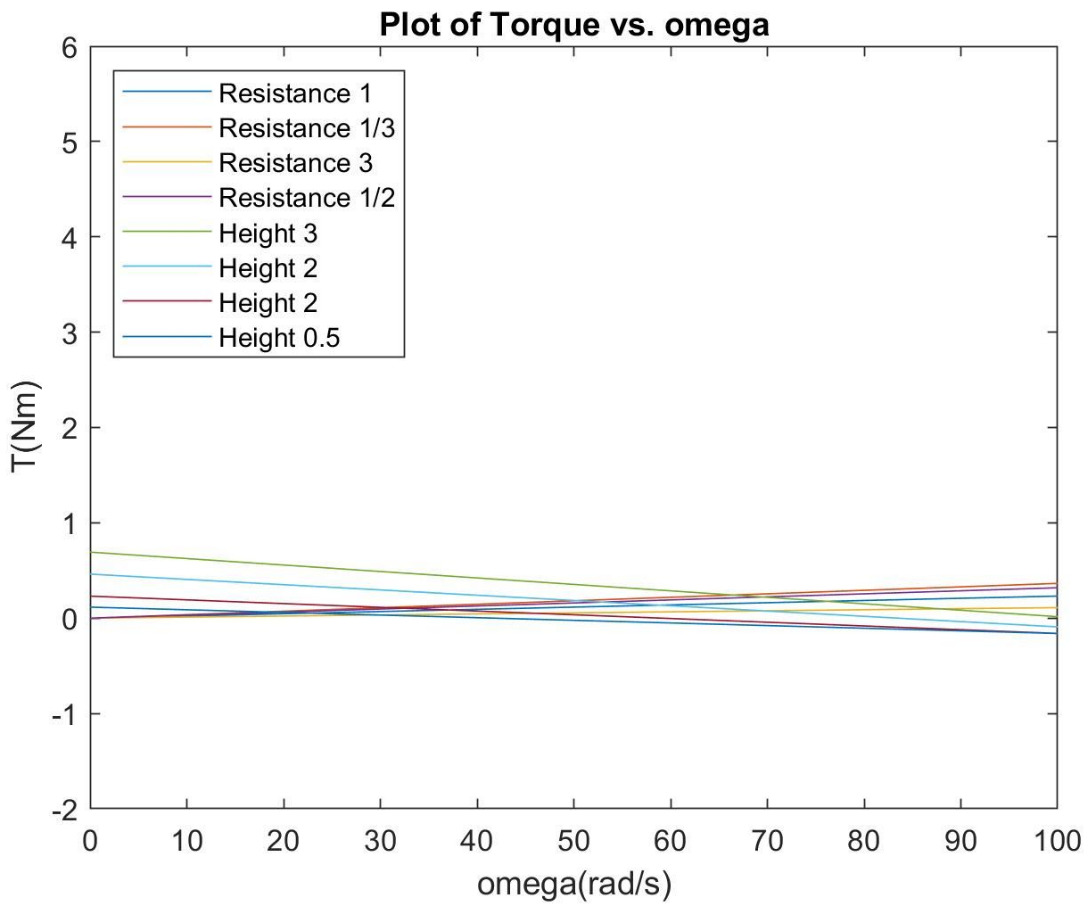

Figure 6: Electrical and fluid mechanical torque vs. rotational speed for prototyped system

Table 3: Ideal angular velocities for various intersection points in Figure 8 (in rad/s)

	Resistance ⅓	Resistance ½	Resistance 1	Resistance 3
Height ½ (m)	18.2	20.1	22.2	26.4
Height 1 (m)	30.3	32.3	36.5	42.4
Height 2 (m)	50.5	52.6	58.7	64.3
Height 3 (m)	66.7	69.3	76.1	83.2

To make Figure 6 easier to see, the four resistance lines were plotted for each height separately below in Figure 7.

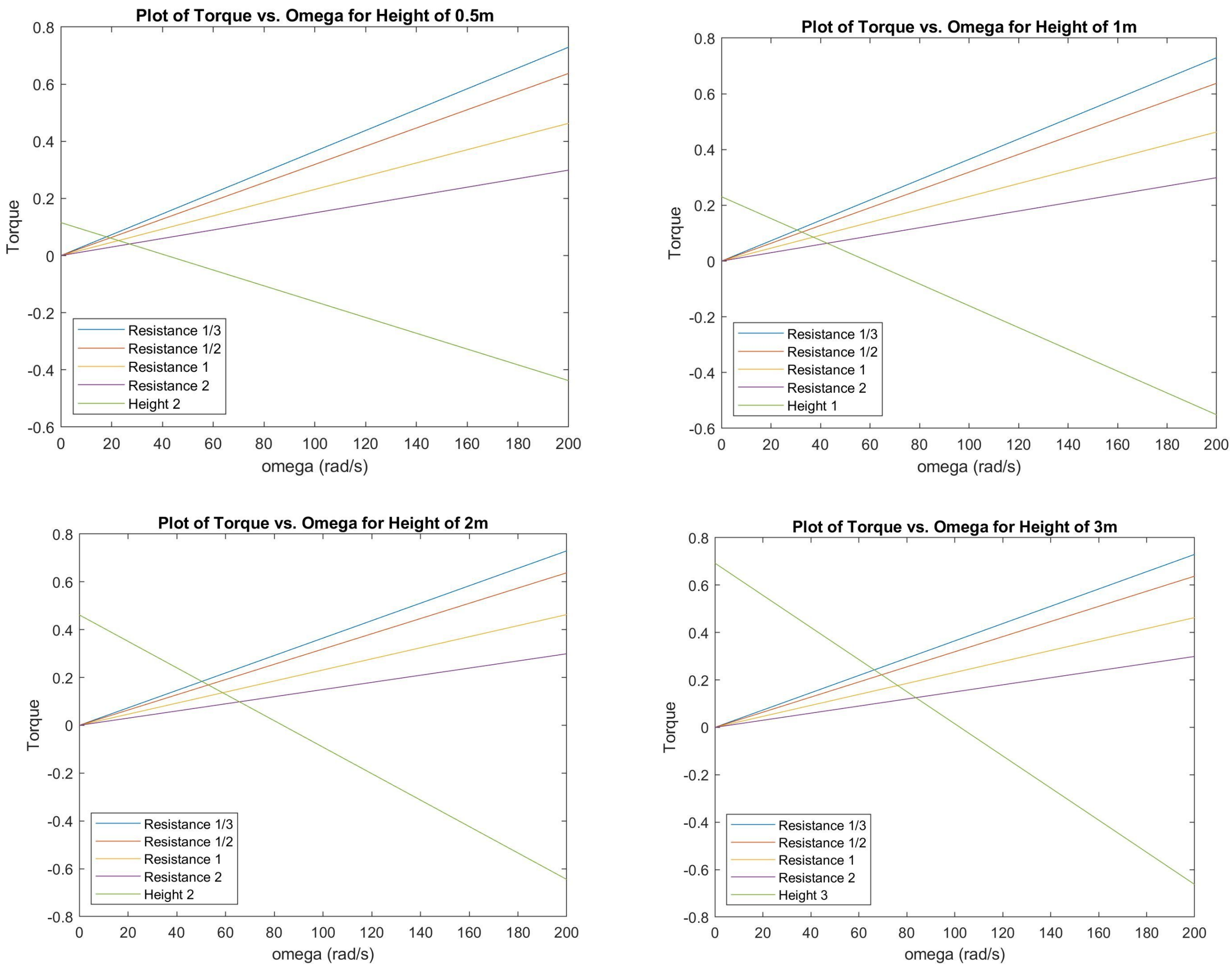

Figure 7: Torque vs. Angular Velocity for various resistances and heights of 0.5, 1, 2, and 3 meters

These graphs display a few patterns. The torque and omega values of the intersection between the height and the resistance curves increase as the height increases. Since power is related to both angular velocity and torque, a higher intersection point leads to more power generated. That means in general, the higher the water head, the greater the power generation, which makes sense physically because there is more potential energy as height increases. There is no clear relationship between change in resistance and change in power because as the resistance values increase, the x values of the intersections increase and the y values decrease, which has no obvious effect on power because both variables related to power change. The lack of conclusive parameters from theory is where the experimental testing of the system was crucial. While testing, the team aimed to test various resistances with various water speeds to find which combinations of height and resistance generated the most power.

Catchment System Design

A water collection tank allows for the system to meter water and only release water when the system will be able to reach a maximum amount of power. Therefore, the addition of the collection tank allows for the system to work in rainy areas regardless of whether any individual storm produces enough water. The integration of the collection into the turbine and motor system is shown in Figure 8 below.

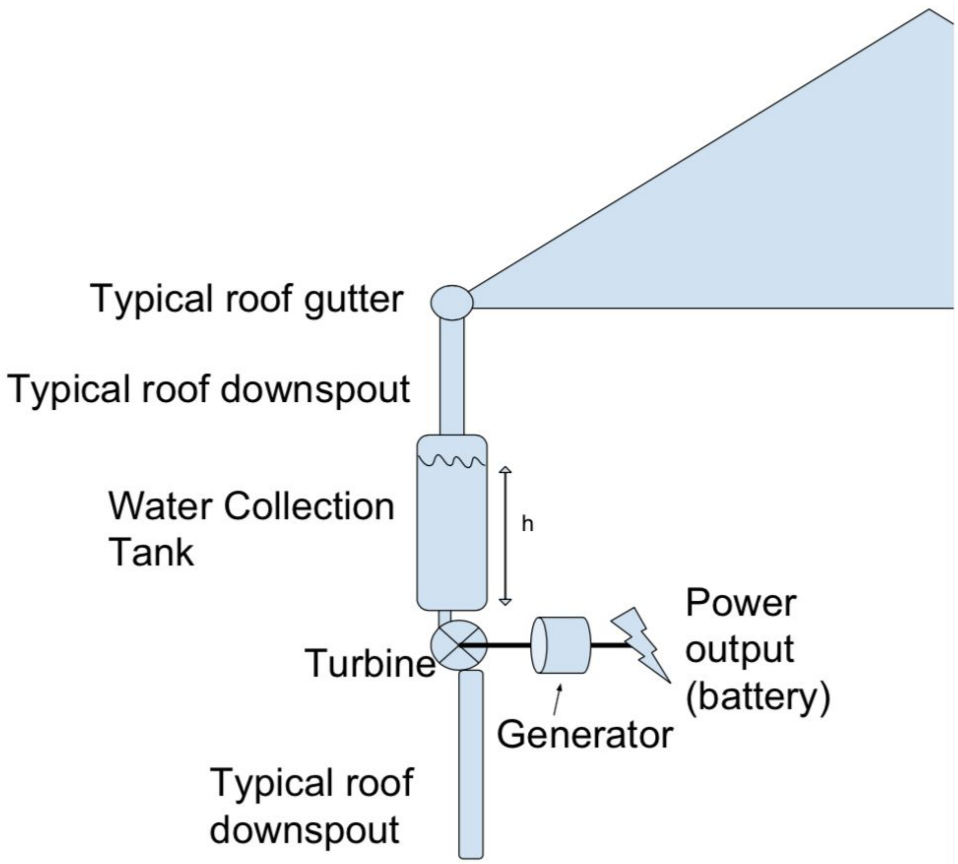

Figure 8: Proposed catchment system design including typical gutter and downspout with design including a collection tank (with a designated height of water), turbine, generator, and battery.

The proposed catchment system is a wall mounted tank with metering. The metering would occur through a floating flapper similar in design to a toilet which would release water once it reached the desired height, or energy.

A proof of concept calculation displayed the scale of a house and gutter system, as shown above, was enough to generate enough power to realistically charge a small device. As this is a form of hydropower, the theoretical hydropower output equation was used

$$P_{th} = \rho q g h$$

where ρ is the density of water (1000 kg/m^3), q is the water flow (m^3/s), g is the acceleration due to gravity (9.81 m/s^2), and h is the falling head of water or available height (m). This outputs the theoretical power in Watts ("Hydropower").

An average American household was used to determine the feasibility. Therefore, an average footprint of 2,700 square feet was used to as the area to gather water ("New US Homes...", 2016). This assumes that all of the water gets rerouted to the catchment system. Additionally, the height of house is assumed to be 25 feet as this is the height of an average two story home ("How Tall Is..."). Finally, as the efficiency is not known for the proof of concept, an efficiency of 80% was assumed as this is the lowest end for small hydropower operations ("Hydroelectric Power"). Finally, it was assumed that the storm event would have an intensity of 1 inch of rain per hour. Although this a large amount of rain, the turbine is designed for large events.

Using these values, it was found that 6.37 cubic feet of water was collected and a energy output of 10.8 Wh was obtained. As an iPhone X ships with a charger that requires 5 Watts, this amount would be able to charge an iPhone 2 times. Therefore, this supports the feasibility of the energy system. The power calculated is theoretical so although it is within a reasonable range, the physical system may have different results. Therefore, testing will be required again after the creation of the turbine.

There is a relationship between the velocity of the water and the power output of the turbine. The ideal power and related water velocity can be attained by controlling the height of the water through

$$v = C_v \sqrt{2gh}$$

where g is the acceleration due to gravity (m/s^2), h is the height of the water (m), and C_v is a constant equal to 0.97 for water ("Flow of Liquids...", 2011). Therefore, the catchment system will be designed to hold the optimal height before releasing.

Testing Results

To test the final design in a controlled environment a garden hose was used. By changing the water pressure in the hose, various values of the water exit velocity could be tested. The velocity of the water was measured by holding the hose level at a certain height *h* from the ground and measuring the horizontal distance (*d*) the water travelled before hitting the ground. The equation

$$h = v_{y0}t + 1/2a_g t^2$$

where a_g is -9.8 m/s/s, the acceleration of gravity on the water and v_{y0} is the initial velocity (in this case, 0 m/s) can be used to find the duration of time that the water traveled, *t*. The known values for *h* and *a* were used for this calculation. Next, the same equation, except modified to include horizontal variables,

$$d = v_{x0}t + 1/2at^2$$

was used to find the initial horizontal velocity of the water when exiting the hose. In this equation, the force of friction on the water by the air was considered negligible, so *a* is 0. The four groups of data points in Figure 9 reflect the four different water velocities that were recorded. A logarithmic regression was then fit to this data in order for a reasonable mathematical expression to be found relating the velocity of the water and the output of the turbine setup.

Statistical Analysis

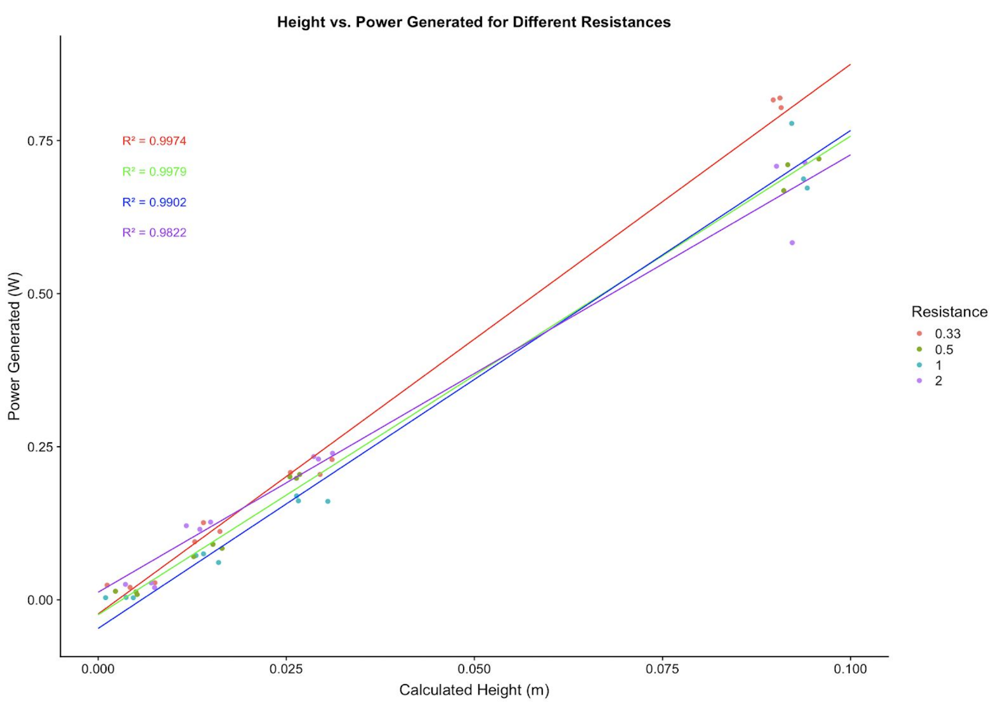

Figure 9. Linear regression analysis of the effect of water velocity (m/s) on the generation output of the system (watts) from data collected during 0.33, 0.5, 1.0, and 2.0 Ohm testing. Regressions fit with R-values of 0.9974, 0.9979, 0.9902, and 0.9822, respectively.

The regression equations obtained from the data analysis leads to an estimate for the output of this setup at higher heights of water. For instance, the regression equation for 0.33 ohms, seemingly the most efficient resistance value after a couple centimeters, is

$$\text{Output (Watts)} = 8.9751*(\text{Height of the water in meters}) - 0.023$$
$$R^2 = 0.9974$$

An ideal height of 1 meter was selected as this was predicted to be the maximum reasonable height for the system. With a height of 1 meter, the power output is almost 9 Watts (8.98). However, to check the capability of this product to begin to charge an attached battery, the voltage must also be analyzed.

Assuming that 0.33 Ohms is the most efficient resistance at 1 meter, the relationship of height to voltage output is represented in Figure 10 below.

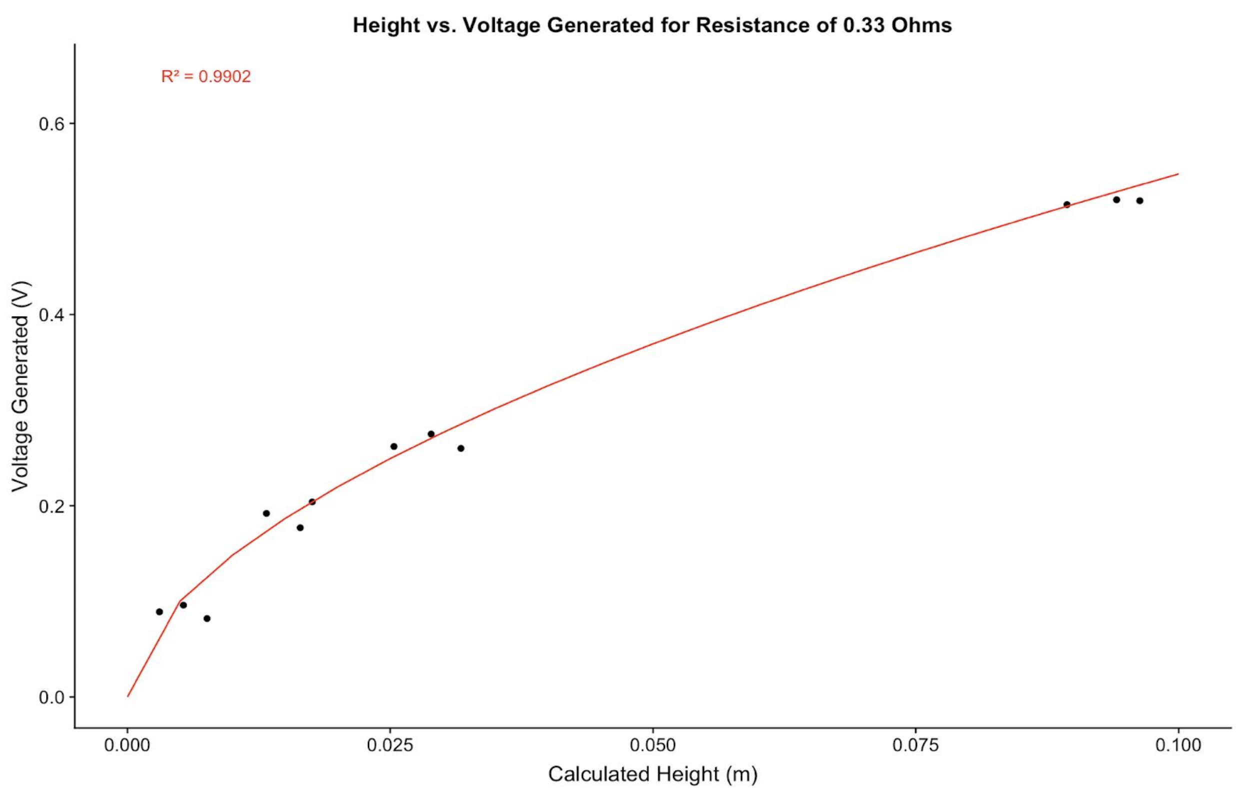

Figure 10. Power regression analysis of the effect of water velocity (m/s) on the voltage generation of the system (volts) from data collected during 0.33 Ohm testing. The regression fit with an R-value of 0.9902.

This regression curve, described as

$$\text{Voltage (volts)} = 2.0171(\text{Height of the water in meters})^{0.5667}$$

$$R^2 = 0.9921$$

can be used to estimate the voltage produced at any height. Using the ideal height of 1 meter, the expected voltage is 2.02 volts. Voltage over some resistance (R), in ohms, gives the current (I) in amps, as shown below.

$$I_{(A)} = V_{(V)} / R_{(\Omega)}$$

Therefore, if the system produces 2.02 volts through a resistance of 0.33 Ohms at one meter, then it is producing 6.11 amps. Due to low costs and relative abundance around the world, the ability to charge a car battery will be used to test the efficacy of this system. A low end car battery charger runs at about 2 amps - at this rate a 48 amp/h battery would need 24 hours to charge ("Using a Car Battery Charger"). Given that the system produces above the low end of a car battery charger, the data predicts that a continuous flow of water from 1 meter could fully charge a 48 amp/h car battery in just under 8 hours.

Theoretical Analysis

The velocity of the jet and power generated by the turbine were measured experimentally, and can be compared to theory to understand the overall performance of the system. The experimental data point with the highest power output was compared to theory by using the experimental jet velocity to find the expected power output for that particular velocity through a spreadsheet. The experimental point chosen was 0.8194 W which was generated at a jet velocity of 1.307 m/s. This particular jet velocity is theoretically expected to produce a power value of 0.9040W of power. These two values have a percent difference of about 9%, which is indicative of a good theoretical model for our system. This power output does not occur at the ideal ratio of u/v = 0.5, but instead occurs at a ratio of 0.9.

Environmental Benefit Analysis

Natural disasters damage the environment as well as lessen human safety and comfort. In the event of a storm and resulting power outages, many people must either go without power until it is restored or rely on dirty sources of energy such as fossil fuel powered generators. Our microgrid system aims to alleviate the hardship of losing power without contributing to harmful environmental outcomes, bridging the divide between access to power and environmental stewardship.

The gutter catchment system is designed to produce no carbon emissions, unlike other backup power systems. A standard 5,000 watt gasoline generator is commonly used to backup homes and properties in the event of a power outage. This type of generator is generally convenient to use, versatile, and large enough to power multiple smaller appliances or a limited selection of larger appliances or housing features such as air conditioning (Davis). Although it can power portions of a home, it also produces 2.6 lbs of carbon emissions per kilowatt-hour produced, or 13 lbs of CO_2 emissions per hour run at full load. This value was calculated multiplying the standard burn rate of a gasoline generator by the carbon dioxide emissions coefficient of gasoline ("Generator Fuel Consumption") ("EIA").

$$\text{Burn rate (gallons/hour)} \times CO_2 \text{ coefficient of gas (lbs } CO_2\text{/gallon)}$$

$$(0.67 \text{ gallons/hour}) \times (19.60 \text{ lbs } CO_2\text{/gallon}) = 13.13 \text{ lbs } CO_2\text{/hour}$$

$$13.13 \text{ lbs } CO_2\text{/hour} \div 5{,}000 \text{ watts hours} = 0.0026 \text{ lbs } CO_2\text{/watt or } 2.6 \text{ lbs } CO_2\text{/kW}$$

This system will be marketed towards home and property owners in regions that experience significant rainfall during storm events and suffer from corresponding power outages. According to data from Duke Energy, power outages in North Carolina and South Carolina can range from just over an hour a year for the average consumer in some locations (Kannapolis, NC – 2016) up to 250 plus hours (Wilmington, NC – 2018). While there is significant variation in the amount of time people are without power, the average Duke Energy customer was lost power for about 18.5 hours per year (based on data from cities across the states during the past 5 years).

In 2018, the mid-Atlantic was hit by hurricanes Michael and Florence, which left millions of people without power for extended periods of time. The average customer in Wilmington, NC in 2018 was without power for 15,000 minutes (250 hours or 10 days) and the city was hit with over 100 inches of rain during the year ("National Weather Service"). If someone ran their generator for 50% of the time that they were without power, they would produce 1,640 lbs of CO_2 over the course of the year due to power loss.

$$13.13 \text{ lbs } CO_2\text{/hour} \times 125 \text{ hours} = 1{,}641.25 \text{ lbs } CO_2$$

In a less extreme situation, a customer who loses their power for the 18 hours in a year may run their backup generator for 9 hours, this would produce 118 lbs of CO_2. A backup generator will produce more power (kilowatt-hours) however in some cases it may produce more power than a home needs or desires. For homes that only need to power small appliances such as wifi routers, lamps, or phone chargers during power outages, our system would produce enough energy while cutting down on the unnecessary creation of CO_2 emissions.

In addition to potential carbon offsets that our system would bring, the gutter system would allow individuals to divert rainwater from flowing into the streets and stormwater runoff system that eventually lets out into local waterways. The gutter water could be stored in a pond for later use or simply allowed to soak into grassy areas. Stormwater that travels along impervious surfaces (such as roads) pick up nonpoint pollutants before making its way to waterways ("DC DOEE"). Reducing the amount of stormwater runoff would reduce the amount of street level pollutants being carried into waterways. Additionally, stormwater runoff is typically is warmer than the habitats it lets out into, and thus when it mixes the stormwater can potentially increase the base temperature of the surface water ("Thermal Impacts").

Target Market Analysis

To address the target markets for a product, the first consideration is where the product would be the most needed and/or wanted. This includes older areas of the US that have outdated power transmission grids, rural US areas, areas with large rainfall, and many developing nations.

To circumvent most policy and city ordinance issues involved with mounting a power-generating system on a building, the target market is individual homeowners. An online survey posted on the Duke Parents' Facebook page survey attracted a small, but representative population of responders, with 91.5% of the participants living in homes that they own (the other 8.5% residing in apartments or rented homes). In addition, as Duke has students from all over the world, it is likely that the responses on this survey are more representative of an overall homeowners population than any other form of simple random survey we would have been able to conduct.

Using the online survey, a sample of 59 non-student responders was obtained. The responses to this survey show promising interest in the storm water collection system, with only 6.8% of responders saying that they would not be willing to mount a collection system on their house or apartment. On the contrary, nearly three quarters of the responders (74.6%) stated that they would modify their gutters to accommodate the system and 18.6% reported that their decision would be based on factors such as size, installation difficulty, etc.

The majority of the data collected was from willing responders in a parent Facebook page. Most likely, these parents reside in areas of the world that have good infrastructure where emergency power would not be a key factor for survival. Nonetheless, we believe there is another market of homeowners with less reliable energy infrastructure. This group includes rural areas and homes, small coastal or island towns, and towns in undeveloped countries. This product would have more utility for these "disconnected homes" than for the surrounding Durham area due to less access to energy backups.

Basic Business Plan

The data collected from the market analysis was used to estimate costs and uses of our product. For the market with fewer power losses, the system needs to be cheap and efficient - properly powering the desired products with minimal required intervention. According to homeowner responses, the ideal cost for the product would lie between \$20 and \$50. The projected cost for the prototype is closer to \$100. Since this system is a passive generator - something that produces energy slowly over time - the durability and longevity of the system is its most important attribute.

Table 4: Cost of Materials to Produce Prototype

Part	Cost
Motor	\$90
Plastic Mounting Piece	\$3
15/64" Drill bit	\$3
Total	\$96

Table 5: Projected Costs for Commercial Unit (large-scale)

Part	Estimated Cost
Turbine	\$5 (if 3D printers are already owned)
Motor	\$30-60
Catchment Tank	\$30
Battery	\$40 ((Standard 48 amp/h car lead cell battery)
Gutter Wire Mesh	\$5
Plastic mounting piece	\$3
Total	\$113-143

As can be seen in Table 4 and 5 above, the cost to produce the prototype was \$96. However, this just included the motor, the part itself, and any other materials required for testing. For the full scale model, the price will range from about \$113-\$143.

Next, the longevity of the system must be determined. As it is mostly a mechanical system, it is expected that the motor will be the limiting factor as this is the most complex part. A motor is estimated to last about 10-15 years (Nailen). Therefore, the system as a whole should either last for this amount of time or will have small, easy repairs. Additionally, to maximize the lifespan, the turbine will be protected with mesh to reduce any damage to the plastic from falling debri. However, the owner would have to periodically clean this mesh.

First, a business plan was created for individual homeowners in the Southeast. Although the cost of the prototype is high, there is a potential for Duke Energy to subsidize the turbines ("Products and Services"). Through this, Duke energy could offset the costs of upgrading the infrastructure in rural areas to make their energy more reliable by instead offering customers a product that would guarantee use of essential appliances during outages. Duke Energy has displayed interest in renewables as it already has a program in South Carolina that offers solar rebates to property owners who own solar array to encourage installations of renewable energy ("Solar Rebates"). Additionally, in North Carolina, in January 2018, Duke Energy proposed two programs for renewable energy: Shared Solar and Green Source Advantage. Shared Solar allows facilities to adopt solar energy without having it on property and Green Source Advantage gives consumers options on how they get renewable energy ("Duke Energy Proposes…").

For the third world country market, the turbine setup would enter the renewable energy market that works to provide access to individual households not connected to a grid. Solar power is currently one of the leading technologies providing this energy. One benefit of the turbine design over solar power is that maintenance would be easier as there are only two parts that could electrically break, the motor or the battery, and it would be easy to determine which was broken. Once broken, the setup would be modular so a new part could be purchased to replace it. In comparison, one of solar energy's main problems is that it is difficult to maintain so owners often abandon the technology as they do not have access to technical support (Da Silva). However, the water turbine could be integrated into the solar system as well by entering the PAYGO system which in this case, would allow for payments to happen on a monthly basis.

Social Benefit Analysis

The social benefits differ according to the target market: whether it is within the rural US or and in developing nations. The social benefit of this product in the US will be the increased safety and ease that comes with power resiliency. In the US, cell phones and wifi routers play a large part in daily life, but are particularly important during emergencies. If there is a large storm event, or any other outage, the product is designed to power these small devices when all other power has failed. This includes the failures of other power storage options, like power banks. Outages of over 6 days, especially in rural areas, are not uncommon and rechargeable batteries may not last this long. Additionally, the battery can power lamps and other small devices. This gives families a space to use electricity in case of emergency. Though it should not be necessary due to natural gutter system collection, the product can even be manually loaded with more water if power is in very high demand. Finally, this product will alleviate the pressure put on utilities to fix all damaged infrastructure after storm events, knowing that their customers have a backup energy source.

Social benefits in developing nations include increased safety and enjoyment of electronics during both storm events and daily. In many developing nations, people spend large amounts of time traveling to charge their phones (Gogla). As the product can be manually filled, it can be used as a microgrid for small device charging. This is especially useful as this product is cheaper and easier to maintain than solar panels. The product can enter the same market as solar in developing countries through PAYGO, which includes credit, data, steady payment. Additionally, the product solves the main problem of solar, lack of maintenance, as the product is low-maintenance with a slow repayment period. Therefore, the product will serve similar functions, but with fewer problems ("PayGo Solar").

This product will be the most useful where transmission lines are the least resilient, nonexistent, or where there is a lot of rainfall. This is particularly in older areas of the US and many developing countries.

Conclusions

The results outlined in this paper are very promising. The data suggests that the system, with a water head height of 1 meter, would be efficient enough to charge a standard car battery - producing nearly 9 watts per hour of flow when utilizing a circuit resistance of about $0.33\,\Omega$. With the relative ease of installation and the ability to be a self-sustaining passive hydroelectric generator, this product would achieve its goal of providing a cheaper, family-sized, emergency power source. The results outlined in this paper have shown that this product could greatly increase the connectivity between victims of a storm event and emergency services while still remaining mechanically and electrically simple enough to be reliable under harsh conditions.

With the right manufacturing costs and collaboration with large power companies, this product may be able to increase safety in the US, but also offset carbon emissions. A further scope for this team to investigate would be the amount of fuel burned in rebuilding electrical infrastructure following a large storm event and whether or not this product could cut that pollution emission.

For the catchment system, there is potential to switch from a mechanical system to an electrical system. For a class-level prototype, a mechanical system was the easiest way to display proof of concept. However, further iterations could include electrical monitoring. This would track the level of the water instead of a floater. Additionally, there is potential for smart home integration with this new system. Currently, the water can only be released when it is at the “optimal level” so an electronic system would allow for the owner to decide when to output water to match their household’s energy demands.

Storm data collection would be useful in future work, but it was sufficient to base this product’s creation on common-knowledge assessments such as: storm severity increases, areas of above-average transmission failures/reconnection times, etc.

In the future, it would be beneficial to test the system’s capabilities at even lower resistance values; during the course of this experiment, only three $1\,\Omega$ resistors were available, which limited the scope of testing. The testing of the turbine should be done in an area without wind to prevent a scattered data set. Additionally during testing, the angular velocity of the system should be measured using a tachometer so that theory and experimental data could be more easily compared. If this product were sold, the turbine should be made out of a more sturdy material, such as stainless steel. Research should also be done to reduce the cost of the system as much as possible. This project served as a promising proof of concept which can continue to grow into a marketable product.

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Appendix

Appendix A: MATLAB Code

```
clear; format short e
%Defining constants
Ra = 0.825;
k = 0.065;
omega = linspace(0,200,100);
%Creating linear anonymous function for i
i = @(Rl)(k*omega)/(Ra+Rl);
% A = k*(k*100)/(Ra+3)
%Making plot of i vs. omega with different Rl values
% figure(1);clf
% plot(omega,i(1))
% hold on
% plot(omega,i(1/3))
% hold on
% plot(omega,i(3))
% hold on
% plot(omega,i(1/2))
% title('Plot of current vs. omega')
% xlabel('omega(rad/s)')
% ylabel('i(Amps)')

%Defining Fluid Constants
roh = 1000;
g = 9.8;
D = 0.15;
rw = D/2;
rjet = 0.005;
Ajet = 7.85398*(10^-5);
%T=
@(h)((2*roh*Ajet*((2*g*h)^(3/2))*(((omega.*rw)/(2*g*h))-(((omega
.*rw)/(2*g*h)).^2)))./omega);
T = @(h)(roh*Ajet*sqrt(2*g*h)*D*(sqrt(2*g*h)-(omega*rw)));
%Plotting Torque
figure(2);clf
```

```
plot(omega,k*i(1/3),omega,k*i(1/2),omega,k*i(1),omega,k*i(2),ome
ga,T(1))
title('Plot of Torque vs. Omega for Height of 1m')
xlabel('omega (rad/s)')
ylabel('Torque')
legend('Resistance 1/3','Resistance 1/2','Resistance
1','Resistance 2','Height 1','Location','Southwest')
figure(3);clf
plot(omega,k*i(1/3),omega,k*i(1/2),omega,k*i(1),omega,k*i(2),ome
ga,T(0.5))
title('Plot of Torque vs. Omega for Height of 0.5m')
xlabel('omega (rad/s)')
ylabel('Torque')
legend('Resistance 1/3','Resistance 1/2','Resistance
1','Resistance 2','Height 2','Location','Southwest')
figure(4);clf
plot(omega,k*i(1/3),omega,k*i(1/2),omega,k*i(1),omega,k*i(2),ome
ga,T(2))
title('Plot of Torque vs. Omega for Height of 2m')
xlabel('omega (rad/s)')
ylabel('Torque')
legend('Resistance 1/3','Resistance 1/2','Resistance
1','Resistance 2','Height 2','Location','Southwest')
figure(5);clf
plot(omega,k*i(1/3),omega,k*i(1/2),omega,k*i(1),omega,k*i(2),ome
ga,T(3))
title('Plot of Torque vs. Omega for Height of 3m')
xlabel('omega (rad/s)')
ylabel('Torque')
legend('Resistance 1/3','Resistance 1/2','Resistance
1','Resistance 2','Height 3','Location','Southwest')
```

Appendix B: R Code (Regressions and Data Visualizations)

````
```{r}
# Read in data and load libraries:
library(tidyverse)
library(cowplot)
veldata <- read_csv("~/Downloads/basscon_data2019_1.csv")
```
````

````
```{r}
# setting up the data to be usable:
veldata <-
  veldata %>%
  mutate(
    voltage = sqrt(res*pow)
  )
veldataboy <-
  veldata %>%
  mutate(
    Resistance = as.character(res)
  ) %>%
  select(-res)
veldataboy
velfor.33 <-
  veldata %>%
  filter(
    res == 0.33
  ) %>%
  mutate(
    Resistance = as.character(res)
  ) %>%
  select(-res)
#velfor.33
```
```{r}
# Regression Lines Code
# Note, regression curves were found using functions in
Microsoft Excel. Data organization and visualization is just
easier in R.
heightscale <- seq(0,.1, by = .005)

#.33 Ohms
#y = 8.9751x - 0.023  R² = 0.9974

new.33 <-
  data.frame(heightscale) %>%
  mutate(
    calpow = 8.9751*heightscale - 0.023
````
````

```
  )

#.5 Ohms
#y = 7.8159x - 0.0244  R² = 0.9979

new.5 <-
  data.frame(heightscale) %>%
  mutate(
    calpow = 7.8159*heightscale - 0.0244
  )

#1 Ohm
#y = 8.1299x - 0.0466  R² = 0.9902

new1 <-
  data.frame(heightscale) %>%
  mutate(
    calpow = 8.1299*heightscale - 0.0466
  )


#2 Ohms
#y = 7.1421x + 0.0125  R² = 0.9822

new2 <-
  data.frame(heightscale) %>%
  mutate(
    calpow = 7.1421*heightscale + 0.0125
  )

# Vel for .33 Ohms
# y = 2.0171x^0.5667  R² = 0.9921

v33 <-
  data.frame(heightscale) %>%
  mutate(
    calvel = 2.0171*(heightscale**0.5667)
  )
```

````
```
```{r}
# Height vs. Power Generated graph
ggplot(veldataboy, aes(x = height, y = pow)) +
  geom_jitter(aes(color = Resistance), height = 0) +
  geom_line(aes(x=heightscale, y=calpow), data = new.33, color =
"red") +
  geom_line(aes(x=heightscale, y=calpow), data = new.5, color =
"green") +
  geom_line(aes(x=heightscale, y=calpow), data = new1, color =
"blue") +
  geom_line(aes(x=heightscale, y=calpow), data = new2, color =
"purple") +
  labs(x = "Calculated Height (m)", y= "Power Generated (W)",
title = "Height vs. Power Generated for Different Resistances")
+
  annotate("text", x = .0075, y = .75, label = "R² = 0.9974",
color = "red") +
  annotate("text", x = .0075, y = .70, label = "R² = 0.9979",
color = "green") +
  annotate("text", x = .0075, y = .65, label = "R² = 0.9902",
color = "blue") +
  annotate("text", x = .0075, y = .60, label = "R² = 0.9822",
color = "purple")

```



```{r}
# Calculation for r = .33, h = 1
heightscale1 <-
  seq(0,1, by = .05)

new.33v <-
  data.frame(heightscale1) %>%
  mutate(
    calvel = 2.0171*(heightscale1**0.5667)
````

````
  )
new.33v$calvel
```

```{r}
ggplot(filter(veldataboy, Resistance == "0.33"), aes(x = height,
y = voltage)) +
  geom_jitter(height = 0) +
  geom_line(aes(x=heightscale, y=calvel), data = v33, color =
"red") +
  labs(x = "Calculated Height (m)", y= "Voltage Generated (V)",
title = "Height vs. Voltage Generated for Resistance of 0.33
Ohms") +
  annotate("text", x = .0075, y = .65, label = "R² = 0.9902",
color = "red")
```
````
````