Proof of Concept: Harvesting Wind Energy from Kites

Further Developing a Renewable Resource to Provide Natural Disaster Relief to Power Coastal Communities

Bass Connections in Energy & the Environment: Design & Innovation

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Abstract

Temporary, mobile, emissionless energy is hard to come by and seldom accessible. An airborne turbine that uses kites to harness wind energy could provide a cheap source of clean energy. In theory, such a model could provide electricity to household appliances in power outages and serve as an additional source of electricity year-round in areas with consistent winds at certain altitudes. This study constructed small-scale models of such a turbine to measure their ability to generate power. Three different models of different scales were tested in a wind tunnel to determine the power they could produce by transferring torque along tethers to a generator. With these results, it is estimated that a full-scale model, with a turbine held aloft by a surf kite 30 m above the ground, could generate 586 W and cost around $700. This indeed is enough power to run certain household appliances. In testing, counter torque inhibited consistent rotation, so the design from this study should be improved upon to maximize a full-scale model's dependability. Testing on small-scale models does, however, indicate that enough energy can be produced from such a system to warrant further attempts at improving the model for full-scale utility.

Introduction

Storms and natural disasters resulting from extreme weather events are the most common causes of power outages (Campbell, 2012). The coast of North Carolina is particularly susceptible to these types of power outages with an average of two tropical storms or hurricanes affecting NC annually (North Carolina Climate Office, 2019). This past fall, when Category 1 Hurricane Florence hit the coast of North Carolina and continued its path across the state, over 900,000 homes lost power between the middle of the state and the coast (Murawski & Stradling, 2018). Typically, when homes are without power for days at a time, backup diesel generators are used in order to power household appliances and provide temporary relief from the effects of the storm. Generators can last several days and are useful for keeping households comfortable and functional during major storm events when the power goes out. However, because generators require a fuel source that is typically gasoline or diesel, there are adverse environmental effects with the emission of carbon dioxide, nitrous oxide, and particulate matter. Major storm events and power outages are inevitable, so finding a more environmentally-friendly alternative that performs similar functions to a backup generator would help reduce an individual's fuel costs and carbon footprint.

One of the driving forces behind this research is to further develop an already existing renewable resource. The most feasible and relatively reliable renewable resource during a storm event is wind. Additionally, wind is abundant on the coast of North Carolina, averaging 4.2 m/s in the heavily populated Wilmington area, for example (Southeast, 2015).

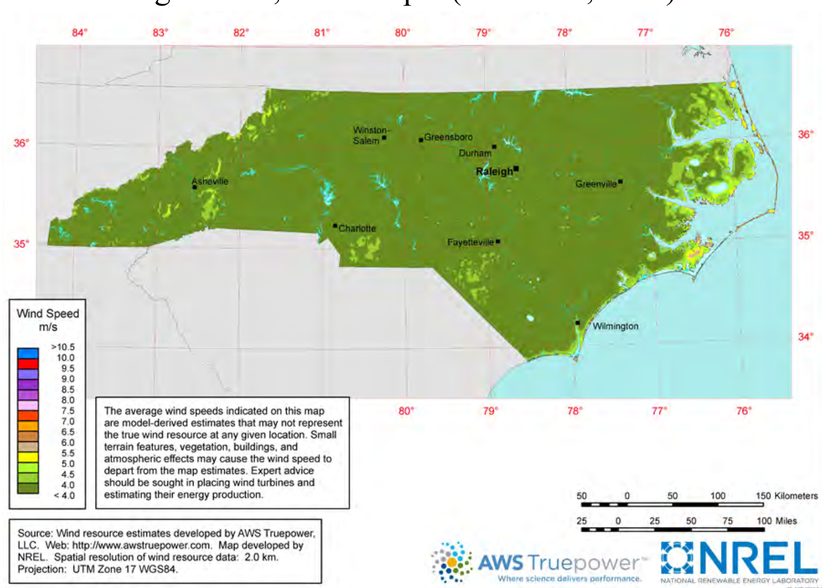

Figure 1. Average Wind Speed at 30 meters in residential communities in North Carolina (WINDExchange, n.d.).

During extreme storm events like a hurricane, these wind speeds are even more severe. To date, considerable research has been conducted to construct and deploy airborne wind energy systems (AWES). These apparatuses usually take up less land area than standard wind turbines, which is ideal for implementing a single energy system unit at one's home. Additionally, less materials are needed, thereby reducing the cost per kWh produced.

Ultimately, the team's goal was to construct an energy system that is accessible in both portability and affordability. Portability ensures ease of assembly and storage so that it does not occupy a considerable amount of space when not in use. The full-scale AWES is to be constructed out of many of the components that make up a tent, namely aluminum poles and polyester fabric. Ideally, the AWES should be user-friendly, mobile, and durable. Setting up the AWES should be as simple as pitching a tent. Affordability is also a large focus of this project, so greener portable energy can be more accessible. Affordability is especially relevant as poor and marginalized communities are often the last to receive power again after an outage (Einbinder, 2018). Creating an energy system that can be competitive with backup diesel generators would enable households across the socioeconomic spectrum to reduce their carbon footprint while ensuring backup energy a cost effective way.

Technical Design

Original Concept

The initial inspiration for the proposed airborne wind energy solution came from an existing kite harvesting mechanism known as a "daisy" rotary kite (or a carousel-style kite) created at leisure by Irish Engineer, Roderick Read. While pursuing a rotary wind style kite seemed appealing, the team has focused on the crossover between this innovate form of wind energy harvesting coupled with a tried-and-true method known as the savonius wind turbine, a drag-based vertical-axis wind turbine. Figure 2 below demonstrates the daisy rotary kite design.

Figure 2. Read's rotary kite was the inspiration for the team's goals and initial design.

The team's kite design features lightweight, tether-fastened, polyester fabric, similar to the rotary kite. It also uses tension to power a generator and drag-based energy harvesting with a central axis, taking advantage of torque without the heavy metal structure of a generic Savonius wind turbine. While most Savonius-style wind turbines typically feature only two vanes to maximize efficiency, the third vane on the new design is hypothesized to allow the turbine to self-start and prevent it from stalling or getting jammed in the wind (Menet & Bourabaa, 2004). The reduction in efficiency is mitigated by larger surface area for each vane and lighter materials, which reduce the turbine's moment of inertia.

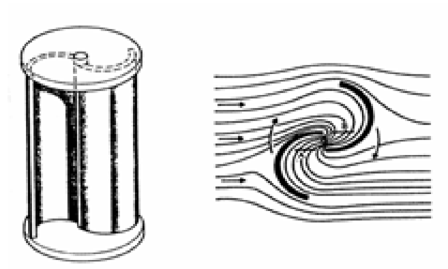

Figure 3. Classic Savonius wind turbine (McNiven, 2017).

The AWES design is similar to a cup anemometer. The cupped vane design allows the kite to capture more air on one side, inducing rotation in one direction. As the backs of each vane are cupped outwards, they experience less drag than the inward-cupped front of the vane, causing the turbine to spin. Another method to increase the efficiency of the turbine would be to cover the back-side half of the turbine in the direction of the source of wind to reduce the torque from wind that pushes against the direction of the turbine's spin.

Figure 4. Cup anemometer (McNiven, 2017).

Description of Approach

The AWES can be broken down into several components: the surf kite, the turbine structure, and the base/energy generation, as demonstrated in Figure 5 below:

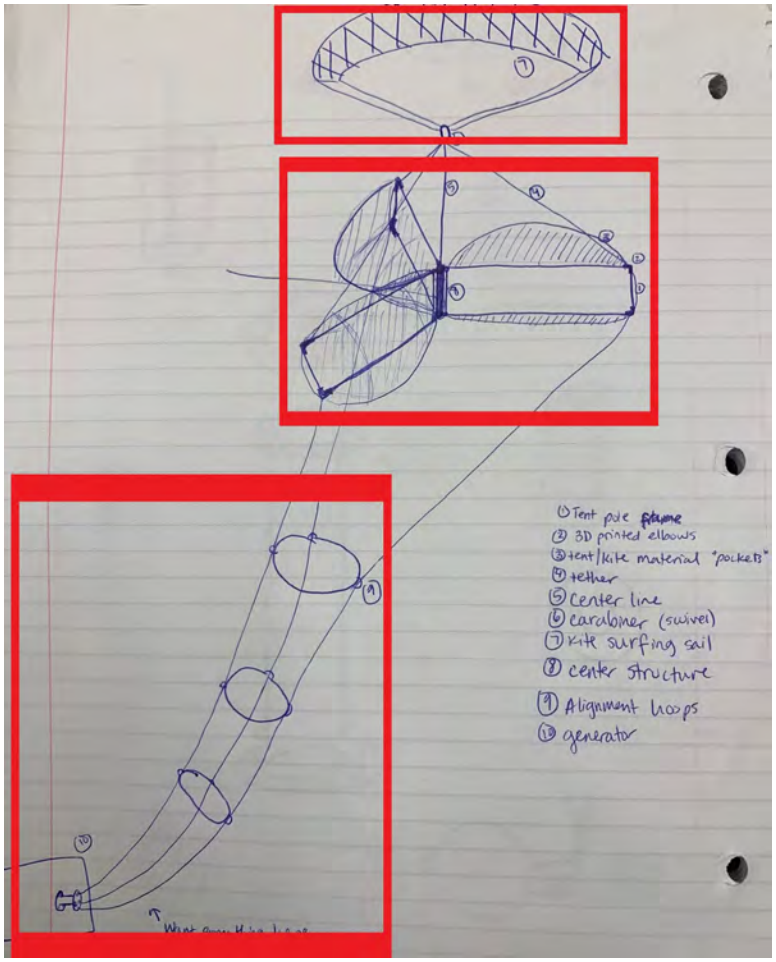

Figure 5. The AWES has three main components: surf kite (top), turbine structure (middle), base/generator (bottom).

The surf kite is the system that supports the entire structure within the air. Even when under the strain of large loads, surf kites are capable of sustaining flight for long periods of time. A system like this is ideal for maintaining a Savonius wind turbine in the air. For these reasons, the team incorporated a surf-kite into the design to act as a stabilizer for the rest of the prototype. Connected through a tether point, the surf-kite takes most of the lift, which allows for the other components to better generate energy.

Suspended by a rotating swivel to the surf kite is the turbine structure itself, which is the drag-based Savonius kite. Ideally, this structure will be completely vertical to allow for maximum energy extraction from the wind. A full-scale model will have vanes that are roughly 1 m tall and 1.5 m wide. In a single kite line, several apparatuses may be placed in series to generate even more wind power.

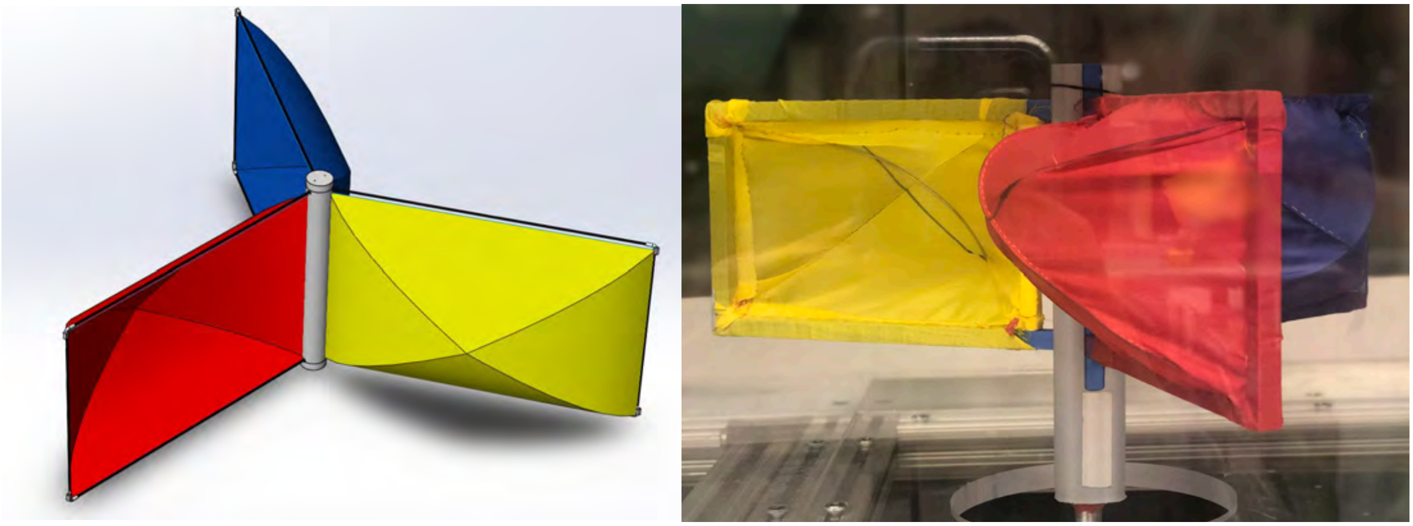

Figure 6. CAD (left) and physical (right) models of the kite structure.

The final portion of the kite is the base, located on the ground. Three tethers, each attached to the bottom outer corner one of the three vanes, will lead down to alignment hoops that hold the tethers in tension. This tension allows the hoops to spin, which in turn power a generator. The evenly spaced rings connected to the ground-based generator is designed to maintain torsional rigidity, which is essential to minimizing efficiency losses. From several tests, it appears that the Savonius kite used in this design offers a mix of torque and angular velocity, compared to a standard Savonius, which offers high torque and low angular velocity. Using a series of gears, this torque will be converted to rotational speed. The generator should be a permanent magnet motor and brushed DC commutator.

Energy and Power Calculations

To derive the energy use from first principles, there are several assumptions:

1. The wind is perpendicular to the plane of the kite vane (this allows for maximum energy extraction from drag, in this setup)
2. The kite area is 1 m tall by 1.5 m wide
3. The coefficient of drag is 1.28*sin(*a*) (NASA, 2015), where *a* is measured from the vertical axis and accounts for kite inclination. This is assumed to be a constant 1.28 average along the face of the vane.
4. At 30 m in altitude, the wind speed is 4 m/s (not accounting for increased wind speed around storm events). Storm events can see wind speeds up to 10 m/s.
5. Savonius-style wind turbines have a tip-speed ratio of $\lambda = 1$, which means that $V_{wind} = \omega * R_{rotor}$ (Zemamou, Aggour, & Toumi, 2017). The radius of the moment arm on which the wind is acting is 0.75 meter and the radius of the rotor is 1.5 meters.
6. The area of the rotor is only for one vane of the kite turbine (1.5 m x 1.0 m)
7. Density of air at 30 m is 1.2215

$$\begin{aligned} P_{Gen} &= T\omega \\ &= F_D * R_{Arm} * \omega \\ &= F_D * R_{Arm} * \frac{V_{wind}}{R_{rotor}} \\ &= (\tfrac{1}{2}\varrho_{air}V^2{}_{wind}A_{rotor} * C_D) * R_{Arm} * \frac{V_{wind}}{R_{rotor}} \\ &= (\tfrac{1}{2}\varrho_{air}V^3{}_{wind}A_{rotor} * C_D) * \frac{R_{arm}}{R_{rotor}} \\ &= 0.5 * 1.2215kg/m^3 * (10\ m/s)^3 * 1.5m^2 \\ &\quad * 0.75m/1.5m \\ &\approx 586\ \mathrm{W} \end{aligned}$$

Plugging in numbers leads to a power generated of 586 W, ignoring the downwash and lift effects of the rotors cupped pockets. Ideally, these effects should cancel out if the kite geometry is perfectly symmetrical and if the kite turbine is upright. However, there are some limits on efficiency. First, Betz Limit defines the maximum efficiency for extracting air from any possible configuration. This limit on capturing wind is $\eta = \frac{16}{27}$ of the total energy available in the wind.. As a sanity check for the above calculation:

$$\begin{aligned} P_{Max} &= \tfrac{16}{27}\varrho r_{rotor}hv^3 \\ &= \tfrac{16}{27}(1.2215\ kg/m^3 * 1.5 * 1 * (10\ m/s\ )^3) \\ &\approx 1085\ W \end{aligned}$$

The maximum power predicted for the kite is less than the maximum theoretical power, which means the kite is not extracting more energy than is allowable. As the Betz limit states that wind turbines cannot extract more than 16/27 (59.3%) of the energy in wind, this wind turbine is 32% efficient compared to the energy in the wind, yet 54% efficient when compared to the Betz limit.

However, the extractable power for a Savonius-style kite is affected by how half of the rotor will face the wind while the back-facing half slightly counteracts the rotor. Classical Savonius wind turbines peak at 15% efficiency (McNiven, 2017). Zemamou et al. (2017) states that the maximum power extracted from a Savonius kite should be almost half of the Betz limit as part of the scooped portion of the wind turbine counteracts the spinning of the rotor. Mathematically, this is:

$$P_{Max} = 0.36\frac{kg}{m^3} * hrv^3 = 0.36\frac{kg}{m^3} * 1m * 1.5m * (10\frac{m}{s})^3 = 540\ W$$

The above equation should be taken as a lower limit to the expected power as this calculation is for steel vane savonius wind turbines. This implies that the pockets are solid and do not collapse. However, there is a larger energy input required to make this turbine spin (as it weighs much more than a kite turbine).

Wind Tunnel Tests

Testing Theory

In order to easily extrapolate energy values from the kite design, a scale-model test in a wind tunnel was performed. The wind tunnel is located in the basement of Hudson Hall on Duke University's campus and is roughly 2 feet wide by 2 feet tall. As a rule of thumb, models should not exceed 10-15% of the frontal area of wind tunnels to avoid skewing results. With this guideline, the prototype scales are 8.33%, 10.42% and 12.5% of the full-scale model, with vanes that are 3" by 5", 3.75" by 6.25", and 4.5" by 7.5", respectively. The 3D printed design of the wind kite is reproduced below, created with the following slicing profile: 2 mm wall thickness, 10% infill, 1.5 mm layer thickness on an Ultimaker 2 printer. The model was then glued together with cyanoacrylate.

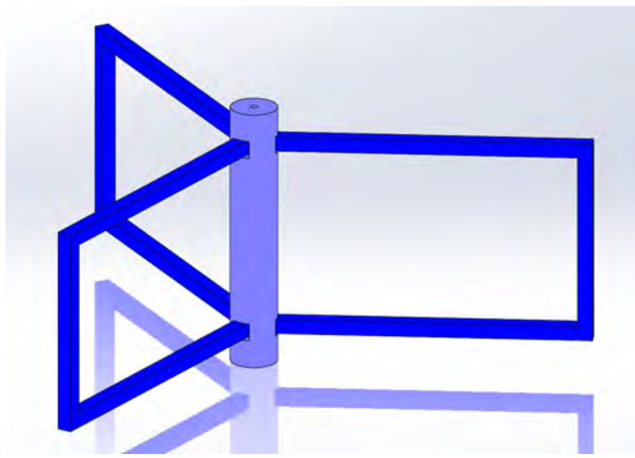

Figure 7. 3D model of prototype of frame for wind tunnel testing.

While this device is considered a wind turbine, the analysis can follow that of a pump or fan based on the fact it is a center-rotating element with fins in an environment with fluid flow. According to Shaughnessy (2005), in Fan and Pump Engineering, power is function of the diameter of the rotating element, the volumetric flow rate, the angular velocity, the density of the fluid, and the viscosity of the fluid:

$$P = f\,(D, Q, \omega, \varrho, \mu)$$

However, the power function can be further reduced using dimensionless groups, known as the flow coefficient, and a form of Reynold's number (differing from the conventional Reynold's number by substituting V with ωD), as such:

$$\frac{P}{\varrho\omega^3 D^5} = g * \left(\frac{Q}{\omega D^3}, \frac{\varrho D^2 \omega}{\mu}\right)$$

Extensive research in pump and fan areas engineering has demonstrated that scaling geometrically similar systems is possible with the principle of similitude and that the performance of a fan and pump is independent of its Reynolds number, so this value will not be calculated. Therefore, if the flow coefficient between two scale models in comparison is the same, then the power coefficient will also be the same. The power coefficient can then be used to scale the power output of the scale models in the wind tunnel up to the full-scale in higher altitude wind speeds.

$$\frac{P_{Real}}{\varrho_{Real}\omega^3_{Real}D^5_{Real}} = \frac{P_{Model}}{\varrho_{Model}\omega^3_{Model}D^5_{Model}}$$

$$P_{Real} = P_{Model} * \frac{\varrho_{Real}\omega^3_{Real}D^5_{Real}}{\varrho_{Model}\omega^3_{Model}D^5_{Model}}$$

The above equation can be further simplified according to the conditions for the full-scale prototype and the scale model:

1. Density of air
    a. Within the wind tunnel, the air density will stay constant (air will not be traveling fast enough to be compressed and the density of air will be taken at sea level). This reduces ϱ_{Model} to 1.225 kg/m^3.
    b. According to tables in Shaughnessy, Katz, & Schaffer (2005), at 30 meters in altitude, the air density is 1.2215 kg/m^3 (ϱ_{Real}). From previous discussion, the wind speed at this height is assumed to be 4 m/s for coastal areas.
2. Diameter
    a. The diameter of the scale models is pre-determined and the tests will run on a model by model basis (10” diameter for the small model, 12.5” diameter for the medium model, and 15” diameter for the large model).
    b. The diameter of the full-size kite turbine is set to be 10 feet (120 inches).
3. Angular Velocity
    a. An important assumption in deducing and predicting the angular velocity of the full-scale model is the tip-speed ratio, which is the ratio of the speed of the tip of a blade of the turbine and the speed of the wind. For a Savonius turbine, this value is roughly unity (Zemamou et al., 2017). This simplification yields $\frac{V_{Wind}}{\omega_{Rotor}R_{Rotor}} = 1$, and in other words, $V_{wind} = \omega_{Rotor}R_{Rotor}$. With $R_{Rotor} \approx 1$ for the full-scale model, $\omega_{Model} = 10$ rad/s.
    b. Wind tunnel tests will confirm the accuracy of the tip-speed ratio for the models.

From these simplifications, an equation can be derived that is based on a constant and several factors that can be found during testing, such as a the power of the model, the angular velocity of the model, and the diameter of the model.

$$P_{Real} = P_{Model} \frac{\varrho_{Real}\omega^3_{Real}D^5_{Real}}{\varrho_{Model}\omega^3_{Model}D^5_{Model}}$$

$$= P_{Model} * \frac{(1.213\ kg/m^3)(10\ rad/s)^3(120\ inches)^5}{(1.225\ kg/m^3)\omega^3_{Model}D^5_{Model}}$$

$$= (2.46E13\ in^5/s^3) * \frac{P_{Model}}{\omega^3_{Model}D^5_{Model}}$$

In order to check similitude between the models, the flow constants needs to be the same in both environments. In each case, the volumetric flow rate (Q) experienced by the kite is equal to the velocity across its cross-section multiplied by its frontal area. The angular velocity of each kite is given by the tip-speed ratio, which means that this variable can be translated the velocity of the kite environment times the diameter of the kite.

$$\frac{Q_{Model}}{\omega_{Model}D^3_{Model}} = \frac{Q_{Real}}{\omega_{Real}D^3_{Real}}$$

$$\frac{V_{Model}A_{Model}R_{Model}}{V_{Model}D^3_{Model}} = \frac{V_{Real}A_{Real}R_{Real}}{V_{Real}D^3_{Real}}$$

$$\frac{A_{Model}R_{Model}}{D^3_{Model}} = \frac{A_{Real}R_{Real}}{D^3_{Real}}$$

$$\frac{A_{Model}D_{Model}}{2\ D^3_{Model}} = \frac{A_{Real}D_{Real}}{2\ D^3_{Real}}$$

$$\frac{A_{Model}}{D^2_{Model}} = \frac{A_{Real}}{D^2_{Real}}$$

$$\frac{D_{Model}H_{Model}}{D^2_{Model}} = \frac{D_{Real}H_{Real}}{D^2_{Real}}$$

$$\frac{H_{Model}}{D_{Model}} = \frac{H_{Real}}{D_{Real}}$$

This result means that the only constraint for testing the two kite sizes is dependent on having geometric similitude between the two models, or in other words, a scaled aspect ratio. The reason why the velocity terms are not important in this similitude analysis is because the power coefficient already accounts for differing angular velocities in models. Therefore, having scaled models proves vital for wind tunnel testing.

Testing Methods

The primary focus of testing was to find a way to measure the energy created from the prototype given variables such as wind speed. To offer a more controlled environment, the wind tunnel located in Hudson Hall was utilized by the team. In this way, proving the concept of energy generation was dependent on scaled models.

In order to compare the scale models to the full models, three variables will need to be found per trial:

1. Power: Calculated from voltage measured for a given resistance
2. Angular Velocity: Measured (in rpm) with a laser tachometer and reflective tape
3. Diameter: Based on the model being tested

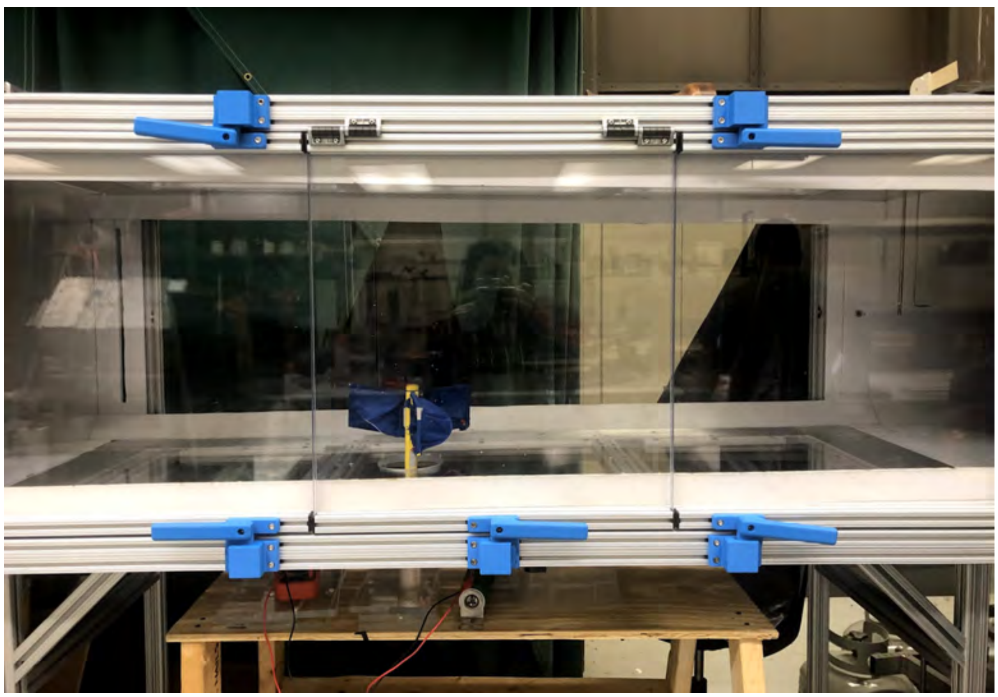

Figure 8. Duke University's wind tunnel with a small-scale AWES prototype inside.

The wind tunnel cross-sectional test area is 661.25 in^2 (23" X 28.75"). As aforementioned, in order to avoid edge effects, compressed air, and undesired turbulence, the models should typically be less that 15% of this area. The largest model features a frontal area of 67.5 in^2 (4.5" X 15").

The power measurements were made with the use of an AMETEK Pittman 1420S009, a 24 Volt brush commutated DC motor. Similar to how a when one plugs a motor into an outlet, a voltage is delivered across the motor's terminals, and the motor spins. Vice versa, if the motor remains unplugged, and is physically spun itself, a voltage is delivered across the terminals that may be measured using a multimeter. In this way, power can be calculated. The kite prototype was attached to the motor in the configuration seen below.

Figure 9. Kite structure model (sans fabric) attached to the motor via a 3D printed coupling.

As described previously, the voltage delivered when the motor is spun needs to be measured. To do so, the motor was connected in parallel to a 1 Ω resistor via alligator clips and voltage was measured across this resistor with a multimeter. To measure the voltage from the experimental setup, a multimeter was set to measure voltage on both 200 mV and 2 V scales (for comparison). Through Ohm's law and the power equation, power is calculated through $P = \frac{V^2}{R}$, in which P is power, V is voltage, and R is resistance. Since the resistor is only 1 Ω , the power can be calculated by simply squaring the voltage measured.

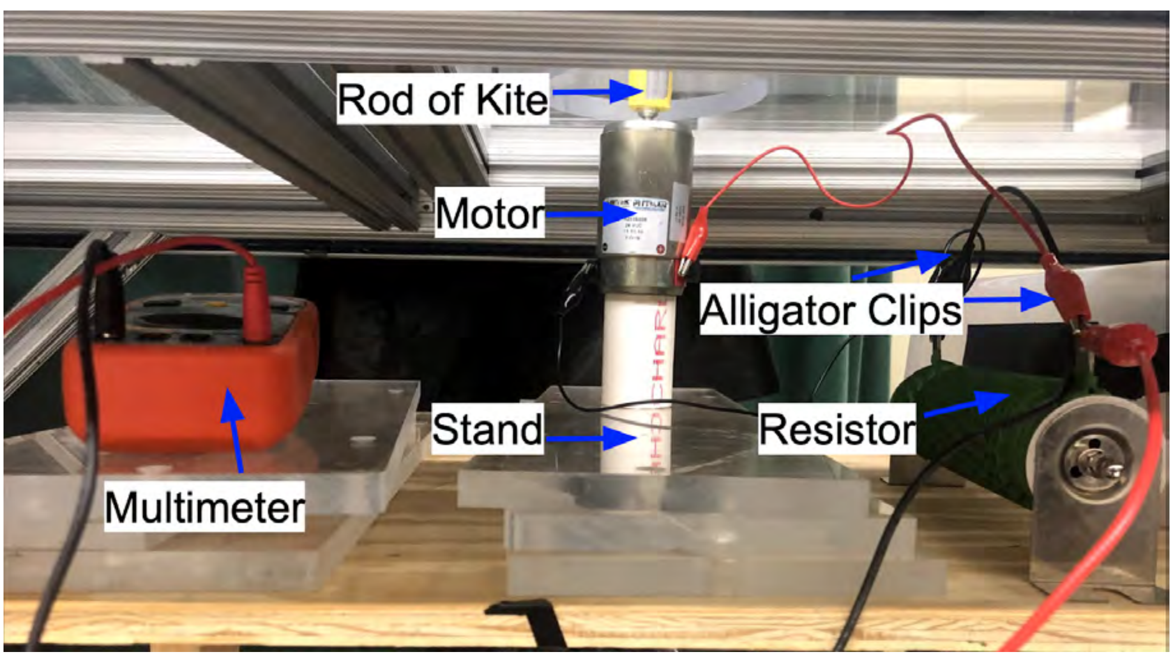

Figure 10. Experimental setup in wind tunnel (bottom half).

Additionally, to measure the angular velocity of the prototype, a laser tachometer was used. Reflective tape was attached to the inner rod of the kite structure as well as one of the tips. In the following figure, the gray reflective tape is shown to be attached to the entire side of the yellow cup. For clarity in the overall experimental setup, the next figure can be thought of as being a continuation from the top of the previous figure.

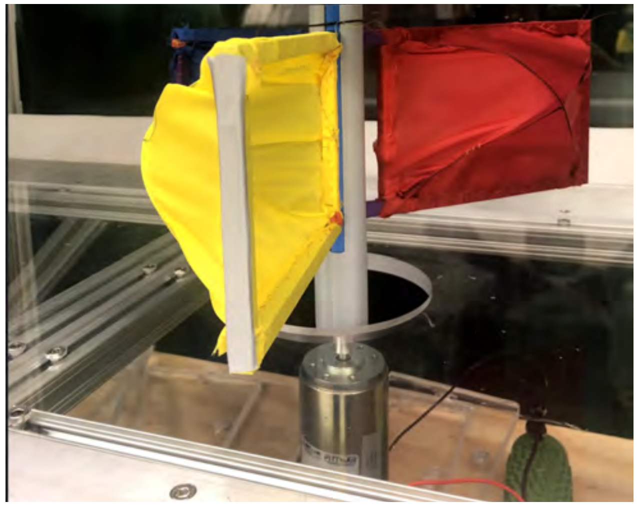

Figure 11. Experimental setup in wind tunnel (top half).

Given the low rpm and low torque nature of the test setup, desirable characteristics of motors for this test setup include those with high voltage, high synchronous speeds, low pole grab, and low starting torque. In order to attach the motor the the kite, an extension of the kite shaft was made to fit (without slip) on the motor shaft. Each coupling is scaled with respect to its given kite turbine model.

Testing Results

Utilizing the data collected and the methods described in the previous section, the following results were calculated.

Table 1. Data obtained from wind tunnel testing.

Model Scale	**Diameter (in)**	**Wind Speed (m/s)**	**Speed of Coupling (rpm)**	**Speed of Tip (rp)**	**Tip-Speed Ratio**	**Angular Velocity of Coupling (rad/s)**	**Model Voltage (V)**	**Resistance (Ω)**	**Power Generated by Model (W)**	**Scaled Power (W)**	**Theoretical Max Scaled Power (W)**	**Efficiency**
10.4	13.75	14.5	73	70	0.772	7.645	0.135	1	0.018	2041.901	3053.811	0.669
10.4	13.75	14.2	62	65	0.732	6.493	0.115	1	0.013	2418.557	2868.159	0.843
10.4	13.75	14.7	70	69	0.751	7.330	0.16	2	0.013	1626.491	3181.927	0.511
											Average	0.674

While there were three sizes of kite turbines tested in the wind tunnel, two sets of data were found to be inconclusive. During testing, the smallest kite and the largest kite would stall during testing regardless of wind speed. For this reason, reliable data was not able to be collected. This is not commonly seen in regular steel wind turbines. Given the nature of the kite material, the fabric pocket is actually being pushed in by the wind. This counteracts the positive effects of making the pockets lightweight and from tent materials.

A three-vane kite structure was decided upon in order to prevent stalling, as there would be a side that captured more wind speed than the other. However, upon testing, it would seem that a more functional design would be a two-vane system because the pockets would collapse inwards and capture wind on both sides. Furthermore, having a stronger and more defined wire frame or pocket shape could prevent stalling and pockets from collapsing. The figure below depicts a two vane steel savonius wind turbine and how the flow of air can be influenced to prevent stalling and counteract some of the losses that the back-facing vane contributes. This could also be used as inspiration for future designs of kite turbines.

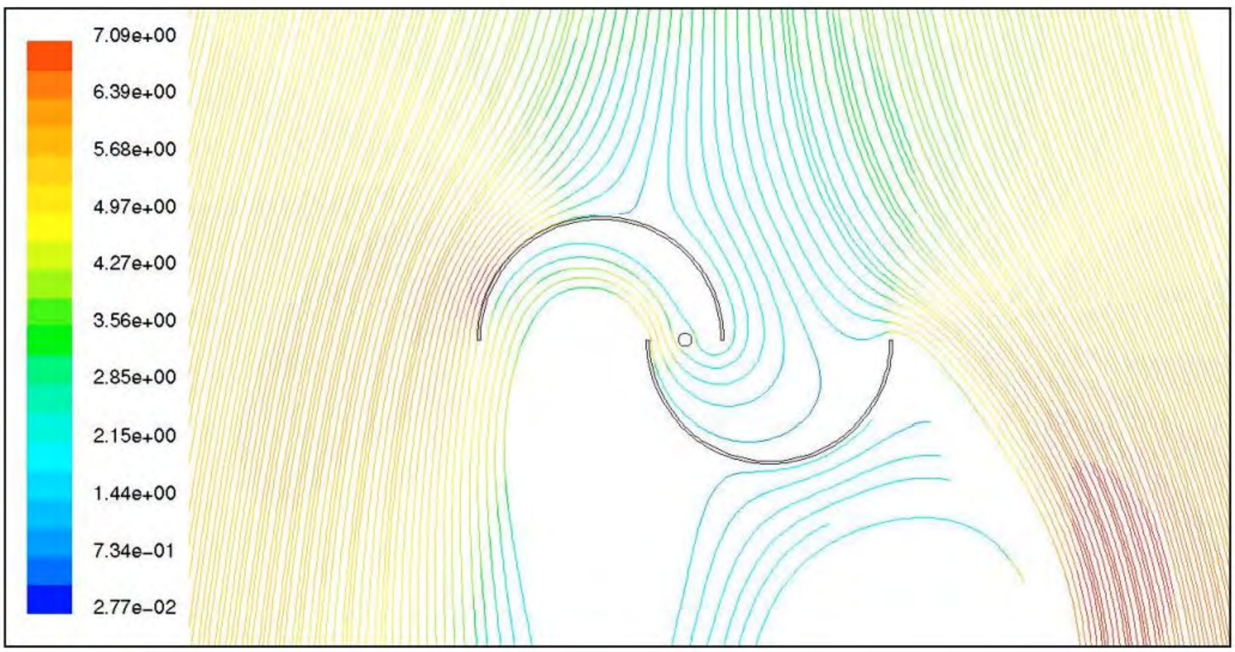

Figure 12. Aerodynamics of a steel Savonius wind turbine (Menet & Bourabaa, 2004).

The tip-speed ratio for the kite system was also calculated for each successful trial, demonstrating a strong correlation between both, as seen in Table 1. However, this discrepancy appeared to affect the assumption made earlier as the ratio is not substantially close to unity, as it consistently falls between 0.7-0.8. While this does affect the theoretical calculations for the wind turbine, Zemamou et al. (2017) and Menet and Bourabaa (2004) both stated that this is the optimum tip-speed ratio for power output on a Savonius wind turbine, so it can be concluded that the optimum design for the kite structure has not yet been reached.

There were also several other factors that made testing difficult. The tether would tangle and stop the kite turbine. As the tethers slacked, the power output would drop. Therefore, a sturdier base plan for the kite tethers (including the rings to keep the tethers from tangling) is recommended for small-scale testing.

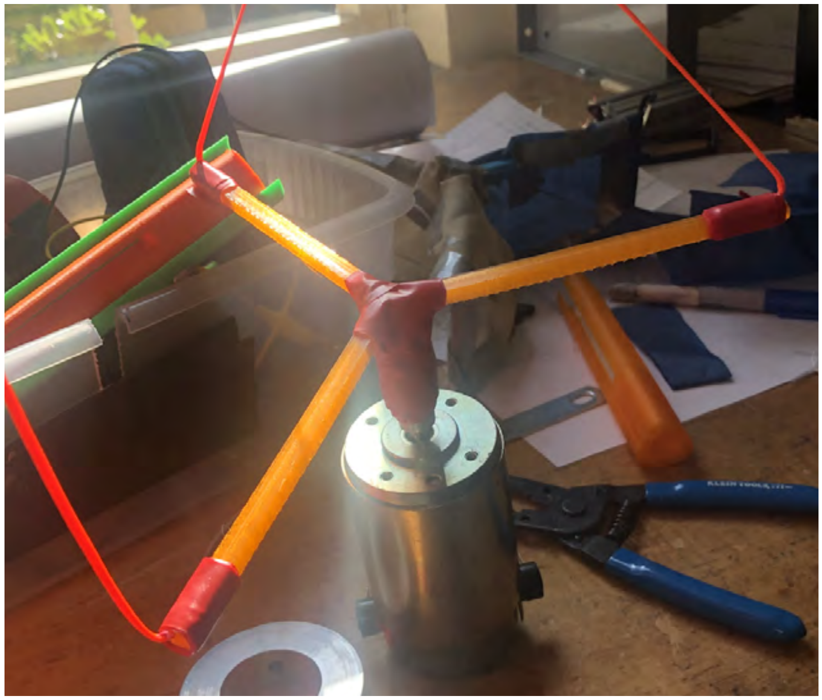

Figure 13. Current base design of small-scale prototype.

Furthermore, the voltage values would vary as the kite turbine saw bursts of wind harvesting potential. These voltage values can be approximated as 1 volt +/- .03 volts. A more accurate method of measuring voltage would be to use a DAQ system and average the voltage values during every run. However, since each kite would have periods of stalling and full speeds, these voltages would also not be entirely consistent. During consistent trial periods for the kite turbine, the common values that the kite turbine displayed were averaged into one number. Future considerations include using a speed regular for the kite turbine to allow consistent voltage values for battery charging.

Environmental Benefit Analysis

The environmental benefit of the AWES can be measured by its carbon offset in relation to energy generation from fossil fuels. The model has the potential to replace diesel and gasoline generators as tools for powering electronics temporarily in the event of a power outage. The carbon offset of replacing generators with a full-scale model of the AWES is calculated with the equation:

$$Carbon\ Offset\ =\ AWES\ Power\ *\ Rate\ of\ Carbon\ Emission\ of\ Other\ Technology$$

The power generated by the AWES is approximated with the previously calculated full-scale average power, 586 W. The rates of carbon emission of other technologies, specifically of diesel and gasoline, are below in Table 2. Table 2 shows the carbon offset per hour to provide a simple comparison between fuels. It also shows the carbon offset per week, which is most relevant to the model replacing generators. In certain areas in the United States, especially rural areas or those ravaged by widespread storms, power outages can last several days, or even over a week. Using a week as an approximation for the length of time over which the model could be used for power in a power outage, it is shown that over two kg of CO_2 could be saved from emission in such an event by replacing generators that use diesel or gasoline.

Table 2. Calculated carbon offset in replacing generators, assuming AWES power is 586 W, using carbon emission rates from U.S. Energy Information Administration (2018).

Fuel	**Rate of Carbon Emission (g CO_2/Wh)**	**Carbon Offset (g CO_2/hr)**	**Carbon Offset (g CO_2/week)**
Diesel	0.2496	146	24,600
Gasoline	0.2433	143	23,000

The AWES also has the potential to serve as a permanent source of clean energy for households. It could be used to power certain appliances or replace a fraction of a household's energy use with cheap, emissionless energy regardless of a storm event. In the case of the model replacing traditional sources of electricity in a home, it is relevant to analyze the long-term carbon offset of the model when it replaces to the two most prevalent utility-scale fuels that emit CO_2: coal and natural gas (U.S. Energy Information Administration, 2019). The carbon offset is calculated using the same equation as before above. The rates of carbon emission of these fuels are shown in the table below, along with the corresponding carbon offsets per hour and per year. The model could save 930 to 1,710 kg CO_2 from emission, depending on the fuel. These calculations show that, if used over a long span of time, the AWES can prevent sizable amounts of CO_2 emissions.

Table 3. Calculated carbon offset in replacing utility-scale electricity generation fuel, assuming AWES power is 586 W, using carbon emission rates from U.S. Energy Information Administration (2018).

Fuel	**Rate of Carbon Emission (g CO_2/Wh)**	**Carbon Offset (g CO_2/hr)**	**Carbon Offset (g CO_2/year)**
Coal (lignite)	0.3334	195	1,710,000
Natural gas	0.1811	106	930,000

Another major benefit of the AWES is it provides clean energy that takes a relatively small amount of ground space. The area the model requires to safely operate is a circle, with its radius equal to the radius of the base (the length of an arm attached to the generator) plus the height of the model in the air, to account for the structure falling to the ground. Using multiple airborne turbines within an area does not increase this operational radius, since turbines can easily be lowered to incremental levels, so no two turbines are operating at the same height and taking wind from each other. The full-scale base radius is 1.52 m. So, to fly the model at 100 ft, or 30.48 m, the ground radius needed to safely operate the model is 32 m. The circular area of operation of the model is therefore 3,217 m^2.

In comparison, the GE 1.5 MW wind turbine, a traditional industrial wind turbine, requires at least 38 acres, or 153,781 m^2, per tower, and implementing multiple can require more area depending on their formation (AWEO). Flying at ~30 m, the AWES requires 97% less operational ground area than a traditional wind turbine. With its relatively miniscule area, the model could provide clean wind energy in places in which harnessing wind energy was previously implausible. The model could thus make wind energy more accessible to densely populated areas without the space for larger wind turbines. If widely implemented, the comprehensive utility of many small wind turbines could significantly decrease the use of fossil fuels to generate electricity in particular communities.

Social Benefit Analysis

Coastal communities, especially in rural areas, are in a unique position compared to their inland counterparts - leading lives inextricable from the effects of nature's constant cycles. In Carteret County alone, the tides dictate fishing times, king moons can shut down schools and fish migrations determine livelihoods (Carteret County News-Times, 2015). Ask anyone in the area what season looms largest, however, and the answer will resoundingly be hurricane season. Especially in the prolonged aftermath of Hurricane Florence, which has left stores still shuttered and some residents still without houses, preparing for the next severe storm is paramount (Payne and Boyd, 2019). It's even shown that the effects of prolonged power outages, including lack of information and slow emergency response, can lead to public discontent and crime (Moreno, 2019). While AWES by no means could have stopped the destruction caused by Hurricane Florence, or Hurricane Matthew before that, it has the potential to ameliorate some of the severe impacts from the long-lasting power outages associated with storms like these, providing a number of valuable social benefits to these communities.

Human health and safety are the primary concerns during any natural disaster, especially during power outages which can cut off communication and essential home services. At the less severe end of the spectrum is the threat of consuming unsafe food when refrigeration units go dark or leaving food to rot - a dangerous situation when access to other food may be difficult (FDA, 2019). An even more serious concern in this realm are medications, like some forms of insulin, that need refrigeration to stay functional (Coleiro, 2012). Refrigerators and freezers dying is an issue that the implementation of the AWES could potentially solve - just one kW is enough to power a mini-fridge or even an energy-efficient full-size model (Silicon Valley Power, 2019). Alternatively, if the electricity is needed elsewhere as well, an ice maker can be powered on just 600 W (DOE, 2019).

Table 4. Common emergency appliances and their energy usage (Silicon Valley Power, DOE, 2019).

Appliance	Power Needed for 1 hour (Wh)
Mini-fridge	1,000
Ice maker	600
Phone charger	6
Laptop charger	60
Small room heater	1,000

More serious human health concerns in the aftermath of a storm revolve around home-care systems for elderly or sick individuals - already groups that will be disproportionately impacted by the effects of severe storms. While the AWES could not power all the various medical devices commonly used in homes - monitors, respiratory equipment, feeding machines, assistive technology, and medication administration equipment for example - it could be used in conjunction with traditional diesel generators to keep essential technology functioning (Story, 2010). By lowering the amount of diesel necessary for each Wh of energy consumed, the AWES could prolong the time before the generator runs dry, potentially allowing enough time for help to arrive.

In conjunction with health, human safety is a primary social concern during power outages following hurricanes. While public safety institutions like the police and fire departments are usually functional after hurricanes - essential personnel are often either exempt from mandatory evacuation orders or choose not to leave - contacting these groups can be impossible (Starkey, 2018). Without electricity for charging, cell phones often die in less than a day. By the time a storm passes and the aftermath begins to be evaluated, many people will have lost their only mode of communication. Charging a typical cell phone requires less than a dozen Wh, meaning the AWES can easily charge a cell phone while also providing power elsewhere (Helman, 2013). Depending on the state of the phone grid, these devices can then be used to call for help, report emergencies elsewhere in the vicinity, or contact loved ones.

These vital health and safety benefits, of course, are only valuable if the AWES is operating. With this fact in mind, the AWES has been designed to be portable, easy to use, and quick to set up. By building the frame out of collapsable tent poles, the AWES can be deconstructed, packed away, and stored until a power outage. The setup process should be no more difficult than constructing the average tent and then letting the wind take over from there. Beyond ensuring that health and safety benefits are provided, this ease of use also opens the door for the AWES to be used for educational activities by schools or even individual parents to teach about renewable energy, the basics of power generation, and safe hurricane practices.

Additionally, the AWES has been designed to not only provide power, but also to be aesthetically pleasing. By mimicking pinwheels and traditional kite designs, the AWES should not be an eyesore in any community and should have minimal to no noise pollution associated with it. This design could potentially allow for the AWES to operate continuously, not just during severe weather events, depending on the needs and desires of the individual.

Finally, it is important to note that while the AWES can, and should, be used by anyone impacted by long-lasting power outages, the design will have the greatest impact in traditionally marginalized communities. Aid and recovery after severe storms is always impacted by the power dynamics of the communities impacted. This played out on the large scale in the aid disparities between Hurricane Maria, which impacted primarily poor and Latinx communities, and other hurricanes in the same season which impacted whiter, wealthier areas (Einbinder, 2019). Even within the same storm, however, there are dramatic differences in the pace at which communities receive help and can recover.

After Hurricane Harvey hit southeast Texas, white and higher-income communities received tens of thousands of additional dollars in aid over black and low-income communities just miles away (Capps, 2018). In Carteret County after Hurricane Florence communities “Down East,” a term referencing the poorer, more rural, communities further east than Beaufort, were without power for days, even weeks longer than in Beaufort and Morehead City and have had an even slower recovery time then the rest of the county (Smith, 2018). Looking beyond race and class, other marginalized groups like the elderly and those with physical and mental disabilities are also in a more severe position after hurricanes, often unable to support themselves alone or advocated for themselves (Szabo, 2018).

While the AWES cannot solve these disparities in storm impacts, it would provide a way for marginalized communities who experience longer power outages than other groups to continue to power essential technologies, potentially helping to lower the recovery time gap between privileged and underprivileged areas.

Target Market Analysis

The AWES has the potential to be most impactful in coastal communities that experience power outages following hurricanes. More specifically, the scope of a target market for AWES will cover the North Carolinian coast due to proximity, apparent demand, and higher potential for influence over hurricane plan and risk mitigation. Other locations were considered in deliberations; with a decision matrix assessment, disaster-affected areas were evaluated highest, and coastal areas were ranked second. Therefore, a combination of the two was decided upon with the target demographic being hurricane-relief in coastal areas. The other potential locations seen below in Table 5 are still possibilities for further expansion following the pilot of the prototype.

Table 5. Decision matrix evaluation for location of prototype launch.

	Wind	**Demand**	**Social Impact**	**Environmental Impact**	**Regulations /Feasibility**	**Total**
Weight (%)	35	25	15	15	10	100
Offshore Wind Farm	10	5	5	2	3	2.95
Offshore Individual Buoys	10	6	5	3	5	2.9
Disaster-Affected Areas	5	10	10	7	7	**7.5**
Residential	2	2	7	8	4	3.9
Coastal	8	7	8	5	6	**7.1**
Farm (Midwest)	6	4	4	4	4	4.7

Wind

The abundance of wind on North Carolina's coast is ideal for the launch of this prototype, as the success of this mechanism is dependent on consistent wind. Consequently, wind was weighed highest in the decision matrix in Table 5. According to Windfinder at any given time, the typical wind-speed along the North Carolinian coast is about 4.5 m/s in the morning. More specifically, the Wilmington area has a yearly average wind speed of 4.16 m/s (Southeast Regional Climate Condition, 2015). Even without a tropical storm, the coastal area has winds speeds high enough to power the AWES. Additionally, constant coastal winds make North Carolina's coast a reliable area for the AWES to generate power.

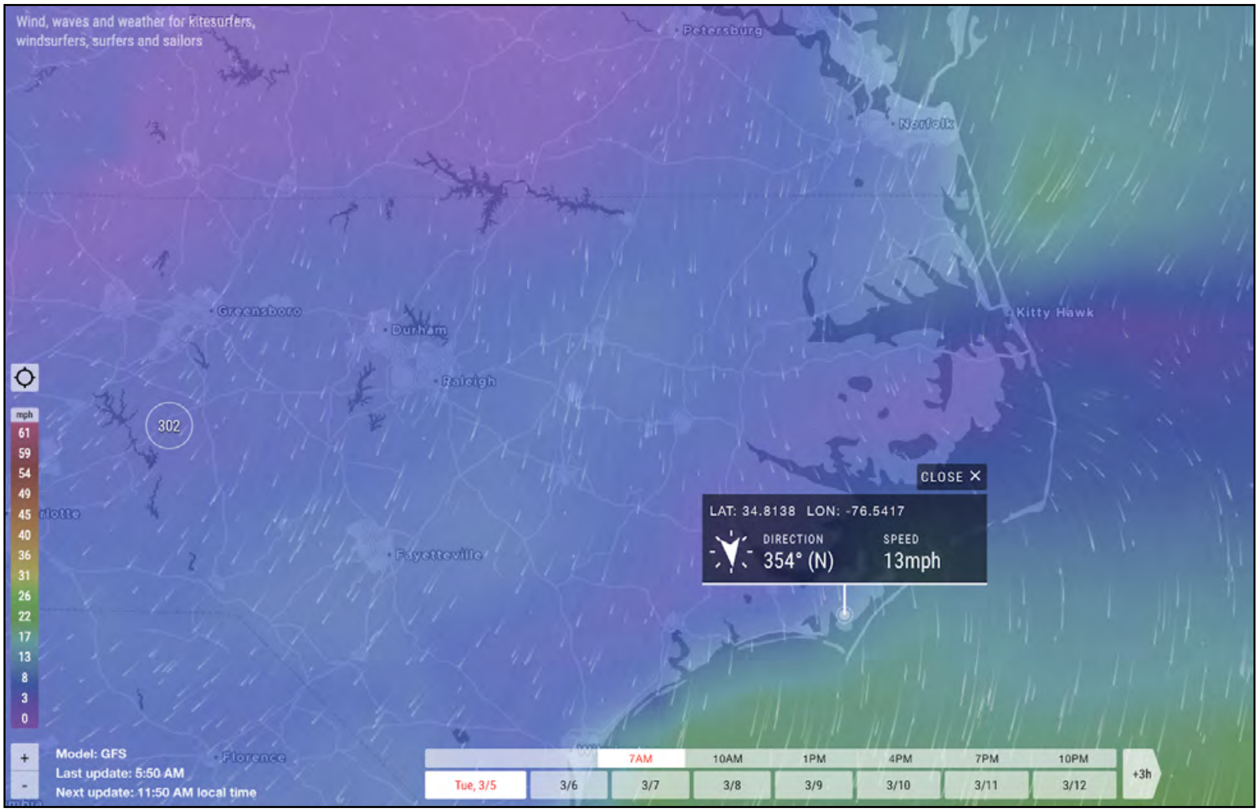

Figure 14. Early morning March wind speeds show promising conditions (Windfinder, 2019).

Moreover, hurricane conditions are marked by powerful winds. With 413 known tropical cyclones recorded, the state of North Carolina is ranked fourth in the number of cyclones that produce hurricane winds (Hurricane Research Division, 2008). During Hurricane Florence, Wrightsville Beach had estimated maximum winds of 40 m/s (Stanglin, Gross, & Mayo, 2018).

Demand

Torrential rains, storm surges, and powerful winds inevitably cause damage to important infrastructure that people rely on for their energy needs. Wilmington is a hurricane hotspot. Hurricane Florence brought 25 inches of rain in flash flooded areas and 10 inches of rain across North Carolina; in response to this, about 10 thousand National Guard troops and civilians were sent out via boats, helicopters, and high-water vehicles (Stanglin, Gross, & Mayo, 2018). With all of this rain, massive flooding and shore encroaching were seen throughout the coast. Many of the places that were hit by Hurricane Michael were then damaged again only a year later by Hurricane Florence, only this time, the span of the storm was much greater (Krupa, 2018). With more research connecting massive storms with global warming, it is unlikely that hurricane events such as these are going to get any better. With every degree Celsius rise in temperature, the air can contain 7% more water; this amplifies extreme rainfall. Along with this, rising sea levels due to melting land ice allow for dangerous storm surges to move further inland (Irfan, 2018). In the wake of such powerful tropical depressions, strategies to protect and save lives must be developed and implemented.

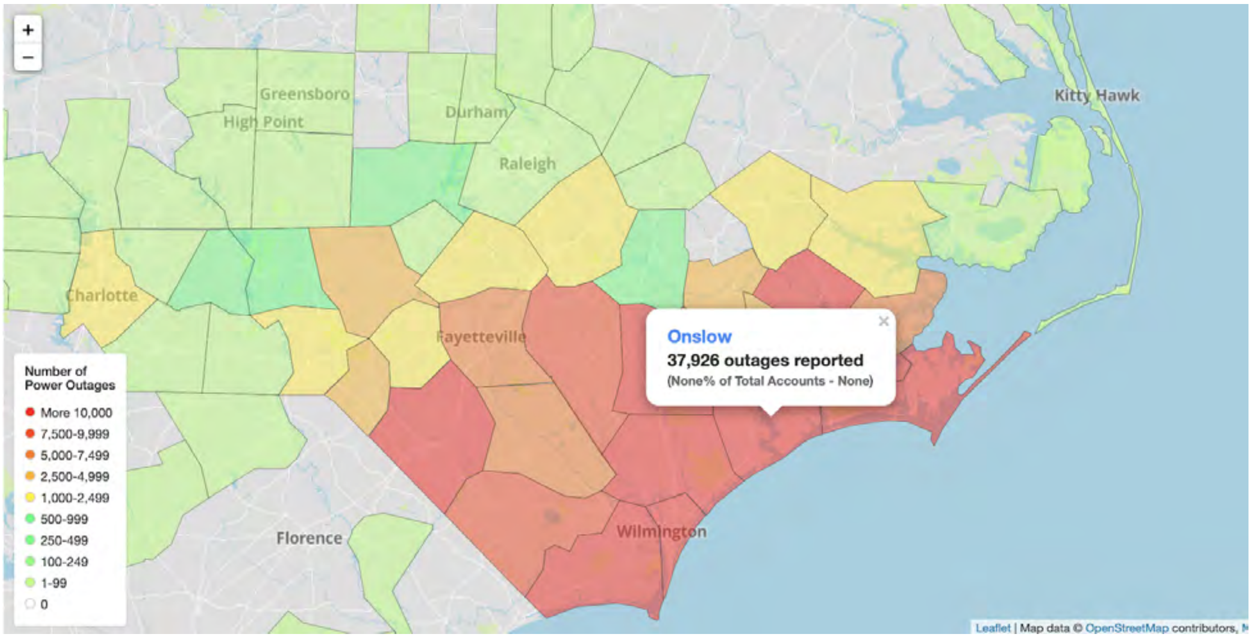

Figure 15. Four days after initial hit, power outages were widespread across NC (Electric Cooperatives of South Carolina, Inc, Duke Energy, North Carolina Electric Cooperatives, Dominion Energy, 2018).

One way this project can contribute to community resilience is by providing temporary energy relief for people during the blackouts and brownouts following a hurricane. A relatively small, low-cost wind system such as this can be best used as a short-term electricity source. The need for such a system is great. Serving 4 million people, Duke Energy supplies most of the Carolinas' electricity. The storm hit North Carolina on a Thursday, and by Saturday, Duke Energy was able to return electricity to 637,000 customers. Still, more than 670,000 still remained without electricity as of Sunday (Williams, 2018).

Even with 20,000 employees dispersed, Duke Energy could not keep up with the demand (Williams, 2018). Additionally,the Army Corps of Engineers started to restore power even when the storm was still happening (Stanglin, Gross, & Mayo, 2018). As of September 18th 2019, there were still hundreds of thousands reported incidents of power outages (Citizen-Times, n.d.). Representatives of Duke Energy have stated that the most hard-hit, coastal areas were unable to be repaired due to high winds and major flooding. More specifically, power restoration was estimated to take weeks due to significant damage to power lines, utility poles, and other essentials to the electric grid (Williams, 2018).

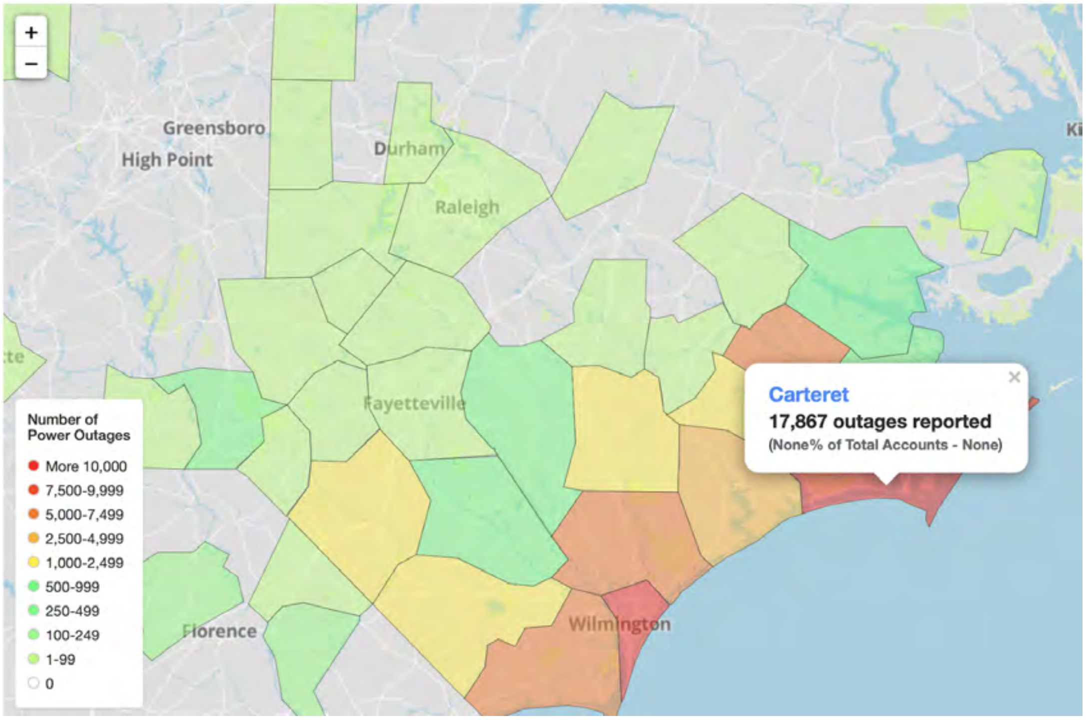

Figure 16. One week following the storms initial hit, tens of thousands were still without power (Electric Cooperatives of South Carolina, Inc, Duke Energy, North Carolina Electric Cooperatives, Dominion Energy, 2018).

Duke Energy's power restoration process prioritizes public safety and maximizing the number of customers with regained power. For example, the first strategy is to locate downed power lines and to fix them (Duke Energy Corporation, 2019). Next, the primary lines (transmission and main distribution) are restored so that electricity from power plants can flow to large geographic areas, subdivisions, and commercial areas (Duke Energy Corporation, 2019). Then, essential services such as hospitals, water treatment facilities, law enforcement, and fire departments are worked on. Finally, the secondary lines (local distribution) for smaller neighborhoods and less-central areas are targeted (Duke Energy Corporation, 2019). In this way, more outages are taken care of in the least amount of time. However, an obvious consequence of this strategy would be that more rural and off-the-grid areas will be without power the longest. The AWES would be capable of alleviating the storm aftermath for these less-central communities.

The target market for the team's AWES is people that are in hard-to-reach places that still need access to electricity. A collaboration with Duke Energy would be possible in dispersing these units prior to hurricane hits, as a strategy in mitigating storm aftermath. In this way, people will have, at minimum, temporary access to electricity before the electric grid in their area is completely restored by maintenance.

Basic Business Plan

To make this product successful, a successful business plan needs to be developed. The product needs to be cheap enough in order to be purchased by those in more impoverished areas. This means the materials used to create the AWES will need to be inexpensive and used sparingly. Currently, the estimated cost of the AWES is around $700 to prototype a full-scale model, as shown in Table 6. However, the team hopes to drive the production cost down with further design refinements. For example, the most expensive component of the design is the surf kite that keeps the entire system airborne and stable as shown before in Figure 5 on page 6. The surf kite's manufacturer could create a surf kite made of less expensive materials tailored specifically to the needs of the AWES. An additional way to offset costs would be to have space for advertisements on the surf kite. Various companies could display their logos in the air while the kite was flying. The companies would be associated with providing natural disaster relief to otherwise marginalized communities, thereby creating a good reputation.

Table 6. Detailed cost breakdown of the full-scale AWES components.

Item	**Description**	**Amount**	**Cost (USD)**
Surf Kite	Aerial anchoring point to hold up kite	1x	200
Tent Poles	Basis for kite structure (11'3" at $20, 16'3" at $33)	2x	53
3D Printed Elbows	Holds tent poles together	6x	0
Polyester Fabric	Waterproof kite material (60" width, $3.95 per yard length, need 4 yards of each color)	3x	16
Nylon Tether	Kite line to hold it all together. Braided nylon (1500 ft).	1x	100
Rotor Swivel	Allows for easy attachment of tethers in various places; separates rotation	1x	30
Alignment Hoops	Allows torque transmission along tether of kite	3x	30
Generator	On ground torque transmission; designed to swivel and reel	1x	100
Fishing Reel	Reels kite in and out to improve efficiency	1x	20
Cylindrical Shipping Container	Doubles as the shipping container for each AWES and the center rod for the apparatus	1x	0
Total			**694**

In addition, the financial incentives offered by governments around the world will hopefully speed up the kite's implementation and create a more accepting market for it. For example, there's a nonprofit company called NC GreenPower Production that will pay owners of small wind-energy systems $0.09/kWh (DSIRE, 2018). With incentives like these, the AWES becomes a much more appealing purchase. The current price of a single AWES is similar to that of other renewable resources in the sense that it is a large upfront cost, but fuel is free. So, after a period of time, the AWES will pay for itself. This concept must be advertised heavily because $700 is not a small amount to pay, especially for a household that cannot afford a portable gasoline or diesel generator. In most places around the world, including the United States, there are many incentives offered toward applying renewable energy solutions. In September 2018, North Carolina was flooded by Hurricane Florence, leaving a significant amount of households without power. In the state of North Carolina alone, there are over 30 policies and incentives surrounding wind energy technologies. Approximately half of these are regulations and the other half are financial incentives (WINDExchange, n.d.). For example, the Recovery Act allows for wind energy projects to receive a 30% cash grant in order to receive more tax equity (WINDExchange, n.d.). This trend spans the United States with every state offering different incentives for the development of these technologies. Because this product would be emerging as a smaller scale business model related to wind technology, there would be many different partnerships and incentives to help the final product be successful.

Conclusion

The team's proposed AWES solution will allow for those people to sustain their lifestyles temporarily and survive until they get their power back after a severe storm event, such as a hurricane. There have been other solutions created to try to combat this issue, however the one described in this report provides an affordable option with multiple benefits and a considerable amount of energy. The simple setup of the base system connected to the retractable Savonius-style kite can be assembled by most and can be deployed in a backyard or on top of a roof.

The data acquired from testing small-scale models of the AWES shows that the prototype can generate energy in both typical and heightened coastal wind speeds, and could thus be a reliable source of electricity as a full-scale model. The principal findings demonstrate the usefulness of a kite turbine as a proof-of-concept. However, while an idea worth exploring, it is still very much underdeveloped in its current design. The focus of the design places emphasis on the aerodynamics of the kite turbine, its manufacturing plan, and how well it works to harvest energy. But, this design needs a thorough reiteration phase and power generation plan to be implemented at a larger scale.

During testing, the fabric pockets had a tendency collapse and cause the kite to stall. An alternative solution to the cross geometry for the frame would be to make a grid. For example, there could be a number of steel cables running left to right and up and down to form a grid that would prevent the back-facing vane from collapsing completely in heavy winds and stalling the kite. Mass manufactured solutions to this include using chicken wire or wire mesh. Another reason for kite stall was due to the torque placed on the rotor from each vane as the kite rotated and faced the wind. A solution to this would be to not have rotational symmetry between the kite vanes, causing a torque imbalance on the rotor and encouraging the rotor to spin in one direction versus another. For two of the three small-scale models, the three-vaned design often stalled in the wind, due to the torque from wind on both sides of the turbine. Decreasing the drag of the back-side of the vanes could increase the effectiveness of the model. A two-vane design may prove to more effectively eliminate such stalling, contrary to initial design ideas.

Future considerations involve the creation of a full-scale prototype. Ideally, this model would be tested with a surf kite, tethers with carabiners and tether rings, and a power generation system (base, battery, regulators, waterproofing, etc.). Given the size of the tethers and the nature of the surf kite, ideal locations include the coastline or an open field on a windy day. The current design for the kite turbine involves tent poles, polyester fabric with steel wire to form the pocket shape, 3D printed corners, and a waterproof shipping tube with a 4 inch-diameter. The shipping tube will be used to ship the materials to their destination and then will become the center of the turbine, thus making the full-scale system as portable as possible. The elastic cord that comes with the tent poles will be used to keep the vanes in compression and keep the kite vanes rigid. An alternative option to replace 3D printed elbows would be mass manufactured elbows. Although there is merit in testing small-scale prototypes, testing a full-scale design is the only method to ensure feasibility and workability.

Outside of emergency generation, the surf kite can be used for recreation and the kite turbine can be stored or placed on top of a house (to help offset energy costs throughout the year). Given the materials used to make the kite turbine, it should be able to withstand the elements and still provide generation (aside from being left out in larger storms).

In terms of electrical design, the power generation should have a compatible charging/battery system or another method of transferring electricity. These electronic components should be waterproofed to extended the life of the kite turbine and to prevent any possible electric shock. Given the rotational speed of the scale models, it would also be advisable to have a gear train of sorts to maximize the rotational speed or torque on the generator shaft. The kite should have several evenly spaced rings (or another method) of preventing the kite lines and tethers from becoming tangled. These rings can also provide consistent tension in the kite line, limiting losses due to slacked lines.

Individually deployed AWES apparatuses have the potential to add a renewable energy resource to the grid, especially around severe storm events. Each apparatus holds the power to improve reliability while decreasing a homeowner's overall cost for electricity and carbon footprint. If a full-scale prototype were to be produced after finding an optimal design and wind conditions using smaller scale modelling similar to those explained in this report, coastal communities could be given temporary relief from natural disasters. Even more so, this concept has the potential to be implemented in other hard-to-reach areas and provide energy access to current energy-deprived communities. Energy access is a very important topic that impacts over one billion people (Rocky Mountain Institute, 2019). Increasing and improving worldwide energy access requires immediate and significant attention from various disciplines.

Overall, this project tested the feasibility of an idea and identified areas of improvement. The team laid the foundation for future energy enthusiasts to continue to advance the design of the AWES to ultimately provide temporary relief to coastal communities affected by power outages caused by natural disasters using a renewable energy resource.

References

Allied Electronics and Automation (n.d.). AMETEK Pittman 14203S009 (Fan, Motors, and Thermal Management). Retrieved from https://www.alliedelec.com/product/ametek-pittman/14203s009/70050468/

AWEO. (n.d.). Retrieved from http://www.aweo.org/windarea.html

Campbell, Richard J. (2012, August). Weather-Related Power Outages and Electric System Reliability. Congressional Research Services. Retrieved from https://fas.org/sgp/crs/misc/R42696.pdf

Capps, Kristen. (2018, October 3). Why Are These Tiny Towns Getting So Much Hurricane Harvey Aid? Retrieved from https://www.citylab.com/equity/2018/10/whos-losing-out-on-hurricane-harvey-aid-in-texas/571327/

Carteret County News-Times. (2015, October 4). School canceled for Monday in Carteret County. Retrieved from http://www.carolinacoastonline.com/

Citizen-Times. (n.d.). Map: Hurricane Florence Power Outages. Retrieved from https://data.citizen-times.com/florence-power-outages/?tf=2018-09-18-18

Coleiro, Daphne. (2012). Storage of Medicines and Medical Devices. Retrieved from https://www.um.edu.mt/__data/assets/pdf_file/0016/153160/Storage_of_Medicines_and_Medical_devices.pdf

Department of Energy. (2019). Energy Cost Calculator for Commercial Ice Machines. Retrieved from https://www.energy.gov/eere/femp/energy-cost-calculator-commercial-ice-machines-0

DSIRE (2018, May 22). NC Clean Energy Technology Center. Retrieved from http://programs.dsireusa.org/system/program/detail/352

Duke Energy Corporation. (2019). How Duke Energy Restores Power. Retrieved April 28, 2019, from https://www.duke-energy.com/outages/restoring-your-power

Einbinder, Nicole. (2018, May). How the response to hurricane maria compared to harvey and irma. Frontline. Columbia Journalism School Fellowships. Retrieved from https://www.pbs.org/wgbh/frontline/article/how-the-response-to-hurricane-maria-compared-to-harvey-and-irma/

Faulhaber (n.d.). Using Wind Energy Efficiently. Retrieved from https://www.faulhaber.com/it/markets/environmental-safety/energy-kites/

FDA. (2019). Buy, Store & Serve Safe Food. Retrieved from https://www.fda.gov/food/resourcesforyou/consumers/ucm076881.htm

Glenn Research Center, NASA. (2015, May). Kite Drag Equations. Retrieved from https://www.grc.nasa.gov/www/k-12/airplane/kitedrag.html

Hurricane Research Division (2008, September 21). "Chronological List of All Hurricanes which Affected the Continental United States: 1851-2995". National Oceanic and Atmospheric Administration. Retrieved from https://web.archive.org/web/20080921102626/http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist18512007.txt

Helman, C. (2013, September 13). How Much Electricity Do Your Gadgets Really Use? Retrieved from https://www.forbes.com/

Irfan, U. (2018, October 03). Hurricane Florence caused up to $22 billion in damages. Climate change made the storm worse. Retrieved from https://www.vox.com/energy-and-environment/2018/10/3/17925470/hurricane-florence-2018-devastation-climate-change-flood-sea-level-rise

Krupa, M. (2018, October 07). Hurricane Florence's toll on US homes and businesses has now hit 11 figures. Retrieved from https://www.cnn.com/

McNiven, N. (2017). Savonius Wind Turbines. Retrieved from http://www.reuk.co.uk/wordpress/wind/savonius-wind-turbines/

Menet, Jean-Luc & Bourabaa, Nachida. (2004). Increase in the Savonius rotors efficiency via a parametric investigation. Retrieved from https://www.researchgate.net/publication/228957621

Moreno, Jenny & Shaw, Duncan (2019, March). Community resilience to power outages after disaster: A case study of the 2010 Chile earthquake and tsunami. Retrieved from https://www.sciencedirect.com/science/article/pii/S2212420918309282

Murawski, John & Stradling, Richard. (2018, September). NC power outages: 900,000 lose power from Hurricane Florence. Raleigh News & Observer. Retrieved from https://www.newsobserver.com/

NC Climate Office (n.d.). Hurricane: Statistics. North Carolina Tropical Cyclone Statistics (1851-2018). Retrived from https://climate.ncsu.edu/climate/hurricanes/statistics

Payne, G., Boyd, J. (2019, February 20). Carteret Long Term Recovery team providing assistance for hurricane victims. Retrieved from https://wcti12.com/news/local/carteret-long-term-recovery-team-providing-assistance-for-hurricane-victims

Read, R. (n.d.). Windswept and Interesting. Retrieved from https://windswept-and-interesting.co.uk

Rocky Mountain Institute (2019, April 28). Energy Access. Retrieved from https://rmi.org/impact/energy-access/

Shaughnessy, E. J., Jr., Katz, I. M., & Schaffer, J. P. (2005). Chapter Three: Case Studies in Fluid Mechanics: Pump and Fan Laws (pp. 124-127). *Introduction to Fluid Mechanics*. New York, NY: Oxford University Press.

Silicon Valley Power. (2019). Appliance Energy Use Chart. Retrieved from http://www.siliconvalleypower.com/for-residents/save-energy/appliance-energy-use-chart

Smith, J.J. (2018, September 15). Down East takes another big hit: Florence joins Isabel, Irene as major weather events for area. Retreived from http://www.carolinacoastonline.com/news_times/article_4d96071c-b8f6-11e8-b185-0bef8859618b.html

Southeast Regional Climate Center. (2015) University of North Carolina, Chapel Hill. Retrieved from http://www.sercc.com/climateinfo/historical/avgwind.html

Stanglin, D., Gross, D. J., & Mayo, N. (2018, September 15). Florence marches into South Carolina, having killed at least 5 people despite dramatic rescues. Retrieved from https://www.usatoday.com/

Starkey, J. (2018, September 15). Beaufort begins recovery. Retrieved from http://www.carolinacoastonline.com/

Story, Molly Follette. (2010). Medical Devices in Home Health Care. Retrieved from https://www.nap.edu/read/12927/chapter/11

Szabo, L, Aleccia, J., Padue, D. (2018, September 13). Hurricane Florence: Understanding why the elderly are vulnerable. Retrieved from https://abcnews.go.com/Health/

U.S. Energy Information Administration. (2018, June). Retrieved from https://www.eia.gov/tools/faqs/faq.php?id=73&t=11

U.S. Energy Information Administration. (2019, February). Retrieved from https://www.eia.gov/electricity/monthly/current_month/epm.pdf

Williams, J. (2018, September 16). More than 730,000 still without power in North and South Carolina. Retrieved from https://www.newsweek.com/

WINDExchange (n.d.). North Carolina 30-Meter Residential-Scale Wind Resource Map. U.S. Department of Energy. Retrieved from https://windexchange.energy.gov/maps-data/199

WINDExchange (n.d.). Wind Energy Financial Incentives. Retrieved from https://windexchange.energy.gov/projects/incentives

Windfinder. (2019, March 4). Wind, waves and weather for kitesurfers, windsurfers, surfers, and sailors [Map]. Retrieved from https://www.windfinder.com/#4/30.3729/-60.9961.

World Bank Group (2016, November). Lighting africa: improving the accuracy of our impact reporting through the multi-tier framework. Retrieved from https://www.lightingafrica.org/improving-accuracy-impact-reporting-multi-tier-framework/

Zemamou, M. Aggour, M. Toumi, A. (2017, September). Review of savonius wind turbine design and performance, Energy Procedia, Volume 141, 2017, Pages 383-388, ISSN 1876-6102, Retrieved from https://doi.org/10.1016/j.egypro.2017.11.047