

RE-DESIGN OF THE WPI KITE-POWERED WATER PUMP AND WIND TURBINE SYSTEMS

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ABSTRACT

This project had two goals. The first goal was to continue to develop a low-cost kite-powered water pump system to be utilized in underdeveloped nations. To accomplish this goal, we made design modifications to the existing WPI kite-powered water pump system to create a periodic motion of the rocking arm. Five significant modifications were performed that allowed us to obtain this periodic motion: altering the transfer arm, modifying the sliding weight mechanism, adding a ground string to the base of the A-frame structure, designing and attaching a latching and unlatching system for the sliding mechanism, and adding an adjustable weight attachment to the end of the rocking arm. Laboratory and field testing demonstrated that these additions and design modifications created a periodic motion, thus allowing the system to independently pump water. The main objective of the airborne wind turbine project is to redesign, build and test a lightweight airborne wind turbine using concepts developed from last year's MQP team. The turbines output will be increased to 300W making it more viable to be used for basic electricity needs in developing nations. The team will re-design the current support system, design and build lightweight turbine blades and using an existing generator develop a whole turbine system. Support system beach testing, scaled wind tunnel testing and full scale field testing will be conducted. The full system is to be implemented under a high altitude kite and used in developing nations.

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1.0 INTRODUCTION

The goal of the water pump project is to build a low-cost water pump system generated by kite power to be utilized in underdeveloped nations. To accomplish this goal, we made design modifications to the existing WPI kite-powered water pump system to create a periodic motion of the rocking arm. The main objective of the airborne wind turbine project is to design, build and test a lightweight airborne wind turbine with an output capacity of 300 watts that can be supported beneath a high altitude kite and implemented in developing nations. The following sections provide insight into each of these topics.

1.1 Water Pump

Clean water is essential to sustain life and thus many communities of remote areas and underdeveloped nations have focused on designing easier and cheaper ways to guarantee water availability. Many countries in Africa as well as parts of Asia and the Middle East face difficulties in accessing reliable water sources due to the climate and geographic location. Water is directly consumed for drinking purposes, but also used for irrigation systems, farming, and for sanitation purposes. Communities that do not have access to clean water face difficulties such as illness, starvation, and other health problems.

Designing reliable water sources will decrease the number of illnesses and increase the amount of water available for each household. A case study of northern Namibia showed the amount of water currently available for each household (Sturm 2009). The majority of the population in Namibia lives in the northern region, inhabiting about 1 million people living on 15% of the country's total area. These people rely on the pipeline that carries water to them from as far as 10 kilometers away. Due to this limited water supply, households are limited on their water consumption. 20% of the population uses water from the communal Ikuku-Amutanga branch limiting their drinking water supply to 150 liters per day. The remaining 80% of the people have private taps that run to their house, and they are limited to 10 cubic meters of water per month (Sturm, 2009). Due to the constant demand of water, the piping is in constant use. If the system encounters any mechanical problems, one million people will be without water. Therefore, these communities are looking to develop alternative ways to both obtain and store water.

A new technological process called rainwater harvesting was tested in northern Namibia (Sturm 2009). This process measured the amount of rainwater collected from iron roof-tiled buildings as well as from ground catchments which collected water from the ground treated surfaces. The results showed that water was successfully collected and stored in a tank, but when taking into consideration the material and labor cost as well as the low annual rainfall, this process was found to be inefficient. Therefore communities in remote and underdeveloped nations are seeking ways to access water most efficiently and cost effectively (Sturm, 2009).

Natural power sources such as wind power can be used to decrease the cost in transporting water from water sources in developing nations. The goal of our MQP project is to build a low-cost kite-powered water pump system that is to pump water in remote areas and underdeveloped nations. This system requires no electricity and the water is pumped from underground. Our MQP design uses wind power to drive a mechanical pump to continuously supply water. This design uses a kite which is able to reach higher altitudes than land based wind turbines, thus accessing higher wind velocities. This design also reduces the overall cost compared to water pumps that use a conventional wind turbine.

1.2 Wind Turbine

The idea of harnessing energy from wind power and using it as a renewable energy source was first developed in the 1970's (Gold 2012). Once the technology was available, entrepreneurs began to develop prototypes and companies to continue the research on the new renewable resource. World energy consumption is predicted to grow by 50% from 2005 to 2030 (Fagiano 2010). Every day we are trying to find a solution to lessen our dependency on petroleum, whether it is through biofuels, solar cells, or wind power. This transition to greater clean energy output has caused an increase in energy that is being produced by wind power. Many are familiar with the traditional steel wind turbines, however recently the idea of harnessing wind power from kites and other forms of airborne wind turbines has come to fruition.

The standard wind turbines are either VAWT (Vertical Wind Air Turbine) or HAWT (Horizontal Air Wind Turbine). As the wind passes through the blades of the wind turbine, it causes the turbine to spin, generating electricity through the generator. A way to increase power generation is to increase the wind speed turning the turbine. An increase in elevation means stronger and more consistent winds (Gold 2012). It is not economically feasible to build a wind

turbine tower over 1000 feet tall, which is our ultimate height goal. Therefore, the most logical solution was to use a kite in order to get the desired conditions for optimal power generation. The initial cost of a traditional tower-based wind turbine is expensive, but then requires low operating costs and no fuel cost (Gold 2012). Wind power from kites also requires low operating costs but it differs from tower-based turbines because it cuts the initial cost significantly and it also cuts the amount of material used by 90% (Gold 2012).

2.0 BACKGROUND

2.1 Previous MQP's

There have been seven previous MQP projects at WPI on the subject of kite power. These projects are outlined in Table 1, shown below. With each team modifying the design, the kite power project has changed over the years. Originally, the purpose of the kite power project was to be able to produce one kilowatt of power (Buckley et. al., 2008). Throughout these years modifications were made which eventually lead to two sub-projects: kite power that is utilized to pump water, and a wind turbine designed to generate 300 Watts of power (Bartosik et. al., 2012).

Table 1: Table outlining all previous WPI Kite Power MQPs

Year	IQP/MQP Title	Students	Main Accomplishments
2007	Wind Power From Kites MQP	Michael R. Blouin Jr. Benjamin E. Isabella Joshua E. Rodden	<ul style="list-style-type: none"> • Designed and constructed the basic A-frame structure and rocking arm. • Selected kite for use in power generation based on testing and mathematical analysis. • Ran simulations based on steady state and dynamic theory of the tested kites.
2008	Kite Power for Heifer International's Overlook Farm IQP	Gabriel Baldwin Peter Bertoli Taylor LaLonde Michael Sangermano Nick Urko	<ul style="list-style-type: none"> • Developed educational exhibits on kite power for use at the Heifer International's Overlook Farm site.
2008	Design of a One Kilowatt Scale Kite Power System MQP	Ryan Buckley Chris Colschen Michael DeCuir Max Hurgin Erik Lovejoy	<ul style="list-style-type: none"> • Completed and tested the demonstrator which was able to generate power as well as autonomously keep the kite aloft for a short period of time. • Performed stress analysis in

		Nick Simone	Cosmosworks and ran power generation simulations in MATLAB.
2009	Development of a Wind Monitoring System and Grain Grinder IQP	Deepa Krishnaswamy Joseph Phaneuf Travis Perullo	<ul style="list-style-type: none"> • Designed a balloon mounted wind monitoring system using an anemometer. • Implemented a small grain grinder to be attached to the power converter on the kite power system.
2009	Design of a Data Acquisition System for a Kite Power Demonstrator MQP	Lauren Alex Eric DeStefano Luke Fekete Scott Gary	<ul style="list-style-type: none"> • Designed data collection system for physical attributes of the system as well as for power generation. • Designed secondary power generation and oscillation control subcomponents. • Further optimized rocking arm and A-frame as well as tested each system and subcomponent.
2010	Design of a Dynamometer For The WPI Kite Power System MQP	C. Kuthan Toydemir	<ul style="list-style-type: none"> • Design and build a dynamometer used to measure torque and power
2010	Re-Design and Testing of the WPI Kite Power System MQP	Adam Cartier Eric Murphy Travis Perullo Matthew Tomasko Kimberly White	<ul style="list-style-type: none"> • Modified system: <ul style="list-style-type: none"> • Use of a more stable and larger sled kite • Upgraded gear shaft • Built mechanism to change angle of attack of kite • Measured tension of kite tether during testing
2011	Design of a Remote Controlled Tether System for the WPI Kite Power System MQP	Michael Frewin Emanuel Jimenez Michael Roth	<ul style="list-style-type: none"> • Developed wireless system to remotely control trailing edge lines of kite to alter angle of attack and side-to-side motion • Designed a control box with two motors, gear boxes, transmitters, and two spools to control the length of trailing tethers.
2012	Design of a Kite-Powered Water Pump and Airborne Wind Turbine MQP	Kyle Bartosik Jennifer Gill Andrew Lybarger Daniel Nyren John Wilder	<ul style="list-style-type: none"> • Re-design of WPI system to add a mechanical water pump and head simulation valve

2.1.1 Water Pump

Prior to our design modifications, the existing WPI kite power system consisted of a wooden A-frame base which supports a metal rocking arm. The complete system is shown in Figure 1 below. This rocking arm contains a sliding mechanism which assists in creating a periodic motion of the rocking arm. The trailing edge tethers of a sled kite (either 36 or 81 square feet in area) are attached to the sliding mechanism. The kite size depends on the wind speed during testing; the 36 square foot kite is used at higher wind speeds to limit kite failure while the 81 square foot kite is larger, generating more power. The leading edge of the kite is attached to the end of the rocking arm with a nylon tether so that when the kite gains lift the rocking arm will rise. The rocking arm lowers when the sliding mechanism pulls on trailing edge tethers to stall the kite, thus decreasing the lift. When the trailing edge tethers are loosened, the angle of attack decreases. This increases the lift, thus moving the arm upward. The rocking arm must cycle in a periodic motion in order to maximize the performance of the water pump (Bartosik et. al., 2012).

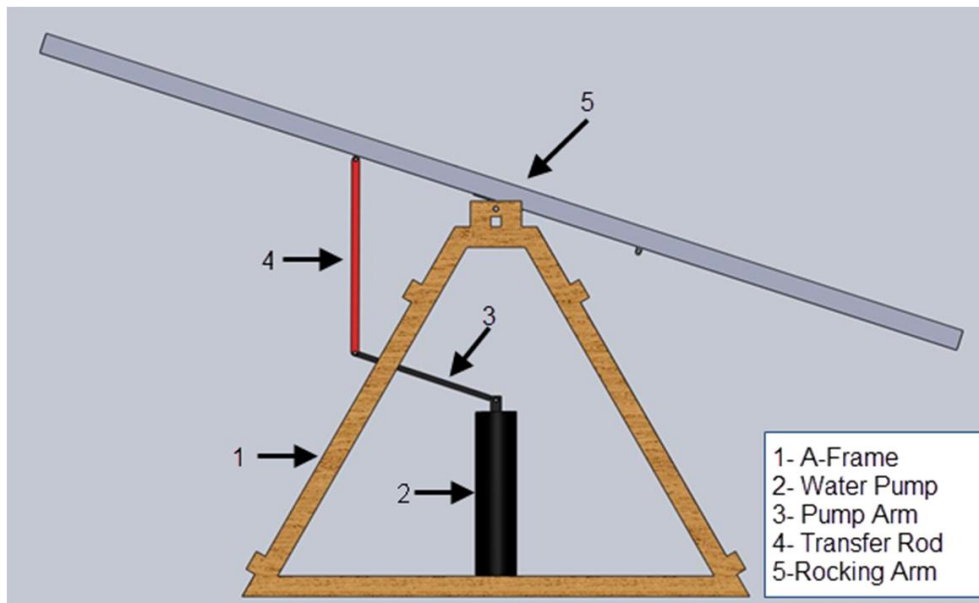


Figure 1: 2012 MQP System (Source: Bartosik et. al., 2012).

The rocking arm and the pump are linked by a transfer rod as shown in Figure 1. Ideally, as the rocking arm moves up and down, the pump will follow a periodic motion, thus pumping water. The pump also contained a head simulation valve, which simulates a pressure drop that occurs as if pumping water from greater depths (Bartosik et. al., 2012).

2.1.1.1 Piston Pump

A previous MQP on Kite Power, (Bartosik et. al., 2012), chose an appropriate water pump for the current system. The 2012 MQP took certain factors into consideration when they were deciding which pump would best suit the system. The group had to decide whether the chosen pump should have either a linear or rotational motion. There were complications with considering a rotational pump as it would create an additional cost through extra parts that would be needed to convert the arcing motion of the rocking arm to rotational motion. There is no budget for extra parts as the system is supposed to be designed at a low cost for underdeveloped nations. With this in mind, they decided a linear motion pump was a better option. The decision of a linear motion pump over a rotational motion pump narrowed down their choice to two pumps, a diaphragm pump and a piston pump. Since piston pumps are used for larger volumes of water and are more common in Africa than diaphragm pumps, the piston pump system was chosen.

The decision was made to use a linear motion piston pump. The previous group then had to choose between either a borehole pump or a force cylinder pump. Borehole pumps have the piston and cylinder in the ground whereas a force cylinder is completely above ground. Due to the setup, force cylinder pumps are limited to pumping water from 32.3 feet. The goal of the low cost system is to be able to pump water from deep wells, so the group chose a borehole pump in which they can pump water from greater depths.

The group decided on buying a Jooste AS 80 standard borehole cylinder, as seen in Figure 2. A long metal rod connects the pump at the base of A-frame to the piston valve at the bottom of the well. The metal rod allows the system to pump water from greater depths.



Figure 2: Piston Pump and Head Simulation Valve

J. Goela performed initial studies on kite power systems, see References 15-19. More recently Olinger & Goela (2010) and Olinger, Goela, and Tryggvason (2013) have modelled the WPI kite-powered system. As stated in Olinger et al., 2013, “The kite power system consists of a kite, a flexible tether, a rocking arm, mechanical linkage, and water pump as shown in Figure 3 below. The kite tether is attached to one end of the rocking arm so that the cross-wind motion of the kite is converted into an up and down motion of the arm about the pivot point B. The arm’s motion is transferred through a mechanical linkage to the piston of the water pump. The water pump is a displacement (or lift) pump consisting of a piston, a connecting rod that extends from the piston through a descending drop pipe to a valve on the piston at the bottom of the well. The rocking arm and mechanical linkage have two main configurations as shown in Figure 3: (1) the *pumping configuration* in which the kite angle-of-attack, lift force and tether tension increase, the piston valve at the bottom of the well closes, the rocking arm and pump piston moves upwards, pushing water up and water flows from the well into the drop pipe and fills it underneath the plunger; and (2) the *return configuration* in which the kite angle-of-attack, lift and tether tension decrease, the piston valve opens up, the rocking arm, pump piston and piston valve (now open) move downwards, and the water in the drop pipe (to be pumped in the next cycle) flows around the piston valve and fills the drop pipe above the plunger.”

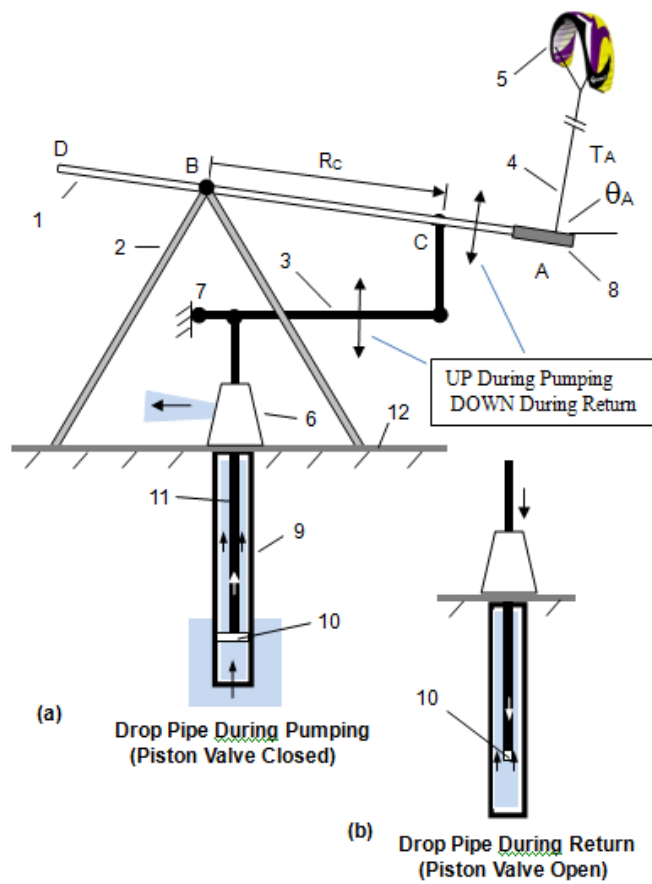


Figure 3: The kite-powered water pump system during the pumping (a) and return (b) configurations. 1-Rocking arm, 2-Support frame, 3-Mechanical linkage, 4-Tether, 5-Kite, 6-Pump, 7-Fixed pivot, 8-Counter weight and kite angle-of-attack mechanism, 9-Drop

2.1.2 Wind Turbine

The current WPI airborne wind turbine system, as seen in Figure 4, is comprised of the turbine support frame, the "Yoke" design, and the vertical axis wind turbine (VAWT) suspended by the sled kite. The "Yoke" design as seen in Figure 5 was chosen because it is simple, keeps the turbine far enough away from the kite to not disturb it, and can easily be modified to fit different size turbines. The support frame is an upside-down "Y" shape with the turbine resting inside of the bottom "V", it is made out of PVC piping because of its light weight and stiffness. The frame was then attached the kite tether using a "double V" of rope connected to a hinge at the top of the frame. The hinge allowed movement of the frame to adjust to the tether angle and the rope system prevented yawing that might occur.



Figure 4: 2012 MQP Kite and Support System (Source: Bartosik et. al., 2012)

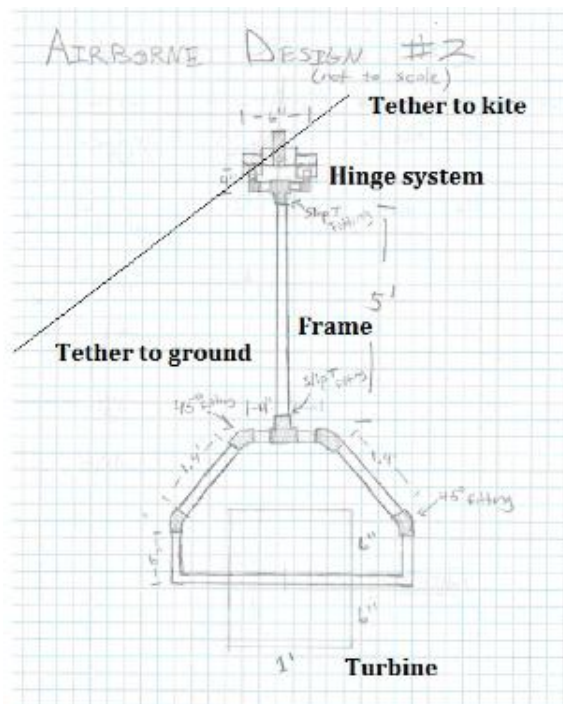


Figure 5: 2012 MQP YOLK (Source: Bartosik et. al., 2012)

A VAWT was decided upon as oppose to a horizontal axis wind turbine because it could generate power no matter which direction the wind was blowing. The turbine that was used was a relatively small turbine with a power output of only 10 Watts but weighing only 2.27 kg. Although the original goal was to get a much high output generator (near 1KW) this turbine was chosen for initial design and testing of concept. The VAWT modified to fit into the PVC and was place horizontally resting in the "V" of the support frame, the tether was replaced with a high gauged wire that could withstand necessary tension from the kite force.

The system was a proof of concept and a viable starting point for the project, results were gathered from wind tests, but the design needs much improvement. The PVC piping with the turbine in place bent a small degree and prevented the turbine from spinning properly. The low power output turbine and high resistance cable to transfer the energy caused the power to dissipate before ever reaching the ground. We will address all of these problems and aim to design a new system that will create a higher power output and operate more efficiently.

2.2 Wind Powered Water Pumps

2.2.1 How Water Pumps Work

The use of renewable energy, such as wind power, has increased among developing nations where electricity is not widely available. Wind power has been utilized to produce power for over 2000 years. Technological advancements have been made to design systems to convert this wind into usable power. One application for wind power is the wind powered water pump that uses a conventional wind turbine. The wind powered water pump is a mechanical system utilizing wind power to produce a force large enough to pump water. The amount of power the system produces is proportional to the size of the rotors and the available wind speed. The power from the wind can be extracted from the equation $P = \frac{1}{2}\rho AV^3 C_p$ where ρ is the density of the air at the corresponding altitude, A is the swept area of the turbine, V is the wind speed, and C_p is the power coefficient. The force of the wind against the blades causes a gear system attached to a shaft to rotate. This shaft is connected to a pump which creates suction, thus transferring water from the ground to the surface. One particular pump system, called the Kijito, is utilized in Kenya for local wind powered pump systems. The rotor diameter ranges from 8 feet to 24 feet, thus making it possible to pump water from 36.5 meters to as deep as 152 meters (Harries 2002).

Converting from a diesel generated pump to a wind powered pump also decreases the cost required to run the system, and eliminates the need to transport the diesel as well. A study in Kenya compared the savings of utilizing a wind powered water pump over a diesel pump (Harries 2002). The pump required a minimum wind speed of 3.5 meters per second. The collected data displayed the annual operating cost of the diesel pump to be \$250 and the wind pump to be \$100. The fuel cost for the diesel pump was \$292 and the wind pump was \$0. The capital cost for the diesel pump system was \$6,000 and the wind pump was \$10,000. Although the wind power system costs more, over the course of time this system will be advantageous, even if maintenance costs are required. The WPI kite-powered water pump system utilizes a PowerSled 81 sled kite, three nylon tethers, rocking arm of square aluminum tube, wooden A-frame, mechanical linkage, pump, sliding weight, latching mechanism, the Joosete Model AS80 water pump, and head simulation valve. The capital cost for these parts is about \$2300 (Olinger et al., 2013). Using wind power avoids the need for electricity and fuel so it can be utilized in remote areas to provide water for local villages and communities.

One main drawback for this system is the continuous need for wind in order to pump water. The WPI kite powered water pump system provides a potential solution. This design utilizes a kite in replacement of the wind turbine, allowing the system to use wind power from a higher altitude thus accessing higher wind velocities. This increases the likelihood for continuous wind supply and thus water supply.

2.2.2 Applications

Developing nations across the world use wind powered water pumps to provide water to sustain life. Many remote areas face the issue of accessing an open water source within a reasonable distance. Since people in developing nations must carry water over a substantial distance on a daily basis, a wind power water pump system provides a way to obtain water without needing to transport it often. The most common applications of the wind powered water pump system are to supply drinking water and to provide an irrigation system for crops, both which are critical to sustain life (Fraenkel et. al., 1999). Other applications such as drainage (from floods) and salt collection are also powered by wind energy. The water supply for irrigation purposes is pumped from between 10 and 30 meters deep (Rehman et. al., 2012). Drinking water is pumped from deeper, sometime reaching as far as 100 meters (Fraenkel et. al.,

1999). Therefore the wind powered water pump allows villages and smaller communities to maintain their own water source for less cost.

Wind powered water pumps make water accessible to remote areas as well as decrease cost and emissions produced during power generation. Some countries that utilize these systems include South Africa, sub-Saharan Africa, Saudi Arabia, Kenya, China, and other Asian countries. Nearly half the population in sub-Saharan Africa did not have a reliable water source. A new wind powered water pump was manufactured and used in Kenya and other surrounding countries. Over the course of 20 years, more than 300 water pumps were installed making clean water a more reliable source (Harries, 2002). China began using wind power to decrease CO₂ emissions. According to “Energy-water nexus of wind power in China”, China produced 25.1% of the CO₂ emissions produced by the entire world. In order to decrease this amount, the Chinese government has aimed to increase wind power generation. The “Energy-water nexus of wind power in China” calculates that CO₂ emissions will decrease by 23% by 2020. Since wind is freely available, clean, and renewable, many countries converted to rely on wind as their primary power source. In 2010, the Global Wind Energy Council Report announced that the world’s wind power usage increased by 22.5%, and that Asia grew to become the largest wind energy market system (Rehman et. al., 2012).

Wind energy is a type of renewable energy becoming widely used across the world because of its lower costs and natural sources. The WPI kite powered water pump system is designed to pump water using wind power, but the wind turbine is replaced with a large kite, which decreases the price of the entire system. This allows for higher altitudes and thus higher wind speeds to ensure a reliable water source for remote areas.

2.3 Kite Power

2.3.1 Advantages

The renewable wind power industry has been dominated by the use of wind turbines mounted on towers. While these turbines have been successful, they have disadvantages. Factors that can be improved upon are their costs, impact on the surrounding environment, and efficiency.

For the purpose of generating a large amount of power from wind power, multiple systems are required in order to actually produce a sufficient amount of power. Numerous wind

turbines are often organized into wind farms and positioned in areas with favorable wind to create power. Not only does the cost multiply from the expensive turbine units, but the allowable number is restricted due to the turbines themselves interfering with each other, creating an oversaturation effect (Biello, 2012).

The altitude of an average large wind turbine's blades is between 80 and 100 meters, where the wind power density is 58 W/m^2 . At an altitude of 800 meters, the wind power density increases to 205 W/m^2 (KiteGen, 2007). However, it is impractical to build a turbine to this height so the standard wind turbine cannot reach the much more efficient high wind speed altitudes (Jha, 2008).

While it is not as serious as the effects fossil fuel power can bring to an area, wind turbines can still cause problems. Some people may not prefer the aesthetic look of wind turbines to them or fear that they can affect the environment in negative ways (Ailworth, 2012). As they spin, the turbines create a constant humming sound from the generator. The blades can throw small debris, such as ice that can form on the blades in cool climates. Bird and bat mortality from wind turbines is also a possible issue (Biello, 2012).

The idea of using kites for generating power is attractive considering the disadvantages of the turbines. Kites are much smaller and easier to make and install. They can fly at higher altitudes and reach higher wind velocities. As a result of the high wind velocities, kites are more efficient as well as cheaper (Goela, 1979). They also would not create as much turbulence as turbines can, allowing a higher number of systems in one area. Kites can also be placed in far more areas than turbines can operate effectively. Kites would be quieter than turbines as well as be less of a threat to wildlife (Biello, 2012). The faster speed in which they can be installed can also allow kites to provide energy to a region quickly, especially in an area that sustained infrastructure damage.

Delft's University of Technology in the Netherlands has a kite power system that has been able to provide 6.5 to 10 kW. While these values are still lower than larger traditional wind turbines, entire systems making use of many kites make up for this detriment (Schmehl, 2012). KiteGen's proposed system is much larger, but can potentially generate 1 GW of power (KiteGen, 2007).

Kites are attractive for developing nations due to their low cost as well as their simplicity. They can easily be adapted to performing a different task other than generating electricity.

Powering pumps to bring water from underground wells to the surface autonomously and without requiring electricity or much human power is a great example of this.

2.3.2 Disadvantages

However, kite power has its own disadvantages. Being held on a thin tether and made of fabrics compared to wide metallic columns and blades make them much easier to damage as well as more difficult to repair the kite, possibly making it more favorably to just replace the kite itself. Kites must also fly at higher altitudes to make use of the more efficient winds, which can make them dangerous to low flying aircraft. This means kite systems must be allowed by organizations such as the Federal Aviation Administration (FAA, 2012). Wind turbines produce more energy than kites can on a single unit basis; commercial wind turbines can generate at least 250kW of power whereas a kite system can generate about 20kW of power (Powerworks, 2012), (Kitepower, 2012). Further, when wind velocity decreases, the kite may fall to the ground and require personnel to launch the kite again.

2.3.3 Summary

The advantages of kite power systems outweigh their disadvantages. Their simplicity and cheap cost would be quite attractive to developing nations, being capable of a wide range of applications. These systems can operate almost anywhere with sufficient winds, be set up quickly, be used as emergency power after a disaster, and work autonomously without damaging the environment.

2.4 Airborne Wind Energy

There are companies building prototypes such as Joby Energy, KiteFarms, and Kite Gen. However, the leader in airborne wind development as of now is Makani Power. Makani merged with Joby Energy in 2009 and was given a 15 million USD in funding by Google (Fagiano, 2009). Makani Power was developed in 2006 by Corwin Hardham, Don Montague, and Saul Griffith. As stated in (Makani Power, 2013), over the first five years of development, and thousands of hours of field testing, the Airborne Wind Turbine (AWT) evolved from a soft textile kite power a generator on the ground to a rigid, high performance wing with onboard generation. In 2007, Makani developed control and steering strategies that lead to the first power generation and autonomous flights. The first demonstration of autonomous flight was completed with ground based steering system with a figure 8 path controller. In 2008, Makani Power

completed three sets of two hour autonomous flights with power generation, and the next year Makani Power's Wing 3 finished a crosswind autonomous flight. In 2010, the Wing 4 prototype included the first onboard power generation, averaging more than 8 kW of power output under autonomous control.

Every company developing wind turbines has varying designs for what they believe to be the best option for wind power from kites. Makani believes that the tip of the blade is the most efficient part of a turbine. This way, their flying wing copies the pattern of the blade tips, making all of the energy, with a fraction of the materials (Makani Power). As of now Makani is the leader in the market, and has made appearances in many scientific magazines including National Geographic (Nat Geo 2012). KiteGen on the other hand believes in generating power from a figure 8 flight path as shown in Figure 6 below, as well as their stem method, also commonly referred to as the spooling line concept; where they release the kite out, and harness the energy from the uncoiling of the tether, then stall the kite and roll the tether back up and continuously do this to obtain the energy. KiteGen is also modeling a KiteGen Carousel, where there are multiple kites tethered around a central generator that spins freely; the kites' motion causes the center disc to spin, and allows energy to be generated.



Figure 6: (Source: KiteGen Research, 2009)

2.4.1 Wind Turbines (Horizontal versus Vertical)

The majority of wind turbines used for power generation today are Horizontal Axis Wind Turbines (HAWT), as shown in Figure 7. The turbine system, including generator and gear box, are mounted atop the tower with the transformer at the base. Having most of the mechanics elevated above the ground creates an apparent disadvantage; the turbine system can be difficult

to maintain and fix any mechanical failures in a tall enclosed tower. The turbine efficiency is a function of height above the ground, wind speed increases with height, and area swept by the blades, the taller and large the blades are the more effective the turbine is at generating power (Jha, 2011). But as the tower gets taller and the blades get longer, structural integrity is lost and maintainability becomes more difficult. Another problem with HAWTs is that the turbine axis also needs to be perpendicular to the wind direction which requires an anemometer and wind vane to measure wind direction, a control system and a mechanical yaw system. This yaw-mechanism combined with a blade pitch system allows the turbine to self-start and maintain high efficiency with variable blade angle of attacks to wind speeds.

Vertical Axis Wind Turbines (VAWT), as shown in Figure 7, are used mainly in low-power applications often to charge batteries because of their lower output capabilities. The generator and gear box system for VAWTs is located on ground level, which makes them easy to maintain, repair and service. The turbine blades spin around a vertical axis thus making them multi-directional requiring no control or yaw-mechanism. The blades employ lift to generate torque by aerodynamic means, which drives the blades around the vertical axis. To this end many systems are designed to create as much torque at ideal wind conditions and thus lack the means of self-starting under certain wind speed conditions. Because of their multi-directional nature, lack of yaw mechanism, and having all major mechanisms (generator and gear box) on the ground, they are ideal for low cost low maintenance systems (Jha 2011).



Figure 7: A HAWT (left) and a VAWT (right)

2.4.2 How Turbines Generate Power

Turbine blades are constructed with an airfoil similarly to that of an airplane wing. Wind acting on the airfoil generates two forces, a lift force and a drag force. Lift is generated from a pressure differential between the top and bottom surfaces of the airfoil, or on a turbine the

leeward and windward sides. The pressure differential is caused by airflow on the leeward side traveling faster than that on the windward side. This creates a force on the low pressure side pulling the airfoil in that direction which can be estimated by Bernoulli's principle (Gipe 2004). As shown in Figure 8, the two components of this force vector are lift and drag. Parallel to the blade direction is the torque which is available to do work through the rotation; while perpendicular to the blade direction is the thrust which must be supported by the structure. Increasing the angle of attack of an airfoil while staying below the stall angle, increases the lift generated by the airfoil, the torque and thus power output.

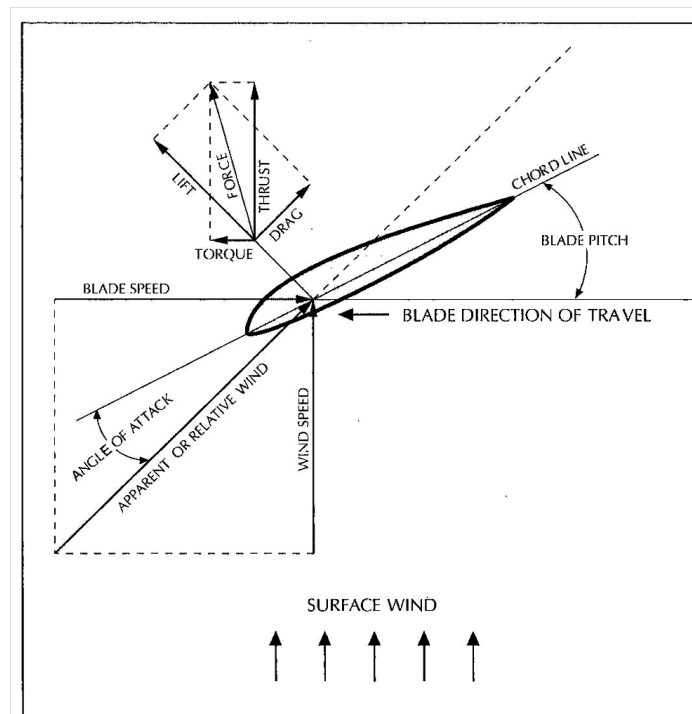


Figure 8: Forces generated by airfoil (Source: Paul, 2004)

Horizontal axis turbine blades are very similar to propeller blades of an airplane with the obvious difference, propeller blades are rotated by a power source to create thrust, while turbine blades are spun by wind to create power. Turbine blades have varying airfoil shapes or angle of attacks along the span because flow velocity varies with position along the blade (Gerogie 2002). The rotor of HAWTs always remains perpendicular to the flow allowing the blades to be designed to maximize power for this constant condition. However, in a VAWT, rotation around the vertical axis constantly changes the relative angle of attack and the local dynamic pressure causing variable torques throughout a single rotation cycle. Therefore the load fluctuates causing

an unsteady output of power from the turbine (Jha 2011). To combat this fluctuating load the turbine blades can be canted into a 60 degree helical twist causing each blade to be pulled on both the windward and leeward sides.

3.0 Project Objectives

3.1 Water Pump

Our team improved the existing WPI kite-powered water pump system to be utilized in underdeveloped nations by:

- Re-designing the transfer arm between the rocking arm and water pump
- Modifying the sliding mechanism that stall the kite
- Adding a ground string that forces the sliding mechanism to stall the kite
- Designing a latching and unlatching system for the sliding mechanism
- Adding an adjustable weight to the end of the rocking arm to tune the system to different wind speeds
- Laboratory and field testing the improved system

Modifications from previous MQP structures as well as new designs were incorporated to achieve a periodic motion of the rocking arm. New additions such as the material of the transfer arm, a ground string attached to the A-frame and sliding weight mechanism, the latching and unlatching system, and an adjustable weight attachment, were made. The ground string and the latching and unlatching system control the stalling and unstalling of the kite. The adjustable weight attachment on the end of the rocking arm was added to aid the rocking arm in lowering depending on the wind speed. Finally, laboratory and field testing of the complete system was performed to ensure the consistent periodic motion and proper functionality.

3.2 Wind Turbine

- To design a wind turbine out of light weight, affordable material that when paired with a generator will produce about 300W-2kW of power
- To design a support system that allows us to hoist our airborne wind turbine into the air with our kite in order to reach high altitudes of approximately 200 feet
- Full cost analysis of propose systems studying various lift systems, airborne versus ground systems and different power output options

4.0 Methodology

4.1 Water Pump

The main goal of our MQP was to re-design a low-cost water pump system generated by kite power to be utilized in underdeveloped nations. To accomplish this goal, we made design modifications to create a periodic motion of the rocking arm. A periodic motion of the rocking arm was necessary in order for the A-frame rocking arm system to continuously pump water. The following list outlines five crucial modifications we performed that allowed us to obtain this periodic motion:

- Re-designing the transfer arm between the rocking arm and water pump
- Modifying the sliding mechanism that stall the kite
- Adding a ground string that forces the sliding mechanism to stall the kite
- Designing a latching and unlatching system for the sliding mechanism
- Adding an adjustable weight to the end of the rocking arm to tune the system to different wind speeds
- Laboratory and field testing the improved system

Figure 9 below shows the location of each design modification.

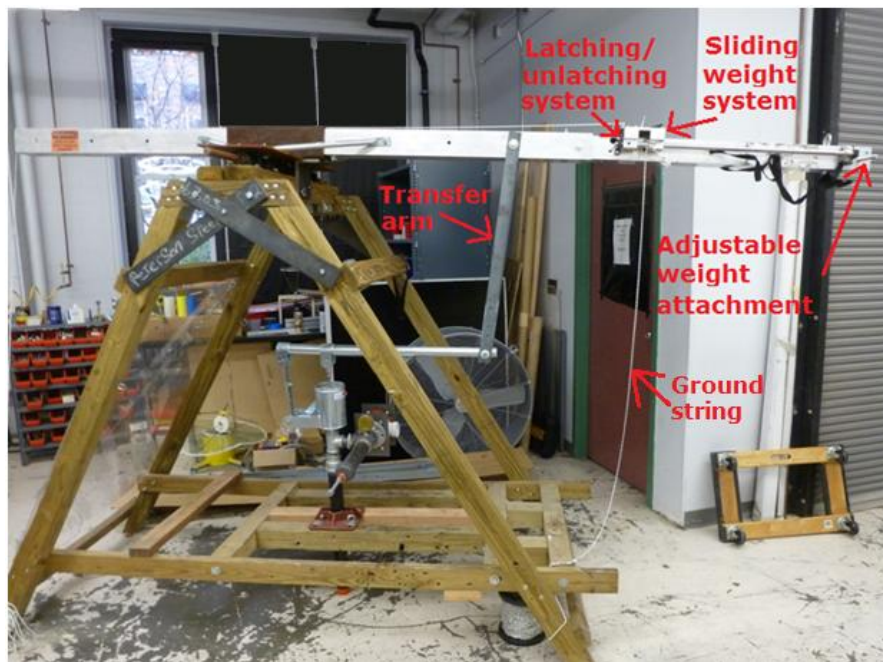


Figure 9: Complete A-frame rocking arm system with design modifications labeled

4.1.1 Re-design of the transfer arm

The transfer arm consists of two metal rectangular pieces that connect the rocking arm to the pump handle, thus “transferring” the motion from the rocking arm to the pump. The motion of the pump and rocking arm move in sync, so when the rocking arm rises, so does the pump, and when the rocking arm lowers, the pump lowers as well. When the pump is drawn upward, water is suctioned up and pumped out of our system. The pump then lowers when the kite is stalled and the rocking arm is lowered. Once the rocking arm is lifted again by the kite, the pump creates suction and more water is released from the system.

The transfer arm from a previous MQP was made of wood. In order to prevent the transfer arm from rotting, we changed the material to steel. We made the transfer arm adjustable so the user can connect the pump handle at different locations. As shown in Figure 10 on the right, we drilled six holes in the steel transfer arm to give a reasonable amount of flexibility when the user chooses where he/she desires the pump to start. To prevent buckling of the metal,



Figure 10: Adjustable Transfer Arm

we added two bolts between the two rectangular pieces. Buckling of the metal would happen in a situation where the kite completely loses lift and the rocking arm comes crashing down. The brackets on the A-frame prevent the rocking arm from crashing down; therefore, the two bolts between the transfer arm are for extra strength and safety to our project. We chose this length because the rocking arm can rise slightly higher than level, allowing the sliding weight system to slide toward the center of the rocking arm and become latched. In addition, the transfer arm falls low enough for the sliding weight to slide to the end of the rocking arm. The sliding weight system and latch system will be discussed in further detail later in the paper.

4.1.2 Modifying the sliding mechanism

The sliding weight mechanism is located on the extension piece of the rocking arm. The mechanism consists of a rectangular metal piece that is attached to rods on the side of the

rocking arm. The mechanism can move freely when the rocking arm rises and falls. The main purpose of the sliding weight mechanism is to control the stalling and unstalling of the kite, which then controls the motion of the rocking arm. Once the rocking arm falls low enough that the latch string becomes taught, the sliding weight mechanism becomes unlatched, the arm rises, and water is pumped. This motion repeats, creating a periodic motion of the rocking arm.

In order for the kite to be stalled by use of the sliding weight mechanism, we attached a crossbar to the side of the mechanism opposite the A-frame. This bar is where the control string of the kite is attached. This ensures higher strength when the kite pulls on the control rods of the kite. With the control string of the kite attached to the sliding weight mechanism, we are able to successfully stall the kite with the movement of the sliding mechanism. To prevent rubbing and wear on the control string of the kite, we cut a larger slot in the rectangular sliding mechanism piece. This larger slot allows more room for the control string to move without chaffing.

In addition to the crossbar for the control rods, we added another crossbar along the face of the rectangular flat plate on the side closest to the A-frame. This crossbar is shown in Figure 11. The purpose of this bar is so the sliding weight mechanism can latch. Without latching the sliding weight mechanism, the kite would never stall long enough to allow for the rocking arm to completely lower and therefore our system would not efficiently pump water. We attached the crossbar on the edge of the sliding weight mechanism, assuring it was at a height equal to the height of the latching system. This way, we were confident our sliding mechanism would slide perfectly into the latching system and remain latched.

Once the rocking arm is lifted by the kite, we wanted to ensure that the sliding mechanism would slide toward the center of the rocking arm to become latched. To help the

mechanism slide, we attached a two and a half pound weight to the top of the sliding mechanism. From previous MQPs, there was a hole in the center of the sliding mechanism. We drilled this hole larger to be 1/2" in diameter. After initially installing the weight,



Figure 11: Latch Crossbar



Figure 12: PVC Piping

we encountered a problem that the sliding mechanism could not latch. We examined the situation and realized that the weight plate was hitting the latch, preventing the crossbar on the sliding mechanism to reach the latch. We needed to add height to the weight so the sliding mechanism itself could latch. Our initial idea was to use wood or metal, but we know wood will rot and metal on metal could result in corrosion, so we decided to use rubber. The height difference we needed to account for was 1 ½", so we drilled holes in the center of two hockey pucks and added those on the threaded rod between the rectangular sliding piece and the two and a half pound weight. Another issue we encountered was that the weight plate was secured on a ½" threaded rod, but the hole in the center of the weight plate is 1". When the sliding mechanism slides on the rocking arm, the weight itself is not stable. To resolve this problem and stabilize the weight, we cut two different size PVC piping; one that fits on the ½" threaded rod, and another that fits over the first PVC pipe and between the 1" diameter hole in the weight plate. To minimize the space difference completely, we wrapped electrical tape around the outer PVC piping until it was snug with the weight plate, as seen in Figure 12 on the left.

In order to attach the ground string to the sliding weight mechanism, we added an eyebolt to the bottom of the sliding weight mechanism on the side closest to the A-frame. The eyebolt was attached in that location to prevent tangling of a ground string that connects from the eyebolt to the A-frame.

4.1.3 Ground string to force kite stall

A major addition to our project was the addition of the ground string. The string connects from the sliding mechanism to the base of the A-frame and assists the sliding mechanism in sliding toward the latched position. This ground string plays a significant role in the periodic motion of the rocking arm. When the rocking arm is down, the ground string has slack. When the rocking arm rises, the ground string becomes taught and pulls the sliding weight mechanism to the fully latched position. Without the ground string, the sliding mechanism does not slide completely down the rocking arm into the latch, and therefore the entire system does not fully operate.

The ground string is adjustable, allowing for each user to adjust the length how he/she prefers. The longer the ground string, the higher the rocking arm will go before the sliding mechanism is pulled to the latch position and stalls the kite. In the same manner, if the ground string is short, the rocking arm will not rise as high. While adjusting the ground string, it is

important to realize that if the ground string is too long, the string will never become taught, therefore will not pull the sliding mechanism to the latched position. If the ground string is sized too short, the rocking arm will not rise high enough to create suction, resulting in no water being released.

In the case that the rocking arm rises too quickly by the lift of the kite, we added a spring between the eye bolt on the base of the A-frame and the adjustable ground string. This spring will absorb the tension of the kite before the ground string itself does, preventing stretching and tearing of the ground string.

4.1.4 Latching Mechanism Design

Holding the sliding weight mechanism in a position close to the center of the rocking arm is a significant piece of how we created a periodic motion of the rocking arm. Once the sliding mechanism is held in place, the kite becomes stalled. While the kite is stalled, the rocking arm lowers and the sliding mechanism is released. When the sliding mechanism is released, the kite is no longer stalled but rather lifts the rocking arm back up. The sliding mechanism then needs to be held in place so the kite can become stalled. Repetition of these steps creates a periodic motion of the rocking arm.

The best idea of how to hold the sliding weight mechanism in place was the idea of a latching and unlatching system. This idea seemed simple enough as a latch would definitely hold the sliding mechanism in place. We installed the latch in a position such that once the sliding weight mechanism could not move any closer toward the A-frame, the crossbar on the sliding weight mechanism would latch completely, as shown in Figure 13 on the right. The complication was thinking of a way to unlatch the mechanism once it was secured.



Figure 13: Latched Sliding Weight Mechanism

We decided to build a wooden frame on the A-frame that extends over the rocking arm, connecting one side of the A-frame to the other. The wooden extension can be seen in Figure 14.



Figure 14: Wooden Extension

We designed the wooden extension piece to extend over the rocking arm as we needed a position that was stationary throughout the rocking arm movement, yet high enough to properly pull the latch open. To help release the latch, we installed an eyebolt at the top-center of this wooden frame extension. This eyebolt is crucial to how the latching system unlatches. Similar to the adjustable ground string, we added an adjustable strap extending from the eyebolt on the wooden frame extension, to the latch on the rocking arm. We added an eyebolt to the rocking arm between the latch and the eyebolt on the top-center of the A-frame extension. The adjustable strap extends through this eyebolt, preventing the strap from getting caught on any other parts of the system. The length of the adjustable strap is significant to the latching and unlatching system working properly.

This adjustable strap is designed to be loose when the rocking arm is up and the sliding mechanism is latched. While the kite is stalled and the rocking arm falls, the distance between the eyebolt on the wooden frame extension and the latch on the rocking arm becomes larger. Due to this increased distance, the adjustable strap becomes taut and pulls the latch open. Sizing the length of the strap is done by starting with the rocking arm as low as it can go and adjusting the strap so the latch is open when the arm is down. If the strap is too long, it will never become taut, meaning the sliding weight mechanism will remain latched. If the strap is too short, the

sliding weight mechanism will become unlatched too early. Releasing the sliding weight mechanism too early means the kite will not be stalled and therefore the rocking arm will not completely fall. If the rocking arm does not completely fall, then there will be less room for the rocking arm to rise. Less room for the rocking arm to rise results in less suction in the pump and as a consequence, less water pumped on the next cycle.

4.1.5 Adjustable weights at end of rocking arm

After modifying the entire A-frame rocking arm system, we realized we had to take into account varying wind velocities. The wind velocity where the A-frame rocking arm system will be operating will definitely affect how effective our system is. To account for the factor of wind velocity and ensure that we can maintain a periodic motion of the rocking arm, we installed an adjustable weight attachment on the end of the rocking arm. A user may want to add more weight to the adjustable weight attachment to assist the arm in falling against a stronger lift in windier conditions, and remove weight from the adjustable weight attachment to assist the arm in rising with a weaker lift in less windy conditions.

This attachment involved drilling a 1/2" hole through the rocking arm and putting a 1/2" threaded rod through it. To prevent the threaded rod from slipping out of either side of the rocking arm, we put two nuts on both sides of the rocking arm; one on the outside metal of the rocking arm and the other on the corresponding inside of the rocking arm. The nut on the inside of the rocking arm is shown in Figure 15 below. Two nuts on both sides of the metal created a lock and the threaded rod became stationary.

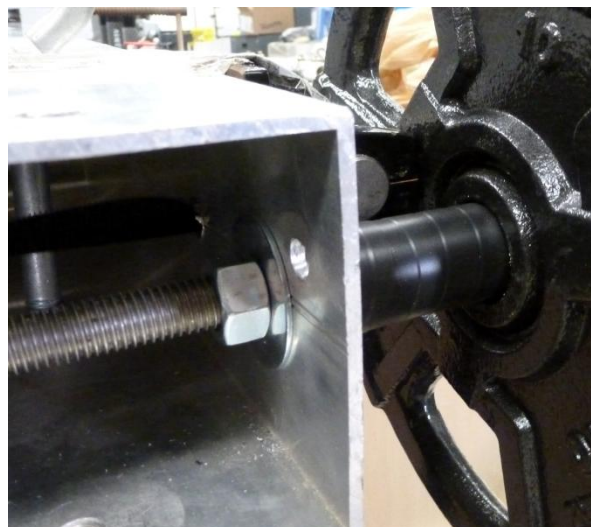


Figure 15: Nut Securing Threaded Rod

Once the threaded rod was intact, we could add weight plates. Similar to the sliding weight mechanism, we needed to account for the unsteady weight plates as the threaded rod is only ½” in diameter and the weight plate has a 1” diameter hole. To stabilize the weight, we did exactly the same process as for the sliding weight mechanism. We cut two different size PVC piping; one that fits on the ½” threaded rod, and another that fits over the first PVC pipe and between the 1” diameter hole in the weight plate. To minimize the space difference completely, we wrapped electrical tape around the outer PVC piping until the weight plates had just enough room to be slid on and off of the piping

4.1.6 Summary

The main goal of our project was to improve upon the existing WPI kite-powered water pump system, with a focus on adding a system to stall and un stall a kite to generate a periodic motion, and thus efficiently pump water. We replaced the existing transfer arm, which was made out of wood, with a steel transfer arm for maximum durability. We added six holes to each of the transfer arm and added bolts across to increase its strength. We also added a ground string that connects from the base of the A-frame to the sliding mechanism. This sliding mechanism slides back and forth on the extension of the rocking arm. The control rod of the kite is attached to the sliding mechanism, so when the sliding mechanism moved back and forth, the kite stalls and unstalls. In order to maximize the stall time of the kite, we added a latch system. This latch system holds the sliding system in a stalled position until the rocking arm completely falls, maximizing the amount of water pumped per each cycle. In order to unlatch the system, we added a string that connected from the eye bolt on the wooden A-frame to the latch on the rocking arm. The length of the string was determined to allow for the rocking arm to fall as far as possible before unlatching, thus allowing the system to maximize the amount of water pumped. In order for the system to function smoothly we added weights to the end of the rocking arm as an adjustable weight attachment. The user can adjust the weight depending on the environment where the system is being used, in order to maximize water pumping efficiency. With all of the modifications and additions, the system was tested to verify if we achieved our desired goals based on the results of generating a periodic motion of the rocking arm.

4.2 Wind Turbine

There were many important aspects in designing a new system for this year’s turbine. The MQP from 2012 built a yolk design support system for a vertical wind turbine. It was a Y

shaped piece of PVC, which hung from the mid-section of the kite tether, which supported the vertical air wind turbine. In some instances, the horizontal direction caused the yoke design to impede the turbines to rotation. The transmission line used to bring the generate power to the ground had too high of a resistance therefore any power generated was dissipated before reaching the ground.

As seen in Table 2, last year’s project was studied and broken down into pieces in order to see the weight distributions of the turbine and generator, and to see where any weight could be adjusted.

Table 2: 2012 Project Break Down

Turbine Blade System	1.32 pounds	30% of total mass
Pipe Base	.888 pounds	20% of total mass
Generator	2.2 pounds	50 % of total mass

From last year’s testing, the MQP team maxed out the kite’s lift ability at ten pounds. This called for the initial weight goal of the 2013 MQP turbine to be 10 pounds as well. The weight used in the 2012 MQP was a 10lbs sandbag, which was placed in the center of the tether. Once the kite had taken flight the weight was lifted off the ground, but began to oscillate up and down, not allowing the kite to reach its maximum altitude. Taking into account the issues presented from last year’s system, our design places the turbine directly underneath the kite, in order to optimize our lift and increase our weight capacity.

For many of the issues previously stated, last year’s turbine system could not produce 300 Watts of electricity; therefore the initial goal was 300W. While looking into the components of the system that could be improved, it was evident that a larger turbine would be necessary to produce 300W of power. However, when referring back to the breakdown of the last years MQP, any larger scale turbine would outweigh the 10 pound maximum.

4.2.1 Turbine Blades

The design of the blades is a large contributor to the amount of power that can be generated from the system. In order to maximize the power output we had to develop a new design for the turbine blades. There were three designs evaluated: the Darrieus Turbine, Savonius Turbine, and the Gorlov Helical Turbine (GHT). The Darrieus Turbine, as shown in Figure 16 below, has a number of straight blades/airfoils which allows slow flows to generate high torque (Gorban, 2011). As the first generation of its kind, it did receive praise for its increase in efficiency, as a cross-flow turbine compared to that of the propeller turbines, with an efficiency of 23.5 % (Gorban, 2011). The Savonius turbine with aspect ratios of about 5 could run at 25% efficiency (Alexander, 1978). Based on the three designs we decided to proceed with the GHT. The design evolved from the Darrieus turbine and capitalized on all of the advantages while eliminating the pulsations presented in the previous design. With the helical design each of the three blades revolve 120 degrees around the turbine axis, this arrangement places a portion of the blades at each degree of rotation. The arrangement of the blades increased the efficiency up to 35% and the durability of the system (Gorban, 2011).

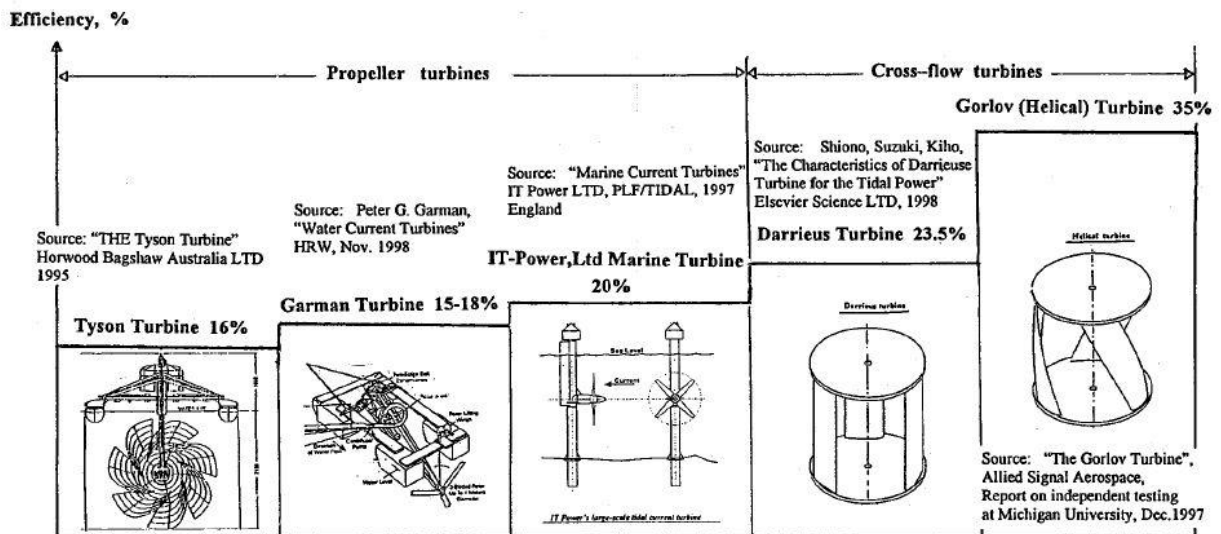


Figure 16: Turbine Efficiencies (Source: Gorban, 2011)

After deciding on the turbine system, the next step was to design a physical model in order to run small-scale wind tunnel tests and gather data. First off, we made some preliminary assumptions of the size of our turbine using turbine power output equations shown below, 5 1/4 ft. tall and 2 1/2 ft. diameter.

$$P_w = \eta P_m$$

$$P_m = \frac{1}{2} \rho A v^3$$

$$A = 5.25 \text{ ft} \times 2.5 \text{ ft} = 13.125 \text{ ft}^2 = 1.219 \text{ m}^2$$

$$v_1 = 20 \text{ mph} = 8.94 \frac{\text{m}}{\text{s}}$$

$$v_2 = 25 \text{ mph} = 11.176 \frac{\text{m}}{\text{s}}$$

$$v_3 = 45 \text{ mph} = 19.7 \frac{\text{m}}{\text{s}}$$

$$\rho = 1.225 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Voltage drop} = 5\%$$

$$P_{w1} = 186.7 \text{ w}$$

$$P_{w1 \text{ actual}} = 177.383 \text{ w}$$

$$P_{w2} = 364.7 \text{ w}$$

$$P_{w2 \text{ actual}} = 346.465 \text{ w}$$

$$P_{w3} = 2,000 \text{ w}$$

$$P_{w3 \text{ actual}} = 1,900 \text{ w}$$

The selection of the NACA 0012 over the NACA 4412, as seen in Figure 17 below, was due to the simplicity and symmetry in the airfoil. Since the NACA 0012 has no chamber, it can be efficient as its angle of attack is constantly changing over the turbine rotation.

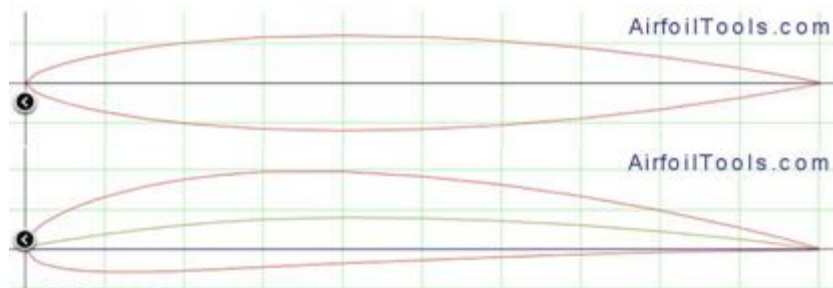


Figure 17: NACA 0012 [Top], NACA 4412 [Bottom]

The NACA airfoils are generated by an upper surface curve and a lower surface curve through equally spaced x-values. In order to sketch the airfoil into the program the coordinates were placed into an Excel sheet and saved as .pts file for Solidworks. The airfoil was now placed on the sketch and we proceeded by using the Helical Sweep command, while inputting the length of 5 ft. and a 120-degree rotation between blades. Finally, the feature was duplicated into three blades, as shown in Figure 18.

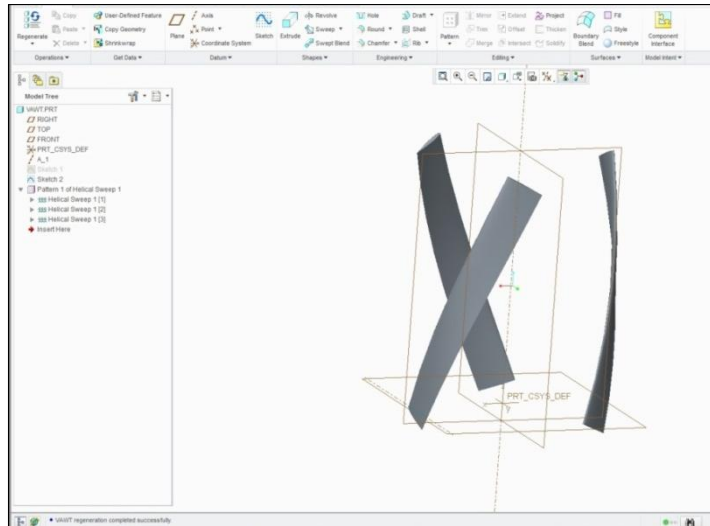


Figure 18: Creo Parametric Helical Blade Model

4.2.2 Turbine Prototyping

Initially the blades were created in Creo Parametric (Pro E) because of the familiarity of the user interface. Though the blades could be easily designed in this program the connection plates to hold the blades in place proved to be a challenge. After several attempts of creating the plates our team decided to convert our turbine blades to SolidWorks, as seen in Figure 19 below, and use this program throughout the rest of our project since there were no issues creating and recreating the plates and blades.

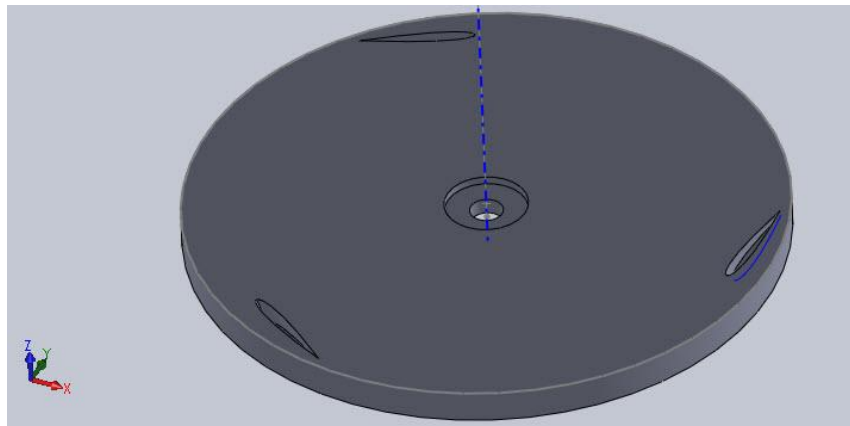


Figure 19: : SolidWorks model of turbine blade hub

We selected a NACA 0012 airfoil for the cross sectional area of the blade for its simplicity and performance. Using SolidWorks we created a helical blade design with a 120-degree twist. Using our CAD model and the Dimensioning Machine we were able to 3D print the prototype blades. The team consensus was to create a solid circular plate as shown in Figure 20 for the prototype but in the full scale design we would remove any excess material in order to decrease the total turbine system weight.

The connection plate was desinged in SolidWorks by extruding a disc into the top and bottom of the blade array. A Boolean function was then used to remove the material occupied by the blade array, creating three pockets on each plate which can be seen in Figure 20. Bore holes were then placed in the centre of each plate to allow the connection of the turbine to the threaded rod.

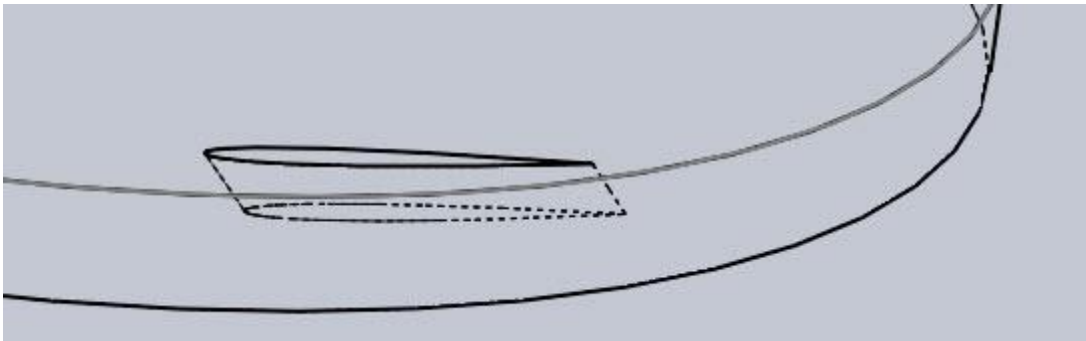


Figure 20: Curved blade connections

Our initial thought was to make the plates out of plexiglas because of the strength, durability and low cost of the material, which is desired for testing in the wind tunnel. If any failure of a component occurred it would be the blades not the connection plates. The strength you would like to observe is of the blades and how they withstand the changes in wind speed. Unfortunately the complexity of the blade curvature did not allow us to use any of the conventional cutting machines (CNC, etc.) this was due to the fact that our plates required an undercut due to the helical sweep, which is nearly impossible to achieve on any of these machines. This machining incapability resulted in a decision to create the plates via the Dimension Machine (DM). The final prototype was made using WPI's DM and ABS plastic for the material as shown in Figure 21.

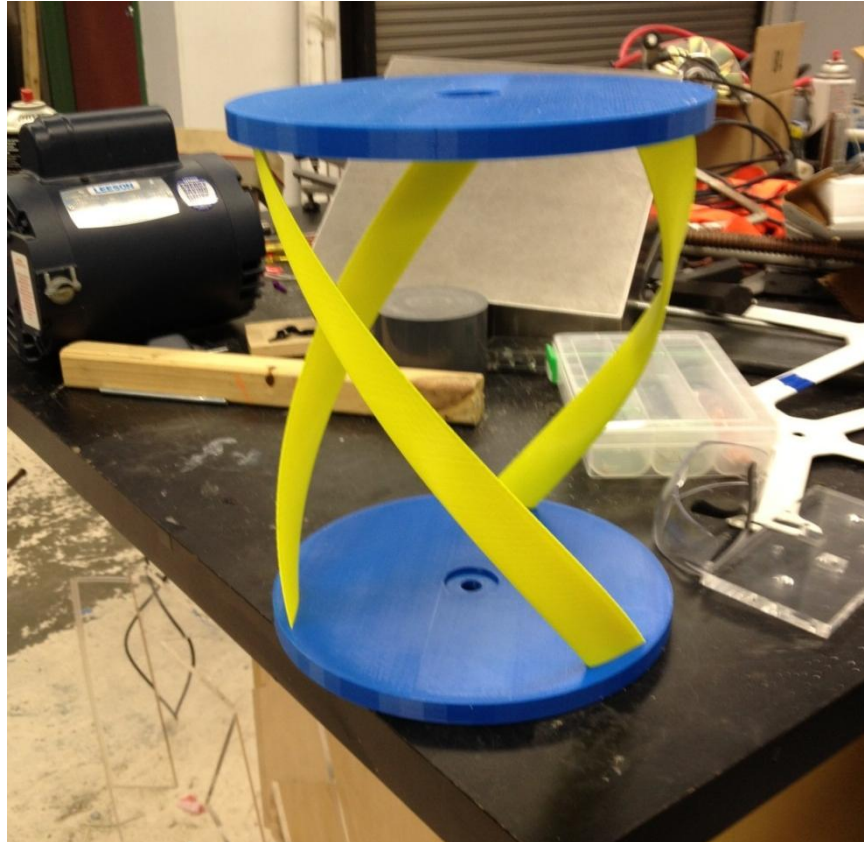


Figure 21: Turbine blades and hub

In order to test in the wind tunnel, it was necessary to design a set up that would allow for the use of a turbine testing system that was being used by other MQP projects, which will be described in more detail in a later section. Using SolidWorks, two collars were designed that could fit over the threaded rod used to secure our turbine as seen in Figure 22.



Figure 22: Turbine set-up collars

These collars would allow us to lock our turbine in place using a threaded rod and a set-screw, and modify our setup to be tested in the wind turbine. After these pieces were designed we were able to begin our testing in the wind tunnel. Due to unreliable equipment that was intended to output power, torque, and vibrations, testing was only able to produce RPM's and turbine cut in speed. By analysing this data alone it was apparent that the turbine needed to be altered in order to operate at maximum efficiency.

It was determined that the cord length needed to be increased to create a greater blade area. This was achievable in two different ways: increase the blades while keeping the swept area constant or keep the blades the same size and decrease the swept area. The latter was chosen because of the size constraints of the DM and difficulties with the scaling of the helical blades in SolidWorks. This new model was then drawn up in SolidWorks and sent out for printing. The results can be seen in Figure 23 below.

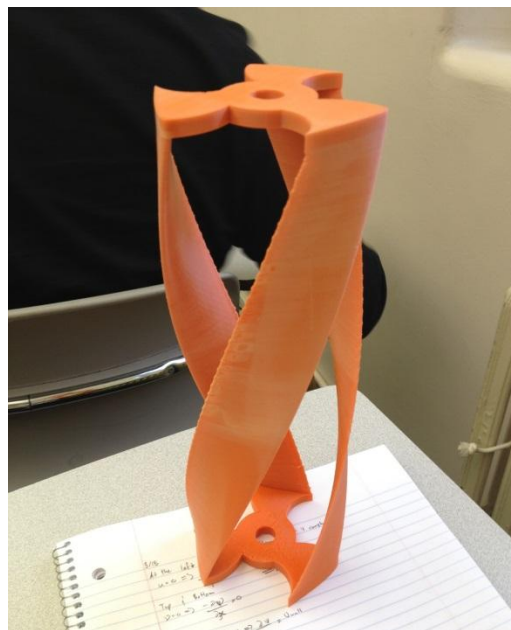


Figure 23: Prototype Mark 2

The Mark 2 Prototype, as seen in Figure 23, was then tested in the wind tunnel to determine if the increase in blade surface area resulted in an increase in performance. Initially the turbine was connected to an RPM meter and a large DC motor in order to determine power output however, the start-up torque of the DC generator was too large for the turbine to overcome. Since the swept area was decreased for the Mark 2, the turbine diameter was lower which in turn lowered the possible output torque. To continue the experiment, the turbine was

tested with just the RPM meter and a bearing. This resulted in high RPM's at very low wind speeds and low cut-in speeds; showing significant performance improvements from the original prototype.

4.2.3 Wind Tunnel Testing Set-up

With the scaled turbine created out of ABS plastic we needed to test it to ensure performance capabilities based of theoretical calculations. Also because the flow fields of vertical axis wind turbines are very complex many factors are hard to calculate and must simply be estimated and then proven in testing such as cut in speed. The turbine helical blades should increase performance by minimizing pulsations to create a more constant torque and fluid rotation speed. Some of the variables that were to be collected in the wind tunnel included power output, torque, rotations per minute (RPM), cut in wind speed, unwanted vibrations or dynamic issues and blade efficiency. To test these factors the team will use a set-up used by other wind MQP turbine teams in the wind tunnel.

The wind tunnel test set up was in WPI Higgins Laboratory Fluids Lab; the turbine was attached by a threaded rod at the top with a generator and the bottom with an rpm meter. These devices are securely fastened through openings in the wind turbine on the top and bottom of the wind tunnel. The turbine is attached to the generator and rpm meter with a half inch threaded rod with custom made collars on each end with setscrews to secure the collar to the devices. The generator is a 443540 Low RPM Permanent Magnet DC Generator and is attached to the wind tunnel as depicted in Figure 24 below.



Figure 24: Wind tunnel generator

The turbines were held in place by nuts and washers on either side of the top and bottom support plates. The rpm meter is measured through a Texas Instrument DAQ box. The generator voltage is measured through a Labview vi. and current is measured with an ohmmeter. The wind tunnel was run from 5 to 40 mph in 5 mph increments and data was collected for each increment.

The full test set up can be seen below in Figure 25. The generator or bearing were attached at the top of the wind tunnel and RPM meter at the bottom with the custom collars. The threaded rod runs through the middle of the turbine which is secured via washers and nuts on the top and bottom plates.

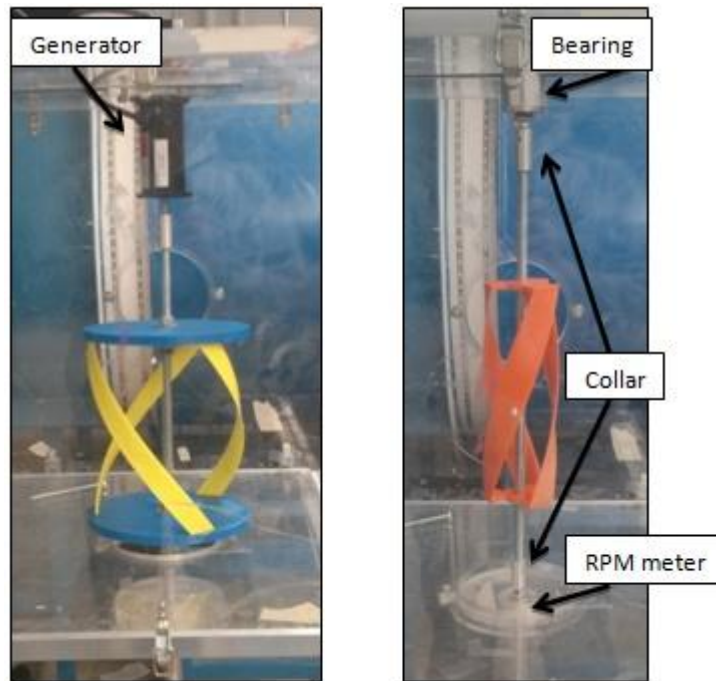


Figure 25: Turbine test set-up

4.2.4 Materials Choice

For the full scale model the largest design limitation was weight, calling for a lightweight material to be used in the turbine construction. Aluminum is cheap, easy to machine, and readily available which would make it an ideal material choice. However, given the weight constraints, using aluminum would not allow for the kite to rise into the air, causing the project to fail. At this point, carbon fiber reinforced polymers, as well as glass reinforced fiber polymers were assessed.

Carbon fibers are an ideal material to use for building our turbine. One of the reasons is the high tensile strength to weight ration. Strength of a material is the force per unit area at

failure and any material that is strong and light has a favorable strength/weight ratio. Materials such as aluminum, titanium, magnesium, carbon and glass fiber, high strength steel alloys all have good strength to weight ratios. However, in this case, the weight of the material is the main concern. Aluminum has already shown to be too heavy for this application, as well as titanium and steel. The young's modulus of carbon fibers reinforced plastics is 181 GPa, while Glass reinforced Polymers are 40-45 GPa, and aluminum in 69 GPa (CES EduPack).

Carbon fibers have a high resistance to fatigue, which is a more important stress factor than tensile strength since centrifugal and compressive loads will be well within the strength envelope. One application that is important however is that carbon fiber, as well as glass fiber, resists salt water, chemicals, and the environment. It is virtually unaffected by acid rain, salts, and most chemicals (NASA).

Although it offers advantages of strength, rigidity and weight reduction, cost can be a deterring factor. Unless the weight advantage is exceptionally important, it often is not worth the extra cost; however, keeping a low weight is our main goal. The low maintenance requirement of carbon fiber is a further advantage. While it is important that the cost remains low since this is for a third world country, it is also vital that repeated repairs are not necessary, leaving the need for a quality material such as carbon fiber. Research has shown no loss of laminate properties after 30 years of weathering.

4.2.5 Support System Design Alternatives

Some of the preliminary designs that were considered included a modified yolk system. The turbine would hang from a certain distance from the kite, allowing it to hang, with a type of retractable arm, even made simply of nylon in order to prevent swinging. We also planned on a support system around the tether to keep the turbine from swinging into the kite tether and becoming tangled and unusable.

The most efficient design alternative would be hanging the turbine directly under the kite, however not interfering with the wind flow to the sled kite. It would be supported by 6-8 tethers on top that would connect to the leading and trailing edges as well as a center hub above the turbine, and two tethers below that connect back to the main tether line. Having the turbine hang so closely to the kite would allow us to gain more lift and allot us more weight, this system can be seen in a preliminary sketch below in Figure 26.

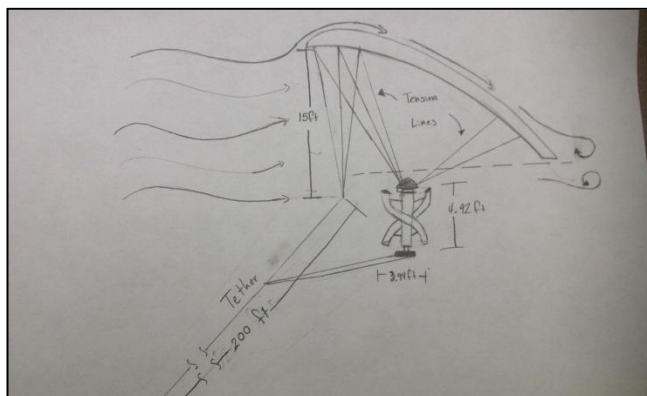


Figure 26: Preliminary Lift System

Once at high altitudes, the lift system will produce necessary lift for the turbine weight. One of the problems is the initial lift to get the kite to the altitude we need. So to combat this attaching weather balloons to the kite will assist in the initial lift. Once the kite is up in the air, the ideal situation would be that the kite would be able to stay in the air, without the balloons, due to the more constituent wind speeds at high altitudes.

4.2.6 Generator Selection

Selection of a generator is the most difficult and most vital part of the airborne turbine design. While regular grounded turbines may choose from a variety of turbines that apply to their rated wind speed, RPM and power outputs, and are not restricted to weight limitations, it is our most vital design parameter. Several generators have been considered, all with some problems that do not fully fit into our ideal specifications. Some of the generators considered were: Aeoles generator, WindBlue, WindyNation, and Windzilla.

The Aeoles generator was part of a full turbine, which was upwards of \$1000, we contacted the company to see if we could purchase just the generator but our inquiry was not answered. The WindyNation turbine produced about 1000W of power, more than enough, but was on the heavy side, about 10lbs. The Windzilla turbine produced about 250W and weighed only 5lbs, however the RPM required to produce 250W was around 2500. This would require the use of a gearbox which would add that much more weight. The last, WindBlue turbine is similar to the WindyNation in power output and weight; however it is already available in our lab as a turbine they've used in previous projects. We will use the WindBlue turbine for initial ground testing and continue our search of a better generator, however the power to weight ratio we need may not be in production of current generator technology, especially not at a commercially available state.

4.2.7 Transmission Cable

In order to transfer the maximize amount of electricity from the turbine to the power storage unit it is imperative to select the appropriate wire gauge for transmission. This is determined by the maximum current produced by the generator, which in the case of the Wind Blue alternator is 40 amps at 2000 RPM's (www.windbluepower.com). The required operating voltage of the power storage unit needs to be sourced, in our project the power storage unit, from the 2008 Kite Power IQP, drew 24 Volts. Using cable length, maximum amperage, and operating voltage the proper wire gauge can be selected via a table (www.southwire.com).

It was determined that the best option for the current generator configuration was using a 4/0 gauge wire with a stranding of 19. This gauge limited the resistance while transmitting the electricity and the larger number of strands allows for greater flexibility in the cable. This flexibility is ideal for a kite wind turbine due to the constant shifting of wind direction. The transmission cable selection is shown in Figure 27.



200 ft	24 Volts/40Amps	Cable size	Lbs/100ft
(Copper)	24V DC chart	4/0(19stranding)	65.33

Figure 27: Transmission Cable Selection

4.2.8 Design Restrictions

The goal of this year's MQP is to re-design a high altitude turbine that is to be flown at a minimum of 1000 feet in the air. The designated testing site was located in Seabrook, New Hampshire. The beach is very narrow and at times densely populated, thus limiting the testing capabilities to a maximum elevation of 100 feet. This inhibits any high altitude testing that would yield valuable data. Testing at the beach's maximum elevation leads to the same issues encountered by pole mounted wind turbine.

The first beach testing was performed in early October in order to get acquainted and comfortable with the kite. This testing showed the power behind the kite at high wind speeds, allowing the study of the measurements and the build of the kite so that future developments could be more informed. After this testing, the realization was made that there is not a way to get both a 300 W output, and stay under ten pounds, which was the limitation set by last year's MQP group.

Another major restriction is the amount of money allotted for use. Everything that is to be done must be a quality product; while fitting into a strict budget. The material chosen was carbon fiber because of its low density and high strength, but the ideal mechanical properties proved to be costly. After the material was selected, it was necessary to investigate other sled kites in order to produce more lift. This could be achieved by increasing the size of the kite since the area of the kite is directly proportional to the generated lift.

The last design restriction would be the use of helium. There has been multiple attempts to incorporate helium balloons into the design; however it is difficult to make a balloon without the resources available at WPI. Also, the cost of helium is extremely high, making it difficult to keep the cost down.

5.0 Wind Turbine Cost Analysis

After scaled initial testing was completed, manufacturing and implementation of a full scale system is unfeasible at this point due to cost constraints. In order to gain funds to further the project into full scale production a cost analysis of a theoretical scaled system is necessary to justify required costs. This analysis will walk through each component in the full airborne turbine design, its material and manufacture cost, and justification of these expenses. Below is a summary of the system components, their cost and the total cost of the whole system.

5.1 Support System

Due to the nature of a kite wind turbines design it is impossible to mount the turbine and generator directly to the kite and tether, as the spinning of the turbine would cause the tether to twist. In order to overcome this design flaw a support system needed to be designed in order to allow the turbine to spin while keeping the generator stationary. This was achieved with an aluminium structure that surrounds the turbines as seen in Figure 28. It was designed for the full-scale turbine and has a projected weight of 22.86 pounds. This structure allows for some flexibility by being able to accommodate multiple lifts system. The cost of such a system including material and machining expenses would be \$1,226.18. As this is a crucial part of the overall system these expense are unavoidable and may even be greater than projected if the overall strength of materials is not sufficient to handle the load presented by both weight and wind speed.

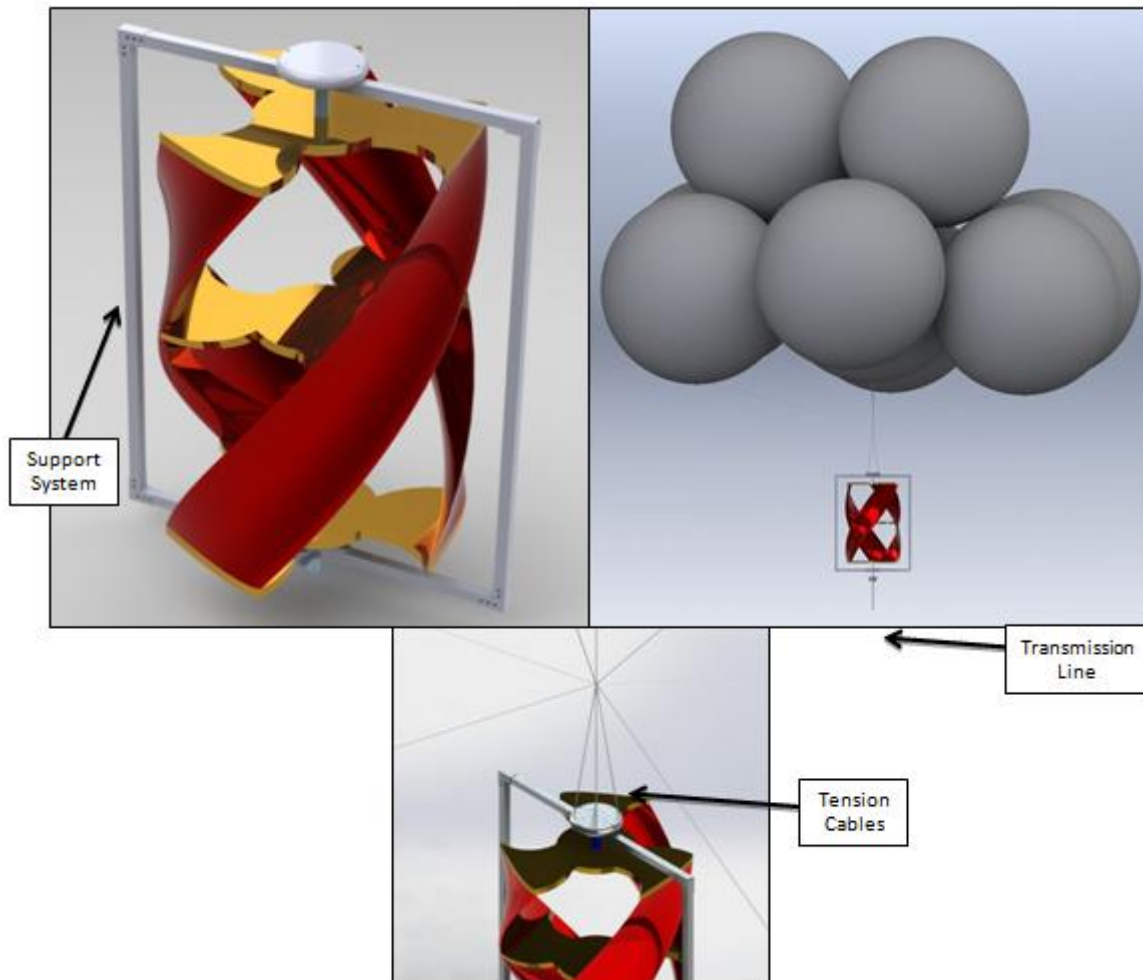


Figure 28: Support system and connection lines

5.2 Lift System

The final total turbine system weighed in at 256 pounds. The lift system was designed to have a factor of safety of 2 due to the close approximation of residential homes. Therefore the lift must equal the total turbine weight times the factor of 2. The equation for lift is:

$$L = 1/2\rho V^2 AC_L$$

The total turbine system included the generator, turbine, transmission cable and support system. The only feasible lift options were a hybrid kite/weather balloon system or a complete weather balloon dependant apparatus.

Table 3: Total Turbine System Weight

Generator	15 pounds
Turbine	76.7 pounds
Transmission Cable	135.66 pounds
Support System	22.76 pounds

An average size balloon is about 1 foot in diameter, and holds 14 Litres of helium. A study done at the University of Hawaii showed a balloon with a 12 ft diameter, which holds a volume of 25,622.05 liters or 905 cubic ft of helium, was able to lift 50 pounds. Another study done by an airship operation company was the net lift per 1000 cubic feet as shown in Table 4. A governing equation for net lift of a balloon is:

$$Net\ Lift = (\rho_h - \rho_{air})V - W_{balloon}$$

Table 4: Hydrogen VS Helium Lift (Airships.net)

	Weight of Lifting Gas (per 1,000 cu. ft.)	Weight of Air (per 1,000 cu. ft.)	Net Lift (per 1,000 cu. ft.)
Hydrogen	5.31 lbs	76.36 lbs	71.05 lbs
Helium	10.54 lbs	76.36 lbs	65.82 lbs

Scientific Sales INC sells a balloon called the 8247 Weather balloon of a 12.5 ft. diameter, with a capacity of 985 cubic ft. The cost of this balloon is \$395.00. The cloud-buster

weather balloon holds 268 cubic ft. and has a net lift of 15.5 lbs. The design system would need at least 4 balloons, at \$66.00 per unit.

The company, Airgas.com quoted the helium and hydrogen for our design. The price for a 300 cubic ft. tank of helium is \$235.08. For hydrogen, the 300 cubic ft. tank costs \$83.57.

Table 5: Price Options of a Balloon System

Company	Product and Quantity needed for 500 lbs of lift	Total Price for 500 lbs of lift
Scientific Sales INC	8247 Weather Balloons cu. ft. 10	3920.00
Balloons Direct	Cloud Buster cu. ft. 40	2640.00
Scientifics Online	16 Foot Balloon, 100 cu. ft. 90	7200.00
Hydrogen	Tank 300 cu. ft. 30	2500.71
Helium	Tank 300 cu. ft. 30	7050.00

Hydrogen and helium both have a tendency to leak out of standard balloons after about 48 hours. This is due to the material of the balloon being porous and the atoms of helium and hydrogen being extremely small (Sensistor Technologies, 2013). The life span of the balloons researched in Table 5 range from 3-6 months. The six months would be for dryer, warmer conditions with minimal temperature changes. The three month life span is assumed since the tests and application would be located by seawater with varying weather conditions, which weakens the material of the balloons quicker (Scientific Sales INC, 2013).

As previously stated the total weight of our turbine system was 256 lbs. Since there is no experimental data of how much our kite/balloon hybrid system can lift, we applied a factor of safety of 2. Therefore, our system must be able to lift 500 pounds all together. Combining the two lift systems required us to analyse the most efficient way of achieving our weight goal.

After analysing the three possible lift systems consisting of solely kite power, kite/balloon hybrid power, and a pure weather balloon system, it was concluded the balloon system was most feasible. The advantage of only having a kite would be the directional stability it presents to aid the turbine in facing orthogonally to the wind, while this may be beneficial to horizontal axis turbines due to the nature of our vertical axis turbine it does not require this

feature. In order to generate the required lift for the system it would call for a larger kite. This proves to be an issue due the fluctuation of wind speeds. The kite/balloon hybrid system is not practical since the turbine does not require a reorientation by the kite, which would be the only function of the kite in this system. Based on the analysis of each lift system, the weather balloon configuration is the most feasible and practical option for the design.

5.3 Generator

To generate enough power to be used in developing nations, a 300W system was initially analysed and viable generators researched. The ‘windblue power alternator’ weighed 12lbs and generated more power than our projected goal. This generator was also purchased in a previous MQP and is available for use on this project allowing no cost. The full weight of the airborne system is the largest limiting factor, so if the total weight is too great, a lighter turbine in our initial power range may need to be purchased. However our lift analysis takes into account the 12lb heavier weight of this generator and its higher power output is an added bonus to the system.

5.4 Turbine

Using the desired turbine blades the group scaled up the design in order to get accurate quotes of the full scaled turbine. Taking into account the total weight of the kite turbine system it was deemed necessary to reduce weight of the system components. The initial material choice for the design was aluminium because of the relative low cost and the ability of our blades being manufactured in the available machine shop. This would reduce the overall dependence on an outside manufacturer and cost of the project. Unfortunately the aluminium was projected to be too heavy for the lift system therefore another material had to be selected. The next logical choice for a material was carbon fiber due to its high tensile strength and low density properties. Using carbon fiber would vastly reduce the weight and eliminate any stress of the blades failing during flight or impact with the ground. After making the selection of material the team sent the final full scale model to various carbon fiber manufacturers to assess the cost of our design. While only one company has returned with a quote the estimated cost of production is so high that pursuing quotes from other companies seems fruitless. The company that completed the quote for the turbine estimated a total cost of \$119,000.00 for one turbine. Translating into an unfeasible option for low cost power production.

5.5 Power Generator Transmission and Storage

After the turbine has generated mechanical energy and passed it through the generator, the following step is to harness the electrical output of the wind turbine. The existing battery storage system to be used was developed and built by a previous IQP in 2008 (Baldwin et. al., 2008). The electrical storage unit is comprised of three systems, the battery bank, a primary system, and a secondary system. The ideal power generation and consumption over a period of time was determined using a table identifying the differences in battery choices. Analyzing the various choices in electrical storage resulted in using “Deka/MK AGM batteries with 12 volt potential and 32.5 Ah capacity per battery with a total of 8 batteries comprising the bank (Baldwin et. al., 2008).” The primary system is designed to undertake loads and undercharge protection for the battery bank. It is comprised of a Xantrex Trace 3624 inverter, shunt resistor, usage meter, and an AC circuit breaker box. The design intent for the secondary system is to handle overcharge protection and is comprised of a charge controller, safety switch, and an electric load divider. The system was developed to satisfy the energy needs for extended periods of time in order to demonstrate various scenarios of energy consumption. It was determined the required energy would be “approximately 600 watts for 5 hours or 300 watts for 10 hours depending on the magnitude of the load (Baldwin et. al., 2008).” Using those numerical values the watt-hours was approximately 3000 and the amp-hours to be 130 amp-hours for the 24 volt system (Baldwin et. al., 2008). Properly recreating the electric load system designed in the 2008 IQP required a review of the cost analysis provided in the report. The cost of each component and overall cost of the system is detailed in Table 6 below. The electrical and storage system developed by Baldwin et. al., (2008) in an IQP project will be reused including the inverter, battery monitor, shunt, circuit breaker box, and battery terminal connector cables. The ground power storage unit will be connected to the kite generator via a 200 foot 4/0 gauge 19 strand copper wire with a nylon jacket and PVC insulator. This transmission cable weighs 65.33 lb/ 100 ft, resulting in a 130.66 lb load on the kite support system.

Table 6: Cost Analysis of Power Storage Unit (Source: Baldwin et. al., 2008)

Item Component	Cost
Deka/MK Battery 8AU1H (T873) AGM, 12 volt 32.5 Ah	\$691.72
Inverter - Trace 3624	\$1,195.00

500A-50mV Shunt	\$21.50
Battery Monitor - Trimetric Monitor	\$194.00
Wiring - #2 gauge battery connectors and between other components	\$199.75
AC Circuit Breaker Box	\$83.00
50 Amp, 250 VAC/ 125 VDC Class R Fuse	\$50.90
Heating elements - Two pack of #SJH126002 - for 12 volt systems- 7" model	\$77.85
Morningstar Tristar Ts-60, 60A Chg Ctlr	\$184.00
Morningstar Tristar Dm Digital Display	\$90.00
Battery Terminal Connector 3/8" UL Listed Anti-rotational Lug, 2 Wire Gauge x10- 7106K94	\$48.30
Safety Switch: 2 DPST, 3-Wire 60 10 15.7" x 6.6" x 5.1" 7524K22	\$81.45
Miscellaneous (plywood, wire, connectors, loads, etc.)	\$350.00
Transmission Cable 4/0 gauge 19 strand (500 ft spool)	\$3,689.00
Total System Cost	\$6,956.47

The designed power being produced from this system is 300 watts for 10 hours, which is the goal of our kite turbine system. Therefore the cost calculated above is accurate to proposed electric storage unit. Assuming the airborne wind turbine produces the energy theoretically calculated, the system will provide relative low cost electrical power and long term sustainability for its users.

5.6 Cost Benefit Ratio

The cost of the airborne wind turbine was normalized over a 20 year life span, since that is the average life span of most wind turbines, in order to calculate an accurate payback period for the initial investment. The initial investment required for this turbine system is \$134,000, which includes a lift system, support structure, turbine, generator, and a transmission apparatus. The system would require a quarterly maintenance to replace the lift system due to degradation of the weather balloons and leakage of hydrogen gas. The maintenance cost results in an additional \$26,000 per year. The energy savings produce by the airborne turbine system, under

ideal operating conditions, is \$2,628. The value was generated using the average USD/kW. Therefore over its 20 year life span the system would never recoup the initial capital cost. The total estimated cost over the 20 years would be \$595,000. Even under ideal operating conditions the system is not economically feasible because the power production will never exceed the yearly maintenance cost.

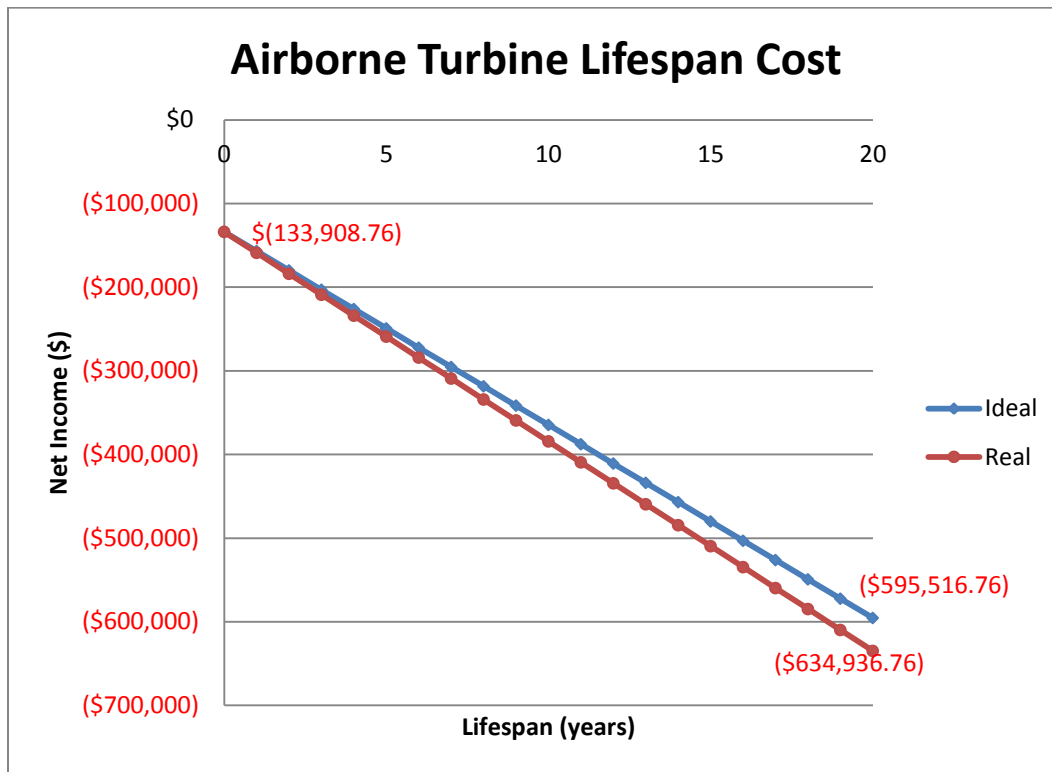


Figure 29: Airborne Cost over Lifespan

5.7 Cost Benefit Ratio of Alternative System

Taking into the unfeasibility of the airborne system, it was deemed necessary to create an alternative design that would meet the project specifications. The underlying cost factor associated with the airborne system was weight constraints, thus leading to necessary use of high cost materials and lift systems. In order to overcome this weight issue the most practical solution was to mount the turbine system on a pole, which enabled the system to use cheaper and heavier materials. By not having to accommodate weight the design allowed for a larger generator, which would produce more energy. The initial cost of the pole mounted turbine system is \$21,000, with nominal maintenance cost. Assuming a 15 kW generator is used; the power

savings generated would be \$5,000 per year, resulting in a payback period of less than 5 years. The cost breakdown of the pole mounted system is shown in Table 7.

Table 7: Pole Mounted System cost breakdown

Pole Mounted	
Pole (17")	\$ 5,580.00
Generator (15kW)	\$ 7,500.00
Turbine (A1)	\$ 3,760.00
Power Storage	\$ 3,366.00
Transmission (100ft)	\$ 731.00

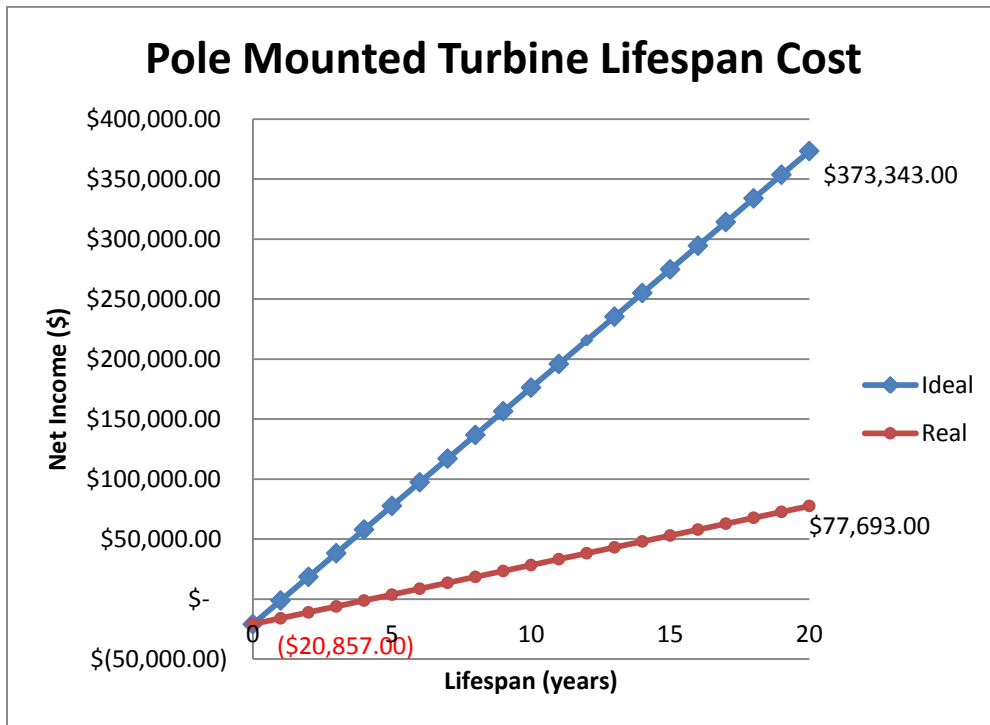


Figure 30: Pole Mounted Cost lifespan

6.0 Water Pump Testing/Results

6.1 Laboratory Testing

Laboratory testing involved the entire performance of the water pump system without the kite powering the rocking arm. This was to familiarize the project team with the water pump system as well as to test the workings of the different individual mechanisms of the entire

system. This was especially true for the repaired head simulation valve and the new ground string and latching system additions that attached to the sliding weight mechanism.

Once assembled, the team used weights on a pulley and muscle power to simulate the force of the kite on the rocking arm. The weights used were approximately 80 pounds on the rocking arm upstroke and 40 pounds on the arm downstroke to mimic anticipated kite tether forces (Cartier et al., 2010). The water pump was capable of pumping water, but the head simulation valve did not demonstrate a change in pressure when adjusted. The sliding weight mechanism was capable of performing the latching and unlatching cycles. It was confirmed that the new latching mechanism worked properly even if a simulated, by use of the pulley system, tether tension load of approximately 30 pounds was applied to the sliding weight mechanism. However, the latch string occasionally became tangled on the rocking arm. Further, an attachment weakness was found in the base of the ground string, where the high amount of stress broke a key ring that linked the strap and spring of the ground string. Based on the results of laboratory testing, we made adjustments to the water pump system in preparation for beach testing.

6.2 Beach Testing

On April 7, 2013 the kite powered water pump team was able to test the full water pump system at Seabrook Beach, New Hampshire. The weather for the day was quite good for kite flying, with constant winds from 10 to 15 miles per hour at ground level with gusts of up to 25 miles per hour. Preparations included digging a 5 foot deep hole to act as a temporary well, assembling the rocking arm, and attaching safety anchors to the A-frame itself as well as the rocking arm to keep it from moving out of control in higher winds and allowing adjustments as the kite was in flight.

With the well filled with a bucket of water, preparations were complete and the kite was launched. Further adjustments to the stalling line, latching system, and ground string were performed to attempt to create a periodic the motion of the rocking arm. The adjustable weight on the end of the arm was set to 10 pounds for most of the testing. Attempts were also made to keep the latch string from getting caught along the side of the arm, including installing a guiding eye bolt atop the rocking arm.

Periodic motion of the rocking arm was obtained. Occasional high wind gusts could overpower the weight on the rocking arm and prevent the arm from lowering. Low wind speeds

prevented the arm from rising high enough, thus the sliding weight mechanism did not reach the latch position. However, during wind speeds between 10-20 mph, the rocking arm achieved perfect periodic motion. The ground string successfully pulled the sliding weight mechanism to the latched position, the kite stalled, the rocking arm lowered, and the sliding weight mechanism was released, the rocking arm was lifted, and the cycle repeated. The complete water pump system can be seen in Figure 31 below.



Figure 31: Kite-Powered Water Pump System with Rocking Arm Down

As for pumping water, the pump was successful at drawing water from the 5 foot depth. Figure 32 is a snapshot of the system pumping water.



Figure 32: Snapshot of Kite-Powered Water Pump System Pumping Water

The head simulation valve was not considered, as the main goal for the day was to achieve the periodic rocking motion and pump water autonomously with the system. Over a 20 minute time interval, 4 gallons of water were pumped. For a volumetric flow rate of 48 liters per hour or about 1200 liters per day, enough water would be supplied for about 25 people per day in a developing nation. Videos and pictures of the testing can be found at <https://www.dropbox.com/sh/dps0gxm18s01wra/5kJATajS9X>.

6.3 Scale Kite Model Testing

A scaled kite model of the full size kite was made to simulate airflow in order to calculate the lift and drag of the full size kite. First the dimensions of the model kite were determined by calculating the aspect ratio. We also had to take into consideration the size of the wind tunnel, which limited maximum size of the kite while still producing accurate data. The width of the wind tunnel was 24 inches, and a distance of 8 inches on either side of the model kite was required to produce the accurate data, therefore the maximum width of the model kite was 8 inches. Using this as our constraint, the rest of the dimensions of the model kite were obtained.

6.3.1 Full Size Kite

The dimensions of the full size Power 81 sled kite were measured using a tape measure, and are displayed in Figure 33 below.

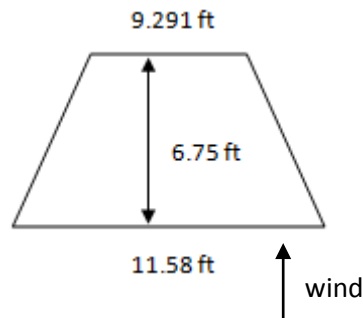


Figure 33: Full size kite dimensions

The aspect ratios were calculated as follows:

$$AR_{bottom} = \frac{11.58 \text{ ft}}{6.75 \text{ ft}} = 1.716$$

$$AR_{top} = \frac{9.291 \text{ ft}}{6.75 \text{ ft}} = 1.376$$

The maximum width of the model kite is 8 inches = 0.667 ft. Using this value, the chord length of the kite was first calculated.

$$AR = \frac{\text{bottom}}{\text{chord}} = 1.716 = \frac{0.667}{\text{chord}} \rightarrow \text{chord} = 0.3885 \text{ ft} = 4.66 \text{ inches}$$

$$AR = \frac{\text{top}}{\text{chord}} = 1.376 = \frac{\text{top}}{0.3885} \rightarrow \text{top} = 0.535 \text{ ft} = 6.4 \text{ inches}$$

Based on the calculations, the dimensions of the model kite are shown in Figure 34.

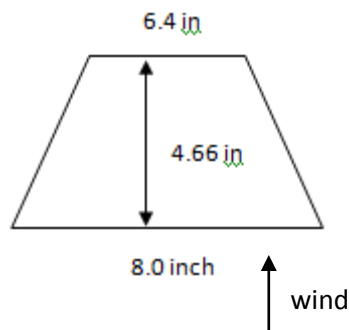


Figure 34: Model kite dimensions

6.3.2 Model Kite

The model kite, Figure 35 in below, was constructed using ripstop nylon a carbon fiber frame, and a wooden and aluminum rod for the mounting segment.



Figure 35: Model Kite

The wooden rod had a length of 4", and an outer diameter of 7/8" and an inner diameter of 1/2" cut 1" deep. The other end of the wooden rod, which does not have a whole through it, was tapered using the sanding machine in the Higgins Lab machine shop. The aluminum rod was inserted into the wooded rod to be mounted in the wind tunnel. The aluminum rod had a length of 1 7/8", an outer diameter of 1/2", an inner diameter of 3/8", and 1/8" inch hole, 1/4" from one end of the rod. This small hole fits a screw which helps secure the kite on the mount in the wind tunnel.

6.3.3 Preparation

In order to keep the ratio of the inertial and viscous forces consistent between the full size and model kite, the Reynold's numbers were the same for both kites. This value was calculated to determine the speed of the wind tunnel to accurately test the model kite. One obstacle we ran into was that the wind tunnel was not able to run at the high speed we required. Therefore we set the wind tunnel to a lower speed, within the range of the machine, to simulate the flying of the kite. The calculation was found at sea level conditions.

$$Re_M = \frac{V_M \cdot c_M}{\nu_M}$$

where: V = velocity = 6 mi/hr = 8.8 ft/sec
 c = chord length = 6.75 ft
 ν = kinematic viscosity = 1.57×10^{-4} ft²/sec

The velocity of the wind tunnel to test the model kite was determined by inputting the new dimension of the model kite chord length.

After calculating the Reynold's number of the full scale kite, the velocity of the wind tunnel to test the model kite was determined by inputting the new dimension of the model kite chord length. The calculations are shown below.

$$Re_P = \frac{V_P \cdot c_P}{\nu_P} = \frac{(8.8) \cdot (6.75)}{(1.57 \times 10^{-4})} = 378,344$$

$$Re_M = Re_P = 378,344$$

$$Re_M = 378,344 = \frac{V_M \cdot c_M}{\nu_M} = \frac{V \cdot (0.3885)}{(1.57 \times 10^{-4})}$$

Solve for V_M to obtain:

$$V_M = 153 \text{ ft/sec} = 46.3 \text{ m/s}$$

6.3.4 Data Collection

Our team performed wind tunnel testing using the wind tunnel in Higgins 016 Fluids Lab. We connected the force balance to the data output box, which displayed the normal and axial forces, pitching moment, and angle of attack. We ran the wind tunnel at 46.3 m/s and varied the angle of attack to obtain the parameters necessary to calculate the lift and drag coefficients and quarter chord moment of the model.

The correlation of the lift coefficient with the angle of attack is represented in Figure 36 below. At an angle of 0° the coefficient of lift is smallest because this is where the least amount of lift is generated. Since the shape of our model kite airfoil is symmetric about the horizontal plane (top surface and bottom surface are the same) the lift coefficient increases as the angle of attack is altered in both the positive and negative direction.

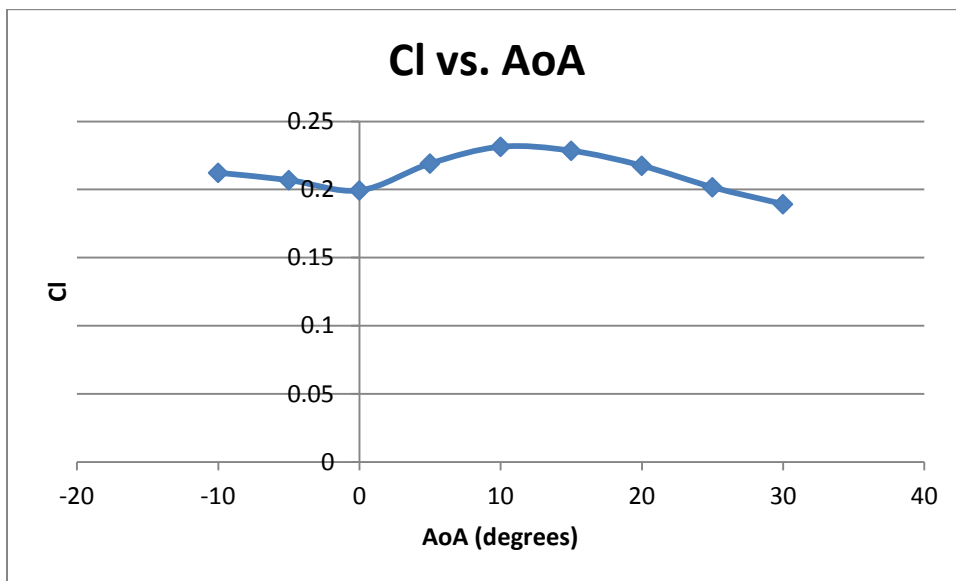


Figure 36: Lift Coefficient vs. Angle of Attack

The relation between the lift and drag coefficient are represented in Figure 37 below. The maximum lift is created when the drag coefficient is 0.09.

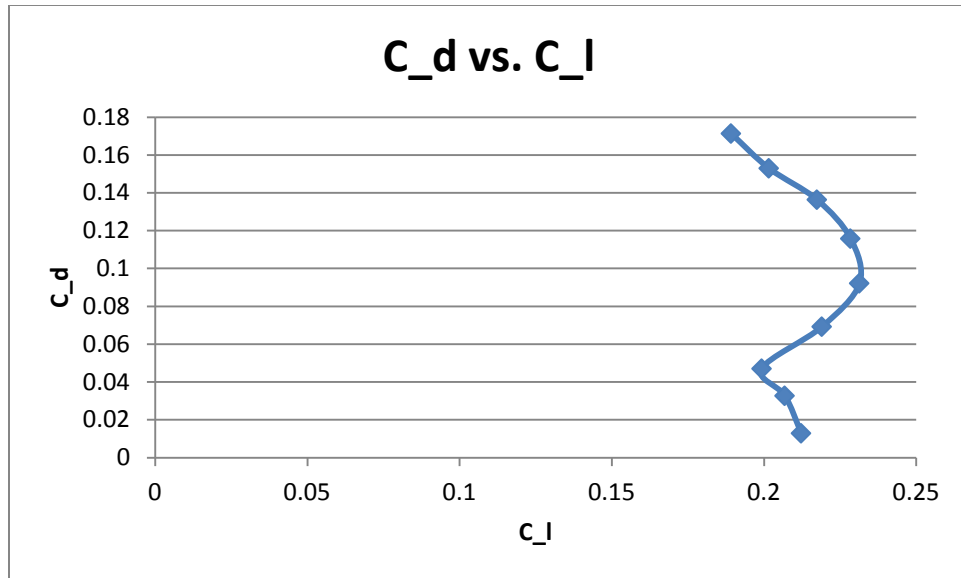


Figure 37: Drag Coefficient vs. Lift Coefficient

Figure 38 below represents the quarter chord moment coefficient in relation to the angle of attack. We can see that as the angle of attack increases, the $C_{m_c/4}$ increases up until around 15° . After this point the $C_{m_c/4}$ begins to decrease.

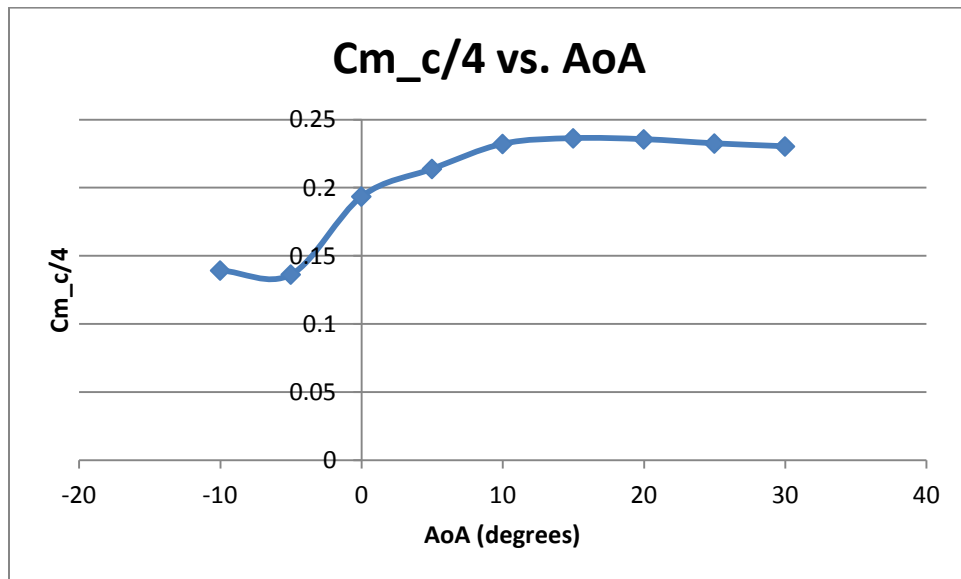


Figure 38: Coefficient of the Quarter Chord Moment vs. Angle of Attack

Table 8 is the data that was collected from our wind tunnel testing.

Table 8: Data Obtained During Wind Tunnel Testing

alpha (deg)	M P (lb-in)	N (lb)	Axial	Pressure
-10	25.22	5.8	1.39	0.05
-5	24.83	5.7	1.42	0.05
0	32.32	5.59	1.32	0.05
5	34.97	6.29	1.4	0.05
10	37.37	6.84	1.42	0.05
15	37.91	7.03	1.48	0.05
20	37.81	7.04	1.51	0.05
25	37.41	6.94	1.5	0.05
30	37.13	7	1.51	0.05

Table 9 below is the parameters of the kite that were calculated based on the data collected from our wind tunnel testing.

Table 9: Parameters of Kite Calculated Based on Data from Wind Tunnel Testing

M c/4 (lb-in)	M LE (lb-in)	X CP (in)	M 3c/8	Lift	Drag	C _l	C _d	C _{m_c/4}
18.2096	16.52035	-2.84834	24.42189	5.953254	0.361754	0.212205	0.012895	0.139288
17.8196	16.159475	-2.835	24.04565	5.802069	0.917824	0.206816	0.032716	0.136305
25.3096	23.6815125	-4.23641	31.55079	5.59	1.32	0.199256	0.047052	0.193598
27.9596	26.1276375	-4.15384	34.10447	6.144052	1.942866	0.219006	0.069254	0.213868
30.3596	28.36745	-4.14729	36.42879	6.489518	2.586147	0.23132	0.092184	0.232226
30.8996	28.8521125	-4.10414	36.94264	6.407431	3.249019	0.228394	0.115812	0.236356
30.7996	28.7492	-4.08369	36.84126	6.099025	3.826695	0.217401	0.136403	0.235592
30.3996	28.378325	-4.0891	36.45502	5.655904	4.29236	0.201606	0.153002	0.232532
30.1196	28.08085	-4.01155	36.16677	5.307252	4.807616	0.189178	0.171368	0.23039

Figure 39 is the image of the kite at 0° with the wind tunnel running at 52.3 Hz. The top image is the kite bending down and the image to the bottom is the kite bending up. These initial angles were made due to the immense force from the high wind speeds.

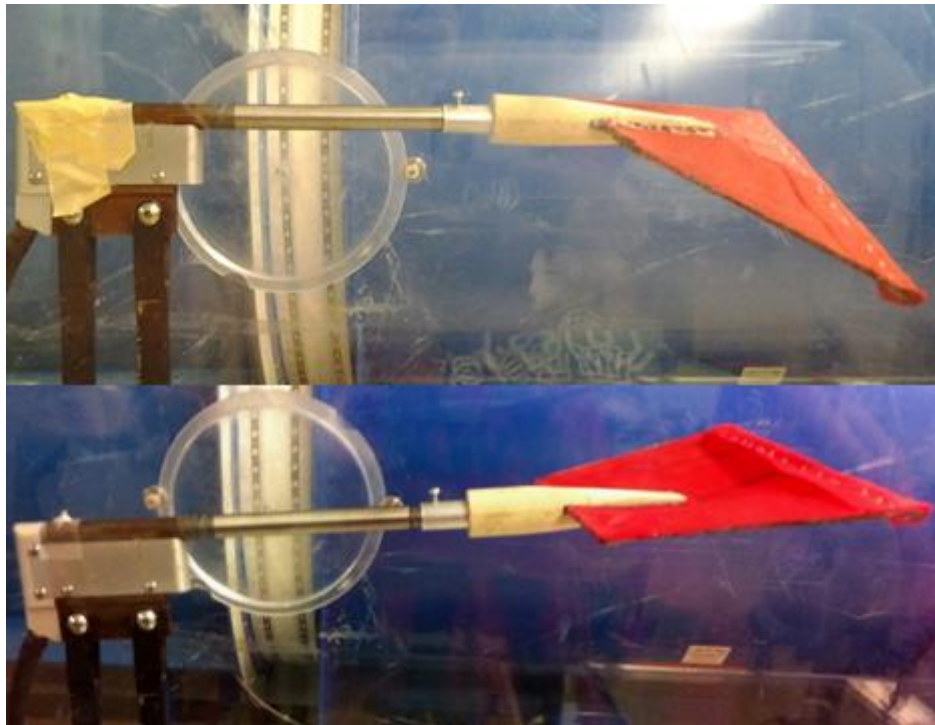


Figure 39: Top: Kite Bending Up at 0° Angle of Attack During Wind Tunnel Testing
Bottom: Kite Bending Down at 0° Angle of Attack During Wind Tunnel Testing

Figure 40 below is the kite during testing at -10° angle of attack. We can see that under the high wind speeds, the kite deformed and caused the mount piece to slightly rotate.



Figure 40: Kite at -10° Angle of Attack During Wind Tunnel Testing

Figure 41 below is the kite during testing at 30° angle of attack. We can see that under the high wind speeds, the kite began to deform and bend upward.



Figure 41: Kite at 30° Angle of Attack During Wind Tunnel Testing

7.0 Conclusions and Recommendations

7.1 Water Pump

The two main additions the team made to the 2012 MQP Water Pump System were the ground string and latching/unlatching system. These two designs allowed us to achieve a more periodic stall of the kite and periodic motion of the rocking arm. After observing the success of the system, the team can envision the kite-powered water pump system being implemented in underdeveloped nations. The system is a practical application for these nations because it is low cost, self-operating, and does not require electricity.

Based on our testing, the main adjustment that can be made to our system is to allow for the kite to be stalled longer. An example of a modification to the current system would be to include a block and tackle type arrangement. This will force the control rods to stall the kite more consistently, and thus ensure periodic motion of the rocking arm. This constant motion will allow our entire system to efficiently pump water. Since our system successfully pumped water, we will be testing the system again in June at Heifer International's Overlook Farm in Rutland, MA. This will provide a new local site for field testing which should help advance system development, and possibly maintain a permanent location for future MQPs. The wind speeds at Outlook Farms will be lower, ranging between 10 to 15 mph, thus allowing the system to pump water in a periodic motion.

7.2 Wind Turbine

Last year's small-scale proof of concept demonstrated that kite powered wind turbine system were possible. However, these tests also presented several obstacles that needed to be overcome for this technology to be implemented in any full-scale capacity. Issues such as system weight, power transmission, support system interference, and power generation required a complete system redesign in order to create a viable product. As design issues were surpassed it became apparent that certain design specifications were out of reach, most notably the \$2,000 price point. By scaling the turbine system up to a point where usable power would be produced, low weight materials and a large lift system needed to be incorporated resulting in prohibitively high system costs. While the system is physically feasible the cost to benefit ratio is too high to justify the production of the turbine.

Upon further analysis it is clear that mid-sized turbines such as the one that we have designed are not feasible for airborne applications. However, the incorporation of the turbine on a pole would drastically reduce costs due to the lack of weight restrictions, enabling the use of cheaper, heavier materials. In addition a larger generator could be incorporated thus increase energy production leading to a short five year payback period. In conclusion, moving forward with this particular mid-sized airborne wind turbine system appears to be a futile endeavor. This is due to the high manufacturing and maintenance cost, and low energy production. Further research and development regarding alternative designs for airborne wind energy, should be pursued.

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