An Analysis of Small-Scale Wind Pump Design for Use in Developing Countries

A Major Qualifying Project submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science

BJS – WI13

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Abstract

Clean water is difficult to acquire in many third world countries. The aim of this project was to design and construct a wind pump that is able to provide water to a rural third world village. The overall design goals of this project focused on affordability and simplicity of design rather than efficiency. These objectives were achieved using a Savonius-Darrieus turbine connected to a rope pump in order to create a system that was robust and easy to construct in a low-technology area. While the WPI prototype would supply 67.4% of the design specified water output, it did not meet initial design specifications. However, in comparison to competitors, this design was the most affordable third world option by a significant margin. With certain modifications, this wind pump would be a cost-effective, low technology method of pumping clean water.

Chapter 1: Introduction

Many developing nations are without feasible methods of obtaining clean, drinkable water. Obtaining water requires walking long distances or crossing through dangerous territory, and this water is often riddled with disease. Additionally, lack of clean water is the root cause of many community development issues such as a lack of education, poverty, poor health, and hunger. The amount of time spent fetching clean water from miles away or at home with stomach pain and diarrhea severely reduces the amount of time needed for work or schooling, sustaining poverty's clamp on community progression (The Water Project). Additionally, clean water is needed for agricultural purposes to aid local hunger and to sell crops for economical advances (The Water Project). Some methods of providing water to areas in need are by wells, water taps, and water purifiers. Unfortunately, water purifiers can be expensive and may not eliminate all pathogens, and wells and water taps still require time and energy to transport the water to the surface. One newer method to deliver water is by use of wind power to pump ground water to the surface. Both the wind turbine and well can be placed in or near villages to help residents easily acquire clean water without of community member assistance.

The aim of this project was to design and construct a wind pump that is able to provide water to a rural third world village. This was achieved by using a Savonius-Darrieus turbine connected to a rope pump in order to create a system that was robust and easy to construct in a low-technology area.

Chapter 2: Background

A Brief History and Development of Wind Power

Wind power is the use of wind's force to generate some form of measurable power or work. The exact origin of the first use of wind power is unknown; however, one of the earliest known uses dates as far back as 3500 B.C. to drive sailboats using aerodynamic lift (Ages). Over centuries, sailors developed their understating of lift and made improvements to the sailboat design (Telsonet). These advancements were implemented in the first windmill found in Persia around the year 900. This windmill was a vertical axis Panemone style that used sheet-like wings, similar to sails, to capture the wind, as seen in **Figure 1**. This device was then connected to pulleys or a similar connection method to grind grain or pump water for harvesting (Telsonet). Similar designs were found in China and the Island of Crete in Greece around 1200 A.D. (Telsonet).

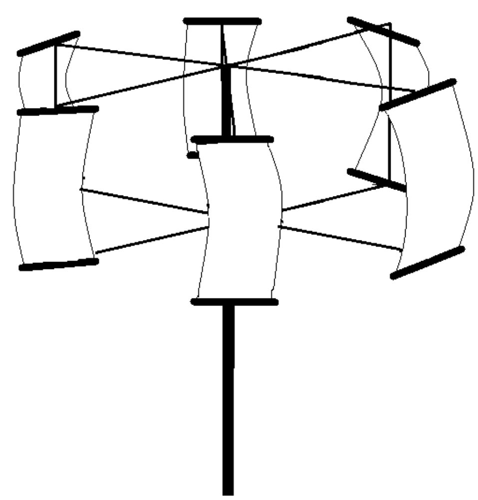

Figure 1: Panemone Windmill Design.

More widespread use of horizontal axis windmills is thought to be a development from horizontal water mills, first seen between 1100 and 1300 in England and Holland. The horizontal axis windmill (**Figure 2**) used drag forces for similar purposes of grinding and sawing timber (Telsonet).

Figure 2. A Dutch tower mill (1400 A.D.). (Telsonet)

One of the major disadvantages of this design was that the blades needed to be manually pushed to face the wind for optimal power generation (Telsonet). Over the next 500 years, the Dutch, as well as other European countries, implemented new technologies designed to improve the efficiency of wind turbines, such as the implantation of aerodynamic camber along the leading edge, twisting of the blade, and appropriate placement of the center of gravity (Telsonet).

Around the same time period, the United States built their first multi-blade turbine for irrigation purposes. From this "American Style" windmill, a trend of homemade windmills used to pump water to farms was replicated across the country (A Short History of Wind Power). This resulted in numerous homeowner innovations tested throughout the nation. Some windmills were used to collect water for steam engines and were built with rotors as large as 18 meters across (Telsonet). Just before the 20th century, Denmark developed large windmills to generate electricity which was adapted by the United States in 1940 for use to power the local utility network during World War II (Wind Coalition, 2013). Unfortunately, the use of wind power decreases with the price of fossil fuels and for a stretch of 30 years was less desirable. When the price of oil rocketed in the late 20th century, wind energy became a viable choice for sustainable energy and has continued to be a growing field of research (Wind Coalition, 2013).

Advantages of Wind Power

Today, wind power has the potential to reduce the amount of carbon dioxide and related greenhouse gases that contribute to global warming (Congress, 2011). As an energy source, wind is free and does not need to be imported from other countries. This is an extremely important advantage of wind power since many countries are dependent upon foreign providers for a large percent of their fossil fuels. As an example, the United States is depended on foreign trade for 49% of their number one energy source, petroleum (Administration, U.S. Energy Information, 2012). In 2009, 83% of the United States' energy was supplied by petroleum, coal, and natural gas, which are three of the major contributors to greenhouse gas emissions (U.S. Energy Information Administration, 2011). For countries that cannot spend millions of dollars towards fuelling each year, the natural and free use of wind can generate large amounts of energy (U.S. Energy Information Administration, 2011). Wind has been praised for its modular capacity since wind machinery can be added in increments to fit many different sizes and needs. Its short construction lead time lowers both costs and risks during construction (Patel, 2006).

Disadvantages of Wind Power

Even though wind power has many positive aspects, there are numerous disadvantages to overcome as well. Most notably, wind speeds and directions are consistently changing, making it difficult to use wind as a consistent power source. Without connecting to the grid or otherwise storing the available energy, wind power is not consistently available. Another large concern is how expensive construction and installation of wind power machinery can be on or offshore. In 2006, the average investment for a wind turbine was between $1300 and $1700 for every kW the turbine would produce (Wind Energy). For perspective, a 5kW turbine would cost between $6500 and $8500 to build and install whereas a 1 MW turbine would cost as high as $1.7 million USD (Wind Energy). Large turbines are also plagued with consistent mechanical failures that occur from vibration or misaligned gearbox connections (PES). Furthermore, the most populous regions are usually the regions that require the most power and are the least-suited to house large wind machinery as cities interrupt wind flow and lack appropriate space. Consumers tend to complain about the lack of aesthetic appeal and the noise that is generated from running as well as the potential danger to wildlife (U.S. Energy Information Administration, 2011).

Current Applications of Wind Energy

In the past 20 years, there have been major innovations in wind energy development. From 2008 to 2009 alone, wind powered electricity generation increased 20% worldwide. Still, wind energy only accounted for 1% of the world's electricity use (U.S. Energy Information Administration, 2011). Many countries have recently seen significant strides in wind technology implementation as wind turbines, both on and offshore, have been installed, wind maps displaying wind patterns from around the world created, and innovative advancements in wind technology researched.

There has also been an increase of wind power use in developing nations as a source of electric power, or as mechanical energy to pump fresh water from wells (Simon, 2011). Due to the strides taken in high-strength fiber material technology, variable-speed electric generators, and the experience gained through continued development of wind technology, the cost and difficulty of construction of wind power has significantly decreased to provide more feasible and affordable wind powered machinery (Patel, 2006). Currently the popularity of wind power is still increasing world-wide. Denmark is one of many countries who are continually planning ahead in the development of wind power. Today, 25% of their electrical power is generated from wind with a goal of 50% for the year 2020 (Cole, 2013). Many countries have similar goals while research and development are continuously taking place in an effort to minimize the earlier stated disadvantages.

Basic Wind Power Theory

In order to properly estimate the anticipated power generation for a wind turbine, certain factors about the area need to be calculated. For example, in order for a wind turbine to be economically viable, there needs to be enough wind at the site to power the turbine. This is referred to as the specific power of a site. The specific power is calculated as follows:

$$(1) \qquad P = \frac{1}{2}\rho V^3$$

Where P is the specific power, ρ is the air density (in kilograms per cubic meter), and V is the air velocity (in meters per second), and the specific wind power is measured in watts per square meter swept out by the rotating blades. This can be thought of as the amount of power that could be extracted from the wind by a 100% efficient turbine. However, no wind turbine can extract all of the power from the wind.

The turbine output power, in watts, can be calculated:

$$(2) \qquad P_o = \frac{1}{2}\rho A V^3 C_p$$

Where P_o is the output power of the turbine**,** ρ is the air density, A is the swept area of the rotor blades, V is the upstream wind velocity, and C_p is a variable known as the power coefficient.

This coefficient, also known as the rotor efficiency, is the "fraction of upstream wind power that is extracted by the rotor blades and fed to the generator (Patel, 2006)." The power coefficient can be calculated as follows:

$$(3) \qquad C_p = \frac{\left(1+\frac{V_o}{V}\right)\left[1-\left(\frac{V_o}{V}\right)^2\right]}{2}$$

The power coefficient is calculated using the upstream wind velocity, V_o, and the downstream wind velocity, V. The maximum theoretical value for C_p is 0.593; this value is known as the Betz coefficient. In practice, however, a realistic estimation for the maximum value for C_p is closer to 0.5 (Patel, 2006).

The power coefficient is closely related to another coefficient, which is known as the tip speed ratio of the rotor. The tip speed ratio, λ, is defined as:

$$(4) \qquad \lambda = \frac{\omega r}{V}$$

Where ω is the rotational speed of the turbine (in radians per second), r is the turbine radius, and V is the wind speed. This dimensionless coefficient, along with the power coefficient, can be related to the efficiency of the turbine.

Figure 3 shows the relationship between the power coefficient and the tip speed ratio for different turbine types. There are multiple different curves which represent different types of turbines. Each curve represents the power coefficient as a function of the tip speed ratio. Each curve (except for the ideal power coefficient curve) has a certain tip speed ratio that will give a maximum power coefficient, and therefore a maximum power. It is advantageous to ensure that the tip speed ratio is such that it maximizes the power coefficient.

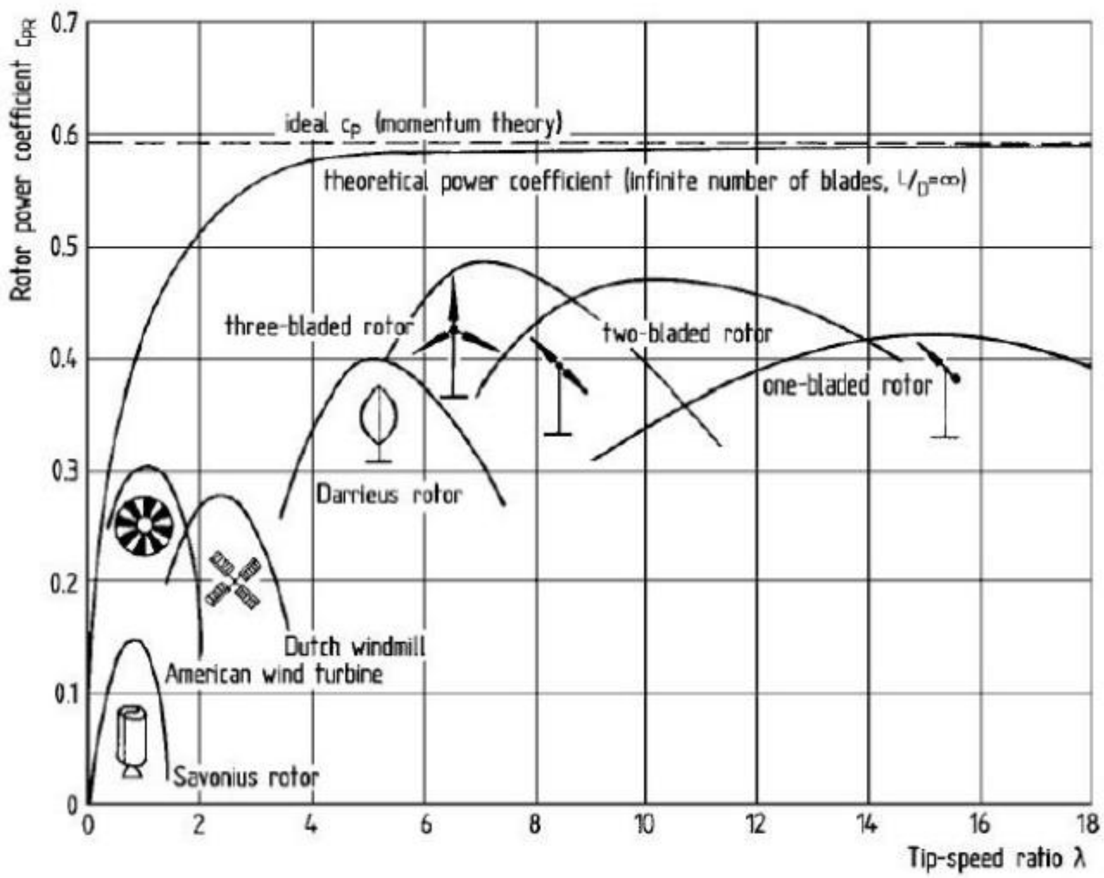

Figure 3: A chart comparing rotor power coefficients and tip speed ratios (Wortman, 1983)

Turbine Site Selection

The viability of a wind turbine depends heavily on the location of the turbine. The site must have enough wind to power the turbine, as well as be clear of obstructions that could cause turbulence. Most commercial wind turbines are designed to be either above obstructions or in an area clear of them. At these heights, the wind is mostly undisturbed and has a higher velocity than wind closer to the ground. However, the wind at any site is not constant, and it varies based on the day.

In order to adequately conclude whether or not a site is practical, the site must be examined over the course of at least a year, ideally multiple consecutive years. Once this information is gathered, it is recorded in a wind map. An example of a wind map for the state of Massachusetts is shown in **Figure 4**.

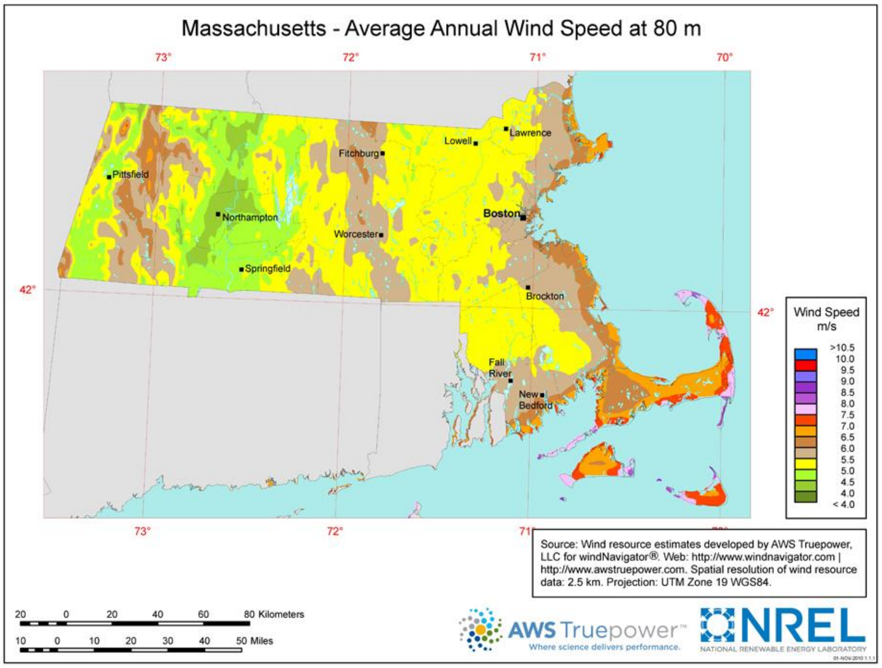

Figure 4. A wind map for the state of Massachusetts (U.S. Department of Energy, 2012)

This information can be used to roughly determine the suitability of a certain part of the United States. For example, in **Figure 4**, the wind speed in in the eastern part of the state (closer to the water) is significantly higher than the wind speed in the rest of the state, making that location a better candidate for a wind turbine than somewhere further inland. However, the potential for a turbine site cannot be absolutely determined from a wind map as the wind speed and direction are constantly changing.

In order to properly validate a specific site for turbine use, the site must be evaluated with respect to the surrounding area. For example, if the location has a significant number of trees, it could cause turbulence, which could reduce the overall effectiveness of the wind turbine. **Figure 5** shows different wind turbine site location characteristics.

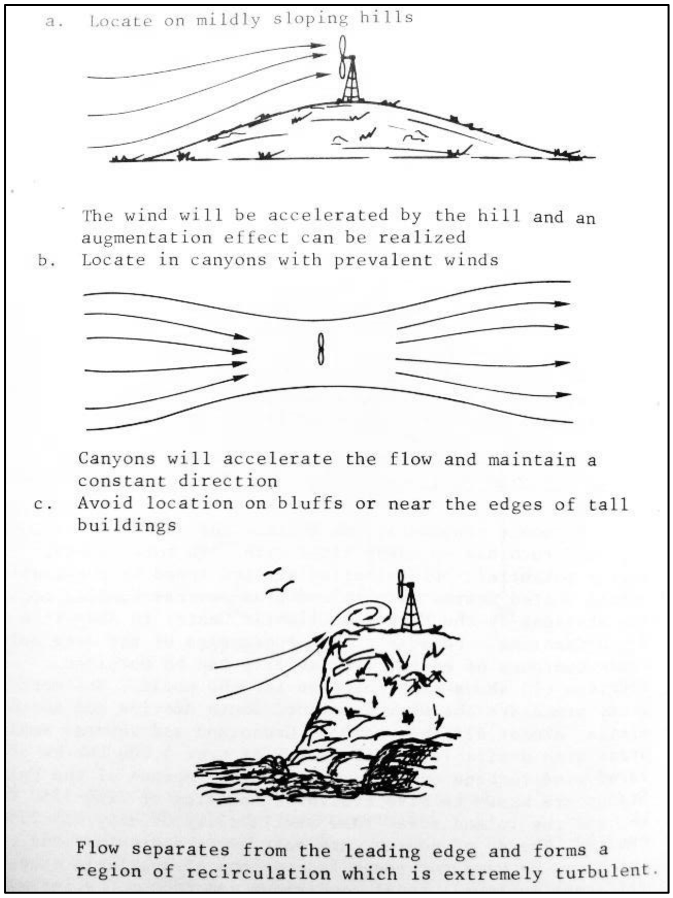

Figure 5. Location characteristics for wind turbines (Wortman, 1983)

Placing a wind turbine on a hill or in a canyon will serve to enhance the amount of wind power available, which in turn will produce more energy (Wortman, 1983). This phenomenon was implemented in the San Gorgonio Pass, near Palm Springs, California. In order to increase the amount of wind power generated, thousands of turbines were placed on a plateau in between two mountains. The wind flow between the mountains was much higher than in the surrounding area. This higher wind speed, in turn, helped generate more power (Wortman, 1983). These types of considerations are more relevant when considering a turbine in the third world – a turbine built there would need to be built with limited resources and would likely not be tall enough to avoid turbulent wind currents that can be generated near the ground.

Wind Turbines and Machinery

Wind turbines are mechanical devices that convert wind energy into electrical or mechanical energy (Paraschivoiu, 2002). Wind is used to turn the blades, which in turn, are used to generate energy. This energy can either be harnessed as mechanical energy (by using the turning shaft to pump water, for example) or as electrical energy by attaching the shaft to a generator, which can power a device or be used or stored in a battery to be used later.

Categories of Wind Turbines

There are two distinct types of wind turbines, which are based on the orientation of the turbine axis. The first is the horizontal axis wind turbine (HAWT), as seen in **Figure 6**. This type of turbine uses a horizontal axis to suspend large rotor blades, which are turned by the wind. HAWTs are either upwind, where the blades are on the upwind side of the tower, or downwind, where the blades are on the downwind side of the tower.

Horizontal Axis Wind Turbines (HAWTs)

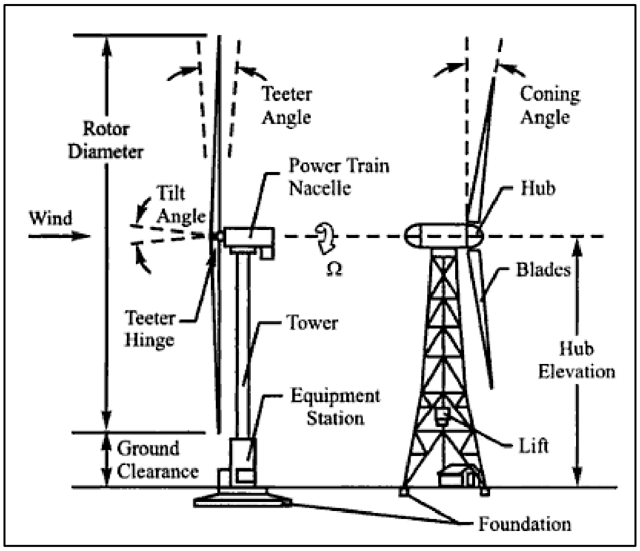

Figure 6. Two examples of horizontal axis wind turbines (Rehman, 2012)

A HAWT relies heavily on the direction of the wind to function. For both upwind and downwind turbines, the rotors should be perpendicular to the wind direction for maximum wind exposure. This is accomplished by rotating the turbine so that it faces the wind, using a motor contained within the nacelle. In fact, a wind turbine with a fixed orientation will catch only 21 percent of the wind energy that a turbine that rotates freely would capture (Wortman, 1983). In upwind turbines, this turbine rotation is accomplished by using a vane to measure the wind direction, which communicates the information to a yaw drive. This yaw drive rotates the turbine so that the turbine is facing the wind to ensure maximum power generation. A downwind turbine does not use a yaw drive; the wind itself optimally orients the turbine. Because the blades are on the downwind side of the tower, they act as a sail: they catch the wind and rotate to follow the wind direction (Patel, 2006). A downwind turbine experiences a phenomenon called "wind shade," where the wind flow is obstructed by an object; in this case, the tower itself. This can lead to a decrease in wind flow through the blades, which will in turn decrease the amount of power generated by the blades. However, downwind turbines can be built with more flexible blades, decreasing the overall weight of the structure. Upwind turbines avoid the wind shade problem that affects downwind turbines by having the blades on the upwind side of the tower, collecting the energy before the wind is affected by the tower. However, this design does not totally eliminate wind shade, as there is also wind shade in front of the tower. An upwind turbine also uses a yaw mechanism to rotate the blade direction (by rotating the nacelle) to optimally catch the wind. This is required because, if left unchecked, the tower could end up rotating too many times in one direction and potentially damaging the internal equipment (Wind Power Wiki).

The operational speed of most wind turbines is not nearly fast enough to generate electricity for most conventional generators. In order to reach the required speed (usually from 1200 to 1800 revolutions per minute) the turbine must have a mechanism to convert the slower rotation of the low speed shaft (used for the horizontal turbine axis) to a faster rotation (for use in the generator) through the use of a gearbox, located at the top of the turbine tower in the nacelle. The nacelle encloses the low speed shaft, the high speed shaft, the gearbox, and the generator. This enclosure sits atop the tower, behind the rotors, and serves to weatherproof the important electrical components.

Vertical Axis Wind Turbines (VAWTs)

A VAWT, unlike a HAWT, does not rely on the direction of the wind to generate power. It relies on a system of blades which lie on a vertical axis and are rotated by the wind, as shown below.

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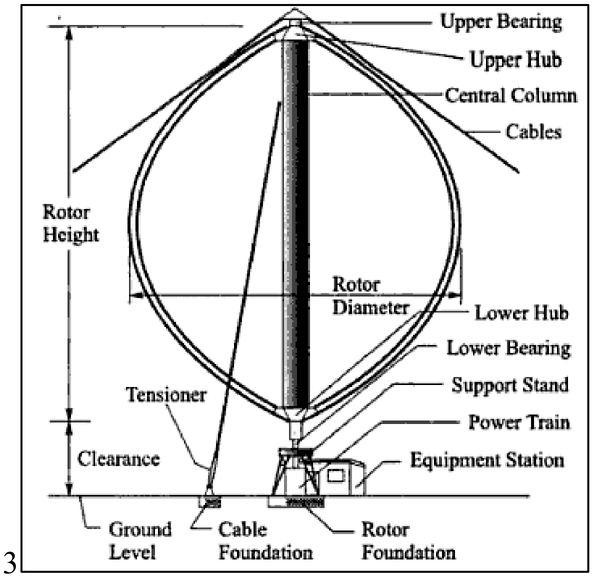


Figure 7. An example of a Darrieus vertical axis wind turbine (Wortman, 1983)

Types of Wind Turbines

There are many different types of wind turbines, each with their own advantages and disadvantages. Many of these different wind turbine designs were researched in order to better understand them and choose one that fit with the proposal of pumping water for a village in a third-world country.

Traditional Windmill

A traditional windmill operates at low speed and produces high torque. It is generally used to produce mechanical power. This design has also been around for many decades allowing for many design advancements and a large data base (Rye, 2008).

Figure 8: A multi-bladed wind turbine design (Rye, 2008)

Aerocam

An aerocam is a HAWT that uses multiple aerodynamic blades which cut a profile in the air that is similar to a water wheel. This also allows it to follow the path of the wind as the blades rotate, which means it requires no mechanical yaw correction. This wind turbine is used for electricity production. One disadvantage of this type of wind turbine is that it is stationary, meaning that it is only one-directional (Inhabitat, 2008).

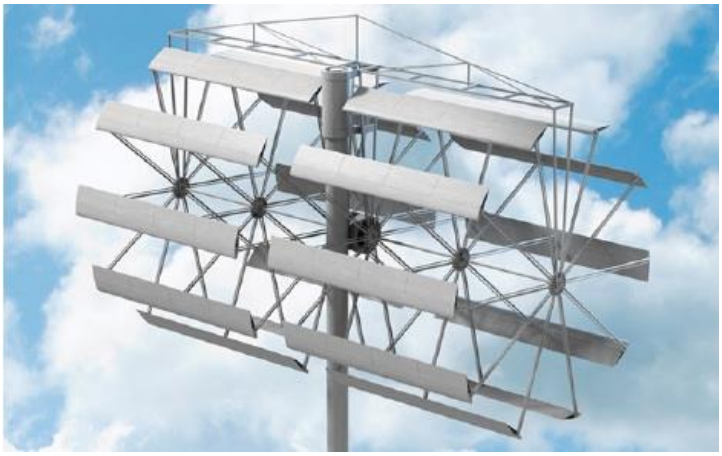


Figure 9: An aerocam wind turbine design (Inhabitat, 2008)

Panemone

A Panemone windmill is a vertical-axis wind turbine. The rotating axis is positioned vertically and the blades move parallel to the wind to catch the wind. The Panemone primarily uses drag force to turn the blades. Wind moves the vanes of a Panemone in a circle to make the drive shaft turn. However, a disadvantage to the Panemone is that it is one of the least efficient types of wind turbines because the wind panels generate no work when returning to the part of the turbine that is upwind (A Panemone (Drag-Type Windmill), 2003)

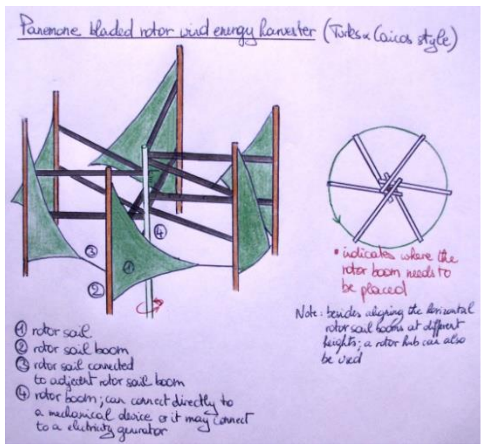


Figure 10: A drawing of a Panemone wind turbine (Wikipedia, 2009)

Darrieus Turbine

Another prominent type of VAWT is the Darrieus turbine. A Darrieus turbine uses thin blades to capture and convert wind energy into mechanical or electrical energy.

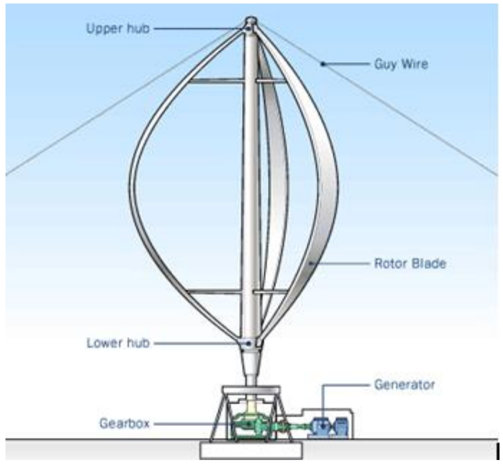


Figure 11. A Darrieus type VAWT (howstuffworks.com, 2006)

The Darrieus type relies on two or more curved blades that rely on wind to revolve around a central column (howstuffworks.com, 2006).

Savonius Rotor

One of the more prevalent types of VAWTs is the Savonius Rotor. The Savonius rotor is less powerful than most HAWTs, and it has a high power to weight ratio. However, the Savonius rotor is particularly useful for situations that do not require a large amount of electric power (Paraschivoiu, 2002). Also, because of the simple design of the Savonius, it is relatively simple to build.

Hybrid Savonius-Darrieus

A turbine design consisting of both a Savonius and a Darrieus wind turbine joins both turbines together in order to gain advantages from each. The advantages of each of the turbines help offset the disadvantages of the other turbine. Combining these two wind turbines results in a turbine that is able to start itself, operate in low wind speed, and produce a high enough efficiency to be able to transfer wind energy over to electrical power (Letcher, 2010)

Helix Turbine

A helix wind turbine uses long blade scoops that are helically shaped to catch the wind from any direction. The helix is similar to the Savonius since it uses drag forces provided by the wind and is self-starting. This is one of the more innovative designs that manipulate the direction of the wind through its blades to increase its rotational velocity (Helix Shaped Vertical Wind Turbines, 2009). An example of this design is provided in **Figure 12**.

Figure 12: Helix Wind Turbine (Helix Shaped Vertical Wind Turbines, 2009)

Wind Turbine Comparisons

For the many wind turbines introduced previously, **Table 1** compares some of the desired characteristics important to this project. Speed, torque, and the power coefficient are important factors to take into consideration as they help determine the performance of the wind turbine. The wind device torque is needed to predict the turbine's compatibility with its intended application. Different characteristics are more relevant for different applications.

Table 1: Wind Turbine comparisons

Type	Speed	Torque	C_D (rotor efficiency)	Lift or Drag	Use
Multi Blade	Low	High	0.25-.4	Both	Mechanical Power
Three Bladed aero foil	High	Low	Up to 0.45	Both	Electricity production
Aerocam	Very Low – Low	High	0.48	Lift	Electricity production
Panemone	Low	Medium	Less than 0.1	Drag	Mechanical Power
Darrieus	Moderate	Very low	0.25-0.35	Lift	Electricity production
Savonius	Low	High	0.1-0.2 (max ~0.3)	Drag	Water pumping, Grinding grain
Combined Savonius and Darrieus	Low – Moderate	High	0.25-0.35	Both	Mechanical Power/ Electricity production
Helix	Low	High	N/A	N/A	Electricity production

Darrieus Turbine

Because it is a VAWT, the Darrieus turbine has certain advantages over a standard HAWT. Most HAWTs require some sort of yaw control mechanism to ensure that that turbine is oriented appropriately with respect to the wind. Because the Darrieus turbine does not rely on wind direction, it avoids this problem entirely. The Darrieus turbine is also typically designed to keep the heavy machinery at ground level, reducing the total weight of the vertical section (Paraschivoiu, 2002). However, this type of turbine is not self-starting.

The Darrieus turbine, in its most general sense, works by generating lift using the rotating motion of the blades. Essentially, most of the “apparent wind” is coming from the air pressing on the blade due to the rotation, and not from the wind itself. The ambient wind on the blade creates a rearward change in momentum, and it is this that propels the blade in the direction of rotation. This phenomenon does not occur unless the blades are already rotating, however. This is why a separate means of starting is requires for the Darrieus turbine (OtherPower).

A simpler type of Darrieus, known as the H-Darrieus turbine, does not utilize curved blades to move, making it easier to design and manufacture. Instead, it uses a number of straight airfoils (usually two or three) to generate the requisite lift. The Darrieus is known for having very low torque (**Table 1**), though its size can be manipulated to provide sufficient torque for different applications.

Savonius Rotor

Another of the more prevalent types of VAWTs is the Savonius rotor. The Savonius rotor is less powerful than most HAWTs, as it uses drag to rotate itself, and it has a low weight to unit power ratio. However, the Savonius rotor is particularly useful for situations that do not require a large amount of power (Paraschivoiu, 2002).

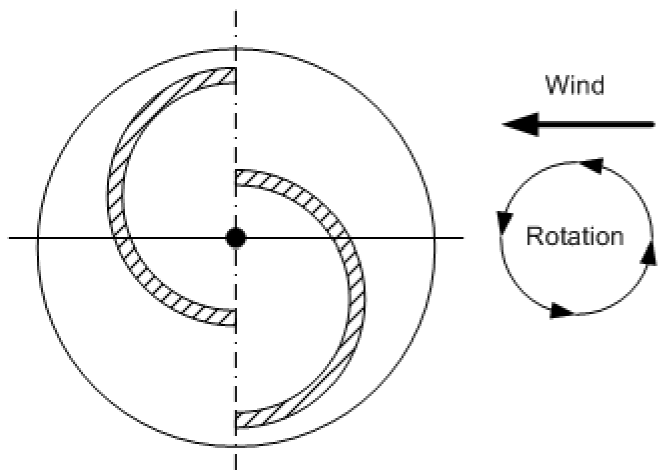
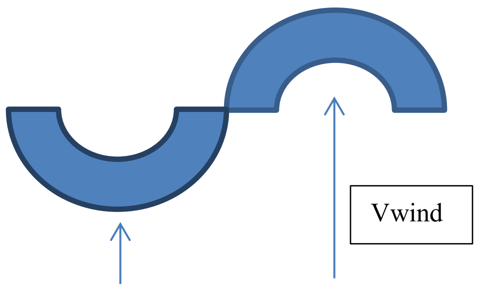


Figure 13. A simple Savonius concept (Experiments with Model Wind Turbines, 2012).

A simple Savonius rotor can be manufactured by cutting an oil barrel in half, inverting one of the halves, and welding the two pieces together in an S-shaped cross-section." The Savonius rotor is easily constructed using little technology.

The Savonius cups can also be offset slightly, as seen in **Figure 13** . This causes the wind to flow through the center gap. This gap flow affects the performance of the rotor. A study was performed that compared the performance of the turbine with the overlap coefficient of the blades to determine the ideal ratio. It was determined that the optimal overlap ratio was 0.242 (Menet & Bourabaa). This shows that it is not optimal for the blades to be joined at the edge.

The Savonius turbine relies only on drag to turn. As such, the total turning torque of the mechanism can be approximated by considering the drag force on the "cups" to be applied directly on the middle of each cup. This can be seen here:



The drag force on a surface can be evaluated as:

$$(5) \qquad F_d = \frac{1}{2}\rho_{wind} A v_{wind}^2 C_d$$

Where ρ is the wind density, A is the cross sectional area, v_{wind} is the wind velocity, and C_d is the coefficient of drag on the surface. For a concave semicircle, the drag coefficient is 2.3, and for a convex semicircle, the drag coefficient is 1.2.

Basic Water Pumping Theory

Many view wind pumping as an underutilized resource for supplying water; however, numerous developing nations have begun to utilize its advantages. (Smulders, 1996). As seen in **Figure 14**, wind pumps can be useful to supply water for a community, for one home, for cattle, or other uses. The uses provided happen to be ideal purposes for a wind pump due to the small head and low wind power needed, some sufficiently working with a wind speed of as little as 3 meters per second (Smulders, 1996). The following figure displays different pump requirements for different pumping applications.

Application	Head				Daily volume (m^3/day)	Typical rotor diameter (m)
	very low < 3 m	low 3-10 m	medium 10-30 m	deep >30 m		
Community water supply			x	x	20 (500 persons)	2.5 to 7.0
Domestic water supply			x	x	1-3 (small farm)	1.5 to 2.5
Cattle watering			x	x	20 (500 head)	1.5 to 4.5
Irrigation	x	x			40-100 (≈ 1 hectare)	2.5 to 5.5
Drainage	x				100	2.5 to 3.5
Salt pans	x				?	2 to 4 (?)

Note

1. These requirements fall in the range of 10-1000 m4/day. In fact 2500 m4/day is about the upper range feasible for mechanical wind pumps (see Figure 2).

Figure 14: Estimated pump head, water volumes, and associated wind pump rotor size (Smulders, 1996)

Mechanical wind pumps are ideal for required water quantities in the range from 40 to 3000 m^4/day, as seen in **Figure 15**. For low flows, a simple hand pump could be used. However, higher volume flow requires either a solar pump, diesel pump, or electric wind pump.

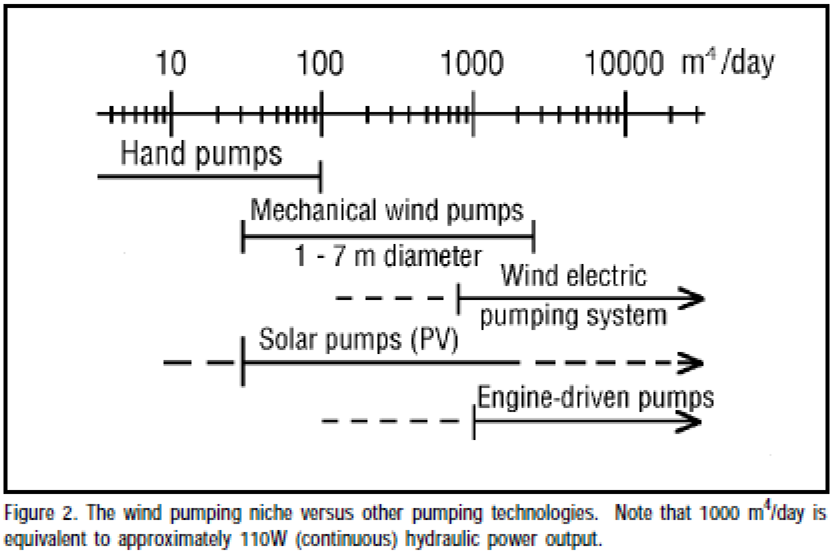


Figure 15: Comparison of Mechanical Wind Pump to Other Pump Devices (Smulders, 1996)

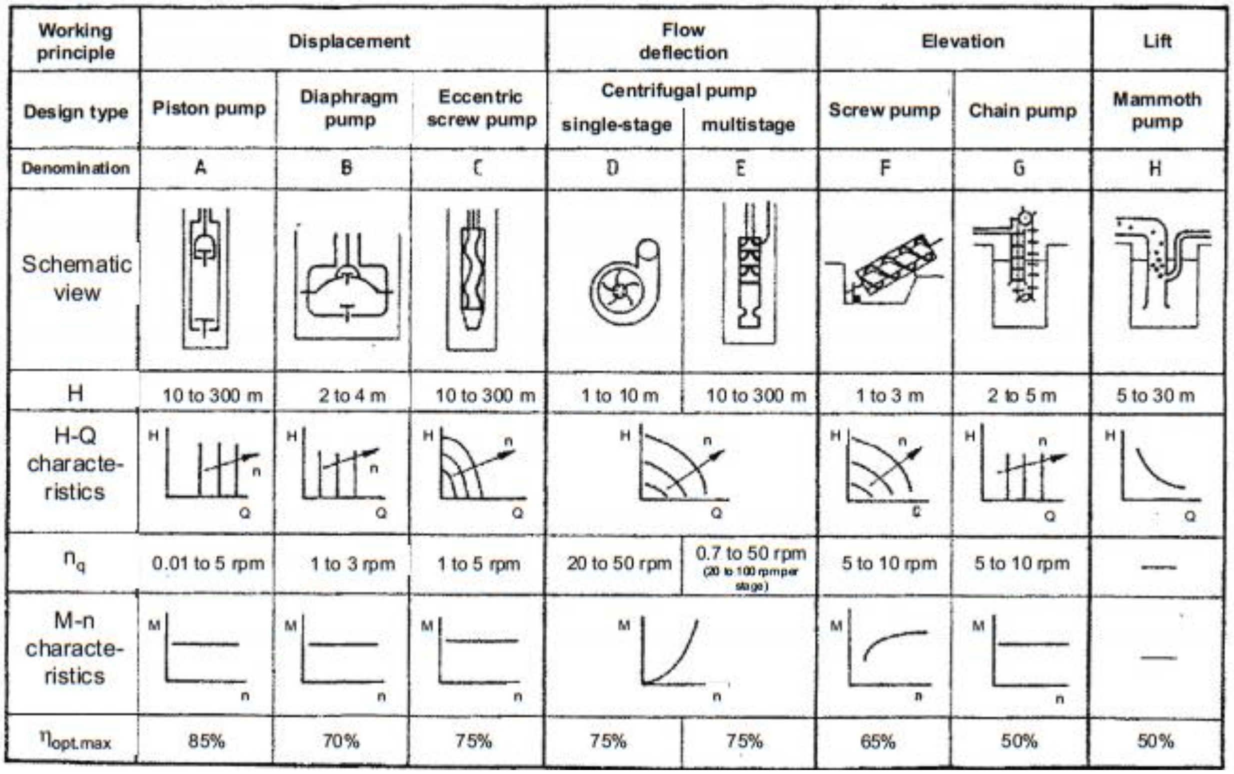
There are many pump characteristics taken into account when deciding the size and style of the ideal pump. Although there are many different types of pumps, general pump theory can be drawn from the Bernoulli energy equation with head loss, shown here:

$$\frac{P_{out}}{\gamma} + \frac{{V_{out}}^2}{2*g} + z_{out} = \frac{P_{in}}{\gamma} + \frac{{V_{in}}^2}{2*g} + z_2 - h_f + h_p \quad (6)$$

Where h_f is the frictional work done per unit weight. This term is usually referred to as head loss (Subramanian). The gravitational constant, denoted by g, is 9.81 meters per second squared, p is the pressure, h is the height, ρ is the density of the water, V_1 and V_2 are the respective velocities, and z_1 and z_2 are the respective lengths. The head of a pump can be simply expressed as "the height to which a fluid may be lifted by the pump in a frictionless piping system (Morrison F. , 1999)" and can be used to compare the effectiveness of different pump designs.

Water Pump Comparisons

Different types of applications require different types of pumps, and each different pump has different characteristics. Below is a figure showing different types of pumps and certain attributes for each.



Working principle	Displacement			Flow deflection		Elevation		Lift
Design type	Piston pump	Diaphragm pump	Eccentric screw pump	Centrifugal pump single-stage	Centrifugal pump multistage	Screw pump	Chain pump	Mammoth pump
Denomination	A	B	C	D	E	F	G	H
Schematic view								
H	10 to 300 m	2 to 4 m	10 to 300 m	1 to 10 m	10 to 300 m	1 to 3 m	2 to 5 m	5 to 30 m
H-Q characteristics								
n_q	0.01 to 5 rpm	1 to 3 rpm	1 to 5 rpm	20 to 50 rpm	0.7 to 50 rpm (20 to 100 rpm per stage)	5 to 10 rpm	5 to 10 rpm	—
M-n characteristics								—
$\eta_{opt.max}$	85%	70%	75%	75%	75%	65%	50%	50%

Figure 16: Different pump types and their characteristics (Gasch & Twele, 2012)

This chart compares many different pump options on the basis of appropriate head size, head versus flow rate characteristics, and efficiency. The three pumps that were considered for this application were the piston pump, the multistage centrifugal pump, and the chain pump (also known as the rope pump).

Figure 17 shows several flow rate and head requirements for different applications. Each of these pumps has different characteristics, making them suited for different characteristics.

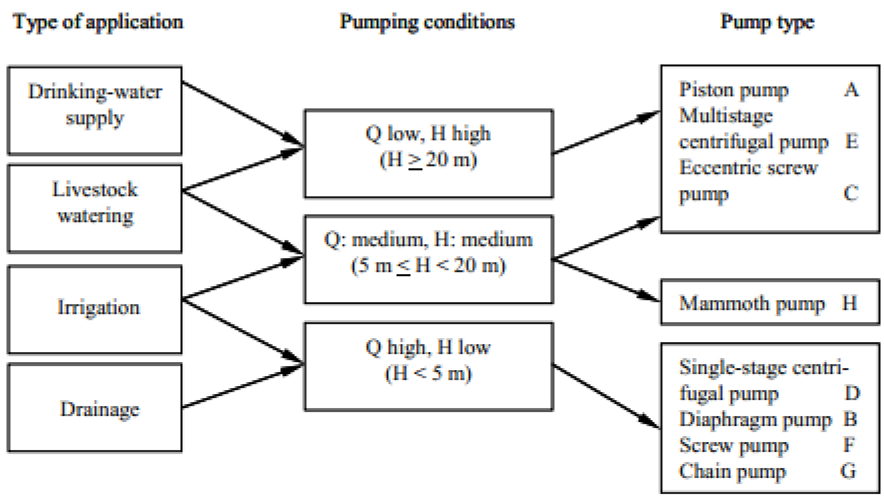


Figure 17 Applications for different pump flow rates and heads (Gasch & Twele, 2012)

In order to construct a pump that will be able to supply a community with drinking water, for example, pumping from the ground, the pump should have a low flow rate and a head ideally greater than 20 meters. For wind pumps, a high head can be generated by the low rotational speed that wind turbines deliver (Gasch & Twele, 2012). After selecting the application, the next step is determining the type of pump to use.

Other than high efficiency and head size compatibility, some of the other major factors that are ideal in a pump for this project's purposes include little wear by non-purified water contents, low starting torque to match the wind-turbine, little maintenance, small oscillating forces, and relative simplicity to other pump options. **Table 2** further compares the three largest head-providing pump options on these characteristics.

Table 2: Pump Type Pros and Cons (Gasch & Twele, 2012)

Pump	Pros	Cons	Notes
Piston pump	• For low rotational speeds, a high total head is delivered • Has been successfully applied to many different types of wind pump systems • Starting characteristics can be improved by design measures	• High wear when pumping dirty water • High starting torque required • High dynamic forces due to oscillating piston	• H-Q characteristics show that total head is ideally independent of flow rate
Multistage Centrifugal	• Can be used to transmit electrical power • Not sensitive to dirty water • Low starting torque • Turbines and centrifugal pumps are both rotodynamic machines	• Difficult to manufacture if the impellers are small	• Has only been applied to wind pump systems with an electric coupling and a submersible motor • Head increases with more stages
Rope pump	• Can lift water up to the required 30 meters • Mechanically simple to build and repair	• Very inefficient • Can be somewhat unreliable	

Piston Pump

Piston Pumps are the most commonly used pump option for wind pumps, currently utilized in thousands of wind pumps on the market. Though the piston pump has some faults, this pump is a fairly straightforward pump to construct, moves at low rotational speeds and is often used for lifting water small distances. The piston pump, denoted as A in **Figure 17**, is suitable for use in boreholes since its exterior design is slim and compact. Some experts believe this reciprocating pump is the most important way of displacing water since the total measured head is not variable to the desired flow rate and can function at low rotational speeds (Gasch & Twele, 2012). Furthermore, **Figure 17** provides some of the disadvantages including the high maintenance due to wear of dirty water and the requirement of a high starting torque. A high starting torque would require a greater power delivered from connected wind device. A cross-section of a piston pump is shown in **Figure 18**.

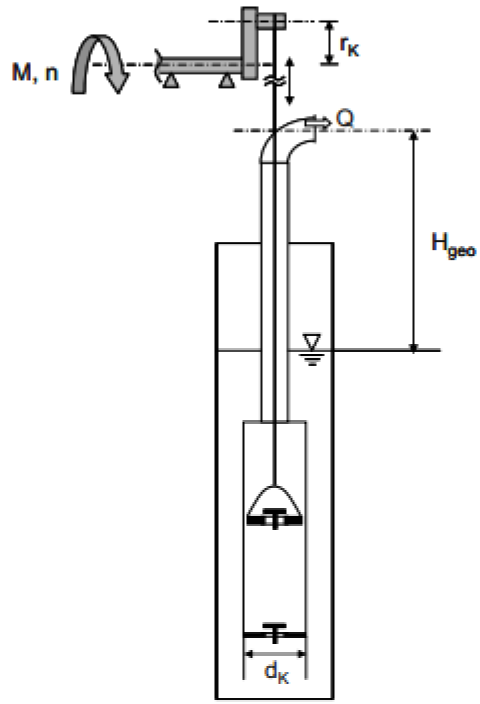


Figure 18. A piston pump. (Gasch & Twele, 2012)

Centrifugal Pump

The centrifugal pump is a relatively complicated pump to build; however, this pump option has a low starting torque and little sensitivity to wear due to water content. Unlike the piston pump, the centrifugal pump directly uses the rotational energy of the turbine, as opposed to a suction system, to move a liquid (**Figure 19**).

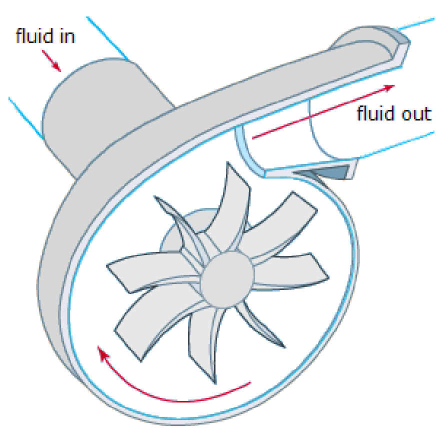


Figure 19. Cross section of a centrifugal pump (Werner Sölken, 2013)

The liquid flows into the center of the pump, where the rotating motion of the impeller is used to push the liquid out from the center, where it flows through the outlet. The pump impeller requires a high rotational speed to move the water. This means that the rotational torque provided by the turbine can be almost directly applied to the pump impeller.

Rope Pump

Another pump type that was discussed in **Figure 16** is the rope pump. This pump is one that can be easily operated and maintained in a third-world setting. As shown in **Figure 20**, the rope pump is a device that rotates a rope around a wheel down to the water source and up through a pipe. The water can be drawn up from wells or boreholes. There are small metal, rubber, or plastic discs with less than one millimeter clearance of the pipe which are attached to the rope and act as pistons to draw water through the pipe. The pipe ends at the water surface where there is a faucet type outlet that releases the water as the rope continues to circle around the wheel. No efficiency was found in the literature, but it is expected to be low, resulting in low flow rates. The expected flow rate is around 40 liters per minute from a depth of 10 meters. The pump can be used by single families or up to 20 families, approximately 100 people (Akvopedia, 2012.)

Rope pumps are being used in over 30 countries worldwide as of 2008. Some of these countries are Nicaragua, Zimbabwe, and Ghana. In Nicaragua, they had previously been using piston pumps. The switch to rope pumps has saved a lot of money annually and has doubled the rural water supply in ten years (Akvopedia, 2012.)

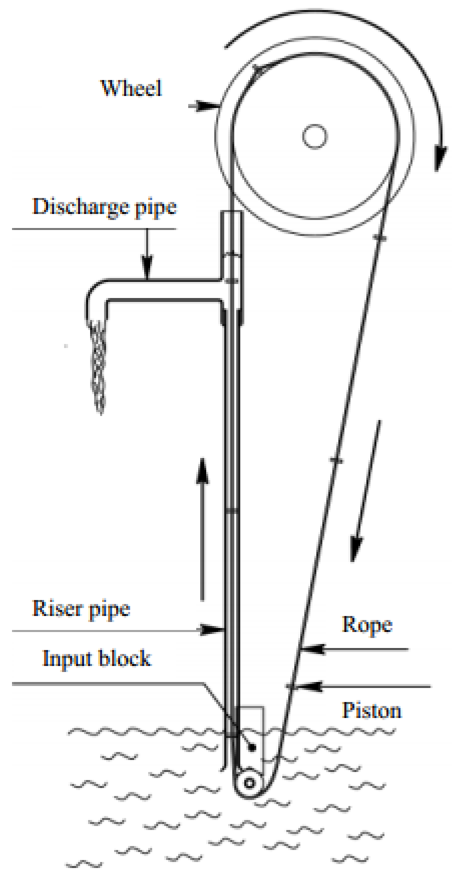


Figure 20: WOT Low-Tech Rope Pump (WOT, 2012)

Current Wind Pump Designs

Current wind pumps are most commonly found on farms and ranches in North America, Africa, and Australia. Farms and other large, open areas that are disconnected from electrical services can largely benefit from wind pumps due to their free wind-driven power, durability, and minimal maintenance (LILI, 2012). As described earlier, wind pump machines are not a new concept, dating back to the 19th century. One example is the American farm wind pump which was a common wind pump used to deliver large amounts of water for agriculture purposes. This wind pump usually has a multi-bladed rotor and is made almost entirely from steel. The rotor is connected to drive a reciprocating pump, generally a piston pump, by way of reduction gearing (Wind Power, 2007). Since its first appearance, the multi-blade piston pump has made many advancements and, today, is the most common mechanical wind pump on the market (**Figure 21**) (Practical Action, 2013).

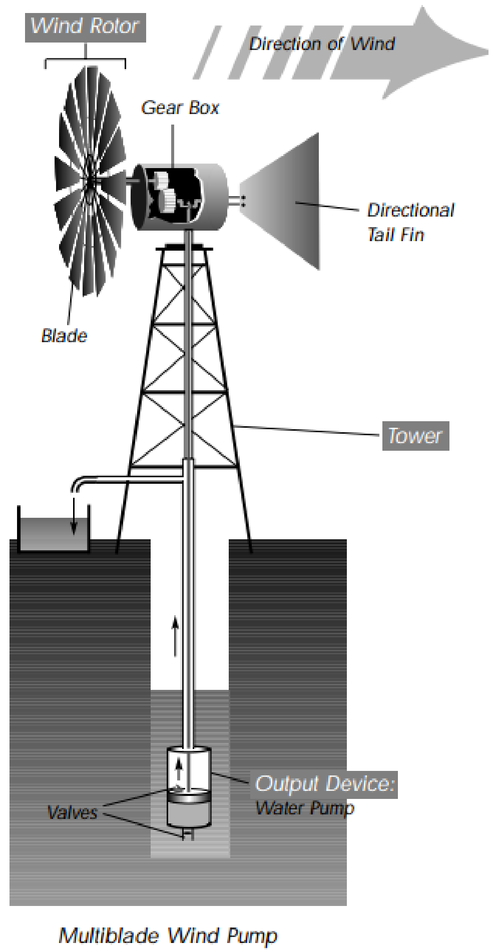


Figure 21: Multi-blade driven piston pump (MacGarry)

Two major innovations on this design include the engineering of a counterbalance for the weight of the rod and the development of variable strokes. Another is the use of 6 to 8 blades of true airfoils, as opposed to traditional windmills, which use 15-18 curved steel plates. These newer generations of wind pumps use direct drive mechanism instead of a geared transmission. The direct drive mechanism helps produce high torque at low wind speeds and control rotor speed at high wind speeds (Argaw, 2003).

Other wind pumps on the market include various battery-connected wind turbines that electrically power pumps. Companies such as TF, Depon, and Dahai manufacture electrically driven wind pumps costing as much as $3000 USD (Alibaba, 2013). Other alternatives of pumping mechanisms include hand pumps and solar driven pumps. Though these are not wind-powered, they give additional insight into the sustainably-powered pump market. The hand pump functions mechanically, and is easily installed; however, requires the physical power and time of community members. The solar-driven pump is electrically powered and is very complex to reproduce (Alibaba, 2013).

Chapter 3: Design

The goal of this project was to design, construct, and test a wind driven water pump that is suitable to provide fresh water to a community in a third world country facing difficulty accessing water. The design takes into consideration ease and simplicity of construction, implementation, and repair, as well as cost and availability of materials.

Location Selection and Specifications

In order to determine an appropriate location for the wind pump, one must consider certain factors. First and foremost, the wind pump is designed for implementation in a third world country using available materials and tools. This limits the design by imposing restrictions on the types of materials. It can be assumed that the majority of readily available materials in the country of South Africa include resources such as wood, scrap metal, bricks, concrete, and old tires. Many more modern technological advances are not easily obtainable there; therefore, certain materials might have to be bought elsewhere. However, a major design goal for this system was to use materials that could be obtained in South Africa in order to allow the wind pump to be constructed there.

Using these types of materials, it would not be realistic to build a turbine with a height of anywhere near 50 to 100 meters. However, the height of the turbine must be high enough to allow the turbine to catch the wind above any major turbulence generated by trees or buildings near the ground.

Figure 22. Fraserburg, South Africa (marked with an A) (Google Maps, 2013)

Second, the wind pump must be built at a site that has suitable wind and water resources. This site should also be located close to an existing village, so that the village is able to access the pumped water. Additionally, the wind speed at this location must be consistently high enough to power the turbine. The wind speeds in Fraserburg for the week of April 20th through the 27th, 2012, are shown in **Table 3.**

Table 3. Wind speeds for Fraserburg, South Africa

Wind Speed for Fraserburg, South Africa (in knots)							
Friday	**Saturday**	**Sunday**	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
5	6	6	14	11	9	4	5
4	6	7	13	11	7	7	5
4	7	10	15	13	5	8	7
5	14	11	16	12	13	12	19
15	15	12	16	13	16	12	22
16	14	13	16	12	15	12	19
9	9	15	13	10	10	8	12
7	5	15	12	9	5	6	
Averages (knots)							
8.125	9.5	11.125	14.375	11.375	10	8.625	12.71429
Total Average (knots) 12.26				**Total Average (m/s)** 6.31			

The total average wind speed for the week is 6.3 meters per second. According to the National Renewable Energy Laboratory, a wind speed of 6.3 meters per second falls into Wind Class 5, rated "Excellent" for wind power production.

Wind Power Class*	10 m (33 ft)	
	Wind Power Density (W/m^2)	Speed(b) m/s (mph)
1	0	0
2	100	4.4 (9.8)
3	150	5.1 (11.5)
4	200	5.6 (12.5)
5	250	6.0 (13.4)
6	300	6.4 (14.3)
7	400	7.0 (15.7)
	1000	9.4 (21.1)

Figure 23. Wind classes at 10 meters (Classes of Wind Power Density at 10m and 50m)

Obviously, further investigations would need to be made regarding the wind speed over the course of an entire year, but this provides a good estimate for a reasonable average wind speed for the region. Wind direction can also be a factor in site selection. If the wind only naturally flows in one direction (in a canyon, for example) then the turbine does not have to change direction based on the wind direction. However, many sites have wind that comes from different directions; in this case, a VAWT (which does not generally rely on wind direction to generate power) could be more useful than a HAWT.

Third, the water well must be able to provide for a community of 500 people. Since the goal is to provide clean drinking water to a small village in South Africa, **Figure 14** shows that for a "Community water supply," a village of 500 people would require a daily volume of 20 cubic meters per day, or about 0.23 liters per second. A map of general water availability in Africa is shown in **Figure 24** as well as the general location of Fraserburg marked with a black arrow.

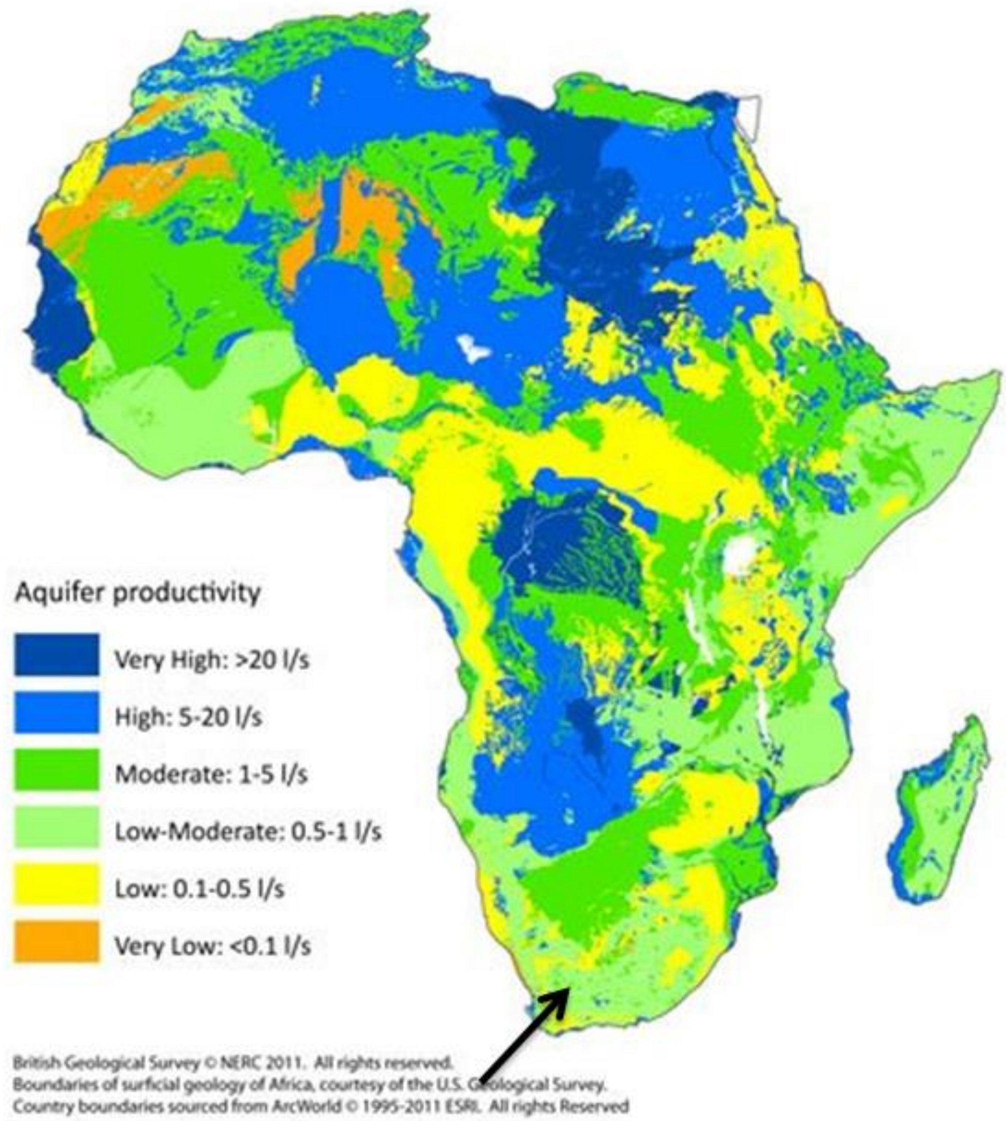


Figure 24. Water availability in Africa (NERC, 2011)

As the figure shows, the area that Fraserburg is located in has a low to low-moderate potential for pumping water (from 0.1 liter per second to 1 liter per second). If the requirement for drinking water for 500 people is 0.23 liters per second, then it should not be difficult to find a location with an adequate water supply.

The overall minimum requirements for a wind pump location involve a combination of wind speed and water availability, as well as proximity to an existing village. Specifically, the water availability of the site must exceed 0.23 liters per second in order to adequately provide water to a hypothetical village of 500 people. Additionally, the wind should be at least Wind Class 4 (“Good”, as seen in **Figure 23**) in order to provide adequate wind power to turn the turbine, and the site should be relatively clear of trees, buildings, and other significant obstructions. Finally, the site should be close enough to an existing village to facilitate water transportation.

Wind Turbine Selection and Design

The first step in deciding on a wind turbine design was determining the importance of certain characteristics and comparing these features of different turbine design options. From the background research, the design options were narrowed down to four: a multi-blade, a Savonius, a Darrieus, and a combined Savonius/Darrieus. By weighing the importance of certain features, the wind turbine most fitting for this project’s purpose was selected. The different turbine features analyzed were the ease of construction in a third world country, the power output, the expected power output during operation, starting torque characteristics (as well as whether it self-starts or not), and the overall efficiency of the device. The design matrix used can be seen in **Table 4**.

Table 4: Turbine Design Matrix

Design Matrix	Multi-blade	Savonius	Darrieus	Combined Savonius/ Darrieus
Feasibility in a Third world Country (50)	.8 / 40	.7 / 35	.4 / 20	.6 / 30
Power Output During Operation (25)	.2 / 5	.2 / 5	.6 / 15	.7 / 17.5
Self-Starting/ Starting Torque (20)	.7 / 14	.8 / 16	.4 / 8	.7 / 14
Estimated Efficiency (35)	.3 / 10.5	.2 / 7	.7 / 24.5	.8 / 28
Total	69.5	63	67.5	89.5

The multi-blade turbine (using a design close to a standard HAWT, but using flat blades instead of airfoil shape blades) performs well in both the third world feasibility category and the self-starting category. Both the Darrieus and Savonius turbines, by themselves, have advantages and disadvantages. The Savonius is simple and easy to construct in a third world and has good torque characteristics, but it has a very low efficiency and provides a low relative torque compared to the other designs. Where the Savonius did well, the Darrieus did not, however. The Darrieus is not able to start itself, and has a complicated design, especially for a third world country. However, it has a better efficiency and can provide the necessary torque for the pump to run. Due to the differences in characteristics between the Savonius and Darrieus turbines, the combined Savonius-Darrieus turbine has some significant advantages over both. It combines the relative strengths of both without succumbing to the weaknesses that both turbines have. The combined Savonius/Darrieus turbine was chosen due to its relatively high efficiency, ease of construction (in the case of an H-Darrieus), and ability to self-start.

Design of Darrieus Turbine

The design of a standard Darrieus turbine is relatively complex, especially when compared to other wind turbine types that were considered. In order to simplify the design, a particular type of Darrieus turbine was used called an H-Darrieus. Instead of using a more complicated, curved blade shape, the blades of an H-Darrieus are straight, making the design and construction of the blades much easier. A comparison between H-Darrieus and normal "eggbeater" Darrieus are shown below in **Figure 25**.

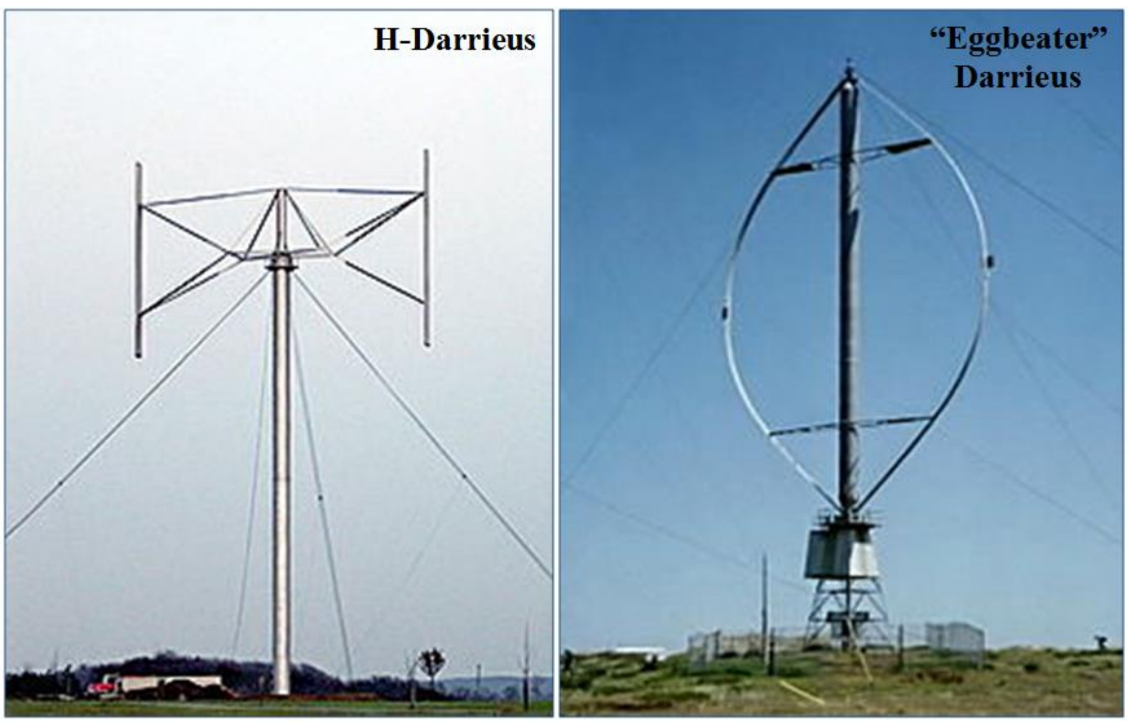


Figure 25. H-Darrieus and "eggbeater" Darrieus turbines (Darrieus Wind Turbine)

By using a straight blade, the work required to shape the blade is significantly decreased; one could hypothetically create a blade using a single piece of material without needing to bend it. The shape of the blade used for the H-Darrieus is a NACA 0015 airfoil. This type of airfoil is very common, especially among hand constructed (so-called “backyard”) Darrieus turbines. Using this airfoil as the blade for a Darrieus turbine generates a net forward force on the blade, which then moves the H-frame around, generating torque on the center shaft. This shaft is then connected to something which utilizes the rotational energy; in this case, a water pump.

Figure 26: Symmetric NACA 0015 Airfoil Shape

Figure 27: Extruded NACA 0015 Airfoil

The design of the Darrieus turbine needed to meet three goals. First, the turbine needs to provide enough torque to power the water pump at an expected average wind speed. Second, the turbine should be able to withstand normal operating forces without mechanically failing. Third, the design should be simple enough to build and maintain in rural South Africa.

Design of Savonius Turbine

The use of the Savonius turbine is to assist the Darrieus turbine. The Darrieus turbine converts the linear motion of the wind into rotational motion that the turbine can use. However, the Darrieus requires an initial rotational speed to move in this manner, because the blades require motion to generate lift. In order to solve this problem, a pair of Savonius turbines was added to the top of the turbine frame. These two turbines will provide the self-starting capability that the mechanism requires. In order to overcome any force, the Savonius was sized so that it was able to start the combined turbine without any help from the Darrieus.

The method used for sizing the Darrieus turbine involved estimating the power required to move the pump. This information could then be used to calculate an approximate size for the Darrieus using the power equation, seen above in Equation 3.

In order to improve the performance of the Savonius turbine, there are a few different options. First, increasing the surface area of the Savonius will allow the turbine to capture more wind, which results in more force acting on the shaft. Second, mounting the Savonius turbine cups further from the central shaft will create a longer radius for the force to act on, which generates more torque on the shaft. Third, reducing the required torque to the shaft would increase the effectiveness of the Savonius without needing to change the size of the turbine. This could be done by reducing the necessary torque. However, because of the specific requirements for the pump-turbine system, this is not a viable option.

The Savonius-Darrieus is normally used as an electric power source storing energy in a battery. In this case, the starting torque can be achieved with the Savonius turbine directly attached to the shaft, without arm offset. Due to the mechanical decision of this project, the new Savonius design is offset 0.149 meters in each direction to generate more torque. The additional torque is needed to overcome the friction and weight of the water being initially drawn through the pump. Some basic design calculations are located in **Appendix C**.

Pump Selection and Design

To determine the most appropriate pump design, a design matrix was based off of the background research and performed on three pump options: the piston pump, the rope pump, and the multistage centrifugal pump. The importance of each desired characteristic was weighed to determine which pump design was most appropriate.

Table 5: Pump Design Matrix

Important Design Characteristics	Piston Pump	Rope Pump	Multistage Centrifugal
Simple Construction 30 points	.5 / 15	.9 / 27	.25 / 7.5
Available Materials 10 points	.75 / 7.5	.95 / 9.5	.4 / 4
Inexpensive Materials 20 points	.7 / 14	.85 / 17	.4 / 8
Total Head (30 meters) 20 points	.75 / 15	.9 / 18	.75 / 15
Wind Device Connection 20 points	.7 / 14	.5 / 10	1 / 20
Total	65.5	81.5	54.5

Before considering the specific needs of the third world device, the centrifugal pump was the most compelling choice. The rotation motion of the centrifugal pump matched up well with the wind turbine's turning shaft. However, in the process of trying to design and construct a possible centrifugal pump, the pump design was very complex and not easily constructed with low end materials. **Appendix C** shows some of the detailed calculations towards use of the multi-stage centrifugal pump.

The most difficult aspect of a piston pump is the placement of the piston itself. The piston would have needed to be within ten meters of the water source to work at an acceptable pressure as shown by rearranging a well-versed pressure equation. Using atmospheric pressure (P) and the density of water at sea level (ρ), the maximum possible head can be demonstrated as:

$$P = \rho g h$$

$$\therefore \quad h = \frac{P}{\rho g} = \frac{101\ kPa}{\left(1000\ {}^{kg}/_{m^3}\right)\left(9.81\ {}^{m}/_{s^2}\right)} = 10.29\ m$$

This caused issues because the piston shaft would have needed to be at least 20 meters long, working in both compression and tension. A shaft this long would be very heavy to lift and would be more likely to buckle under the required loads.

The ultimate choice for this project is the rope pump, due to its favorable head characteristics and ease of design and construction. Rope pumps are very easy to reproduce, can be made out of available materials, and require low maintenance (WOT, 2012). Additionally, rope pumps can lift water approximately 35 meters, and would only require a right angle belt drive or gearbox to connect this pump to the wind shaft. The rope pump is a design not often used. Though its simplicity, affordability, and high head are great advantages, its inefficiencies may deter many, but its minimal use generates a great lack of awareness. The few cases that rope pumps are used, they are built to be driven manually. This design is an innovative attempt to match a rope pump with a non-manual mechanical driving force.

Connecting the Turbine and the Pump

For this design, the turbine rotates vertically so that the shaft follows the z-axis while its rotational velocity falls in the x-y plane. The pump rotates horizontally so that its rotational velocity moves in the y-z plane, perpendicular to the rotational speed of the turbine. This means that whichever connection used, the rotations need to connect at a right angle. Two options include a gearbox power transmission and a belt drive.

Gearbox Power Transmission

The relation of the rotational speed and torque of each machine is:

$$(7) \qquad (\tau\omega)_{turbine} = (\tau\omega)_{crankshaft}$$

Figure 28: Right Angle Worm Gear (Gears and Stuff, 2006)

Standard gearboxes are pre-made and sold by many manufacturers. Ratios such as 1:1, 1:2, 1:5, and 1:10 are easily found for parallel rotating gears as well as right angle gears (**Figure 28**) as in needed in this case. There are also many manufacturers who build custom gearing for special cases. Unfortunately, the price of an inexpensive gearbox ranges from fifty dollars to hundreds of dollars depending on the needed size and ratio. As such, the price of a gearbox is too expensive for the purposes of this project.

Belt Drive Power Transmission

An alternate method of power transmission is the belt drive. Similar to gearboxes, belt drives can be used to transmit rotational energy with a change the direction of rotation. **Figure 29** shows an example of a belt drive which could be used for a wind turbine.

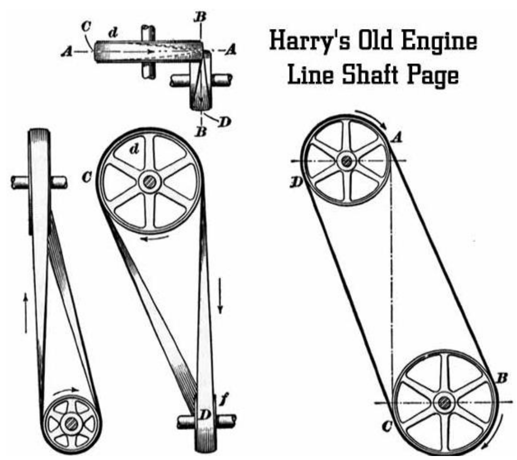


Figure 29: Right Angle Belt Drive (Matthews)

While most gearboxes generally have complex designs, a belt drive is simple enough to be usable for this application. It would simply be two wheels connected by a belt which can be twisted to achieve the desired turn angle. Additionally, the simplicity of its design makes construction and implementation cheaper and easier. In general, however, belt drives tend to be less reliable than standard gearboxes, resulting in a greater chance of mechanism failure during normal operation.

For the final turbine-pump design, the belt drive was selected. The materials required to construct a belt drive are fairly easy to find, and even if the drive fails, it is easy to repair. A conventional gearbox would be more expensive and would require additional time and money for routine maintenance.

Prototype Construction

Utilizing the design matrix, a Savonius-Darrieus Rope pump design was decided as the final product of this project.   The construction of the wind turbine was done in two separate parts, the Savonius turbine and the Darrieus turbine, and the rope pump was mirrored after a Dutch design for third world nations. The construction methods for these three sections are as follows.

Savonius Turbine Construction

The base for the Savonius turbine was a 5-gallon bucket sawed in half. This method was the easiest way to approximate the cup-shape necessary for the Savonius design. In order to affix the cups to the center shaft, two 1 foot long aluminium shafts were attached using angle brackets, as seen below in **Figure 30**.

Figure 30: Savonius Turbine

In order to affix the arms securely to the turbine, holes were drilled in the arms and angle brackets were attached with bolts. These bolts made it easier to attach and remove the arms because they were not permanently attached. This modular setup made it easier to store the components during construction and transportation. Because the thickness of the plastic sides of the buckets were too thin, they were reinforced on each side with ½ inch thick plywood to give the nail something to grip instead of the plastic. This method proved to be very effective in keeping the arms securely attached to the turbine.

Overall, the construction of the Savonius turbine was fairly simple and straightforward, which fit with the goal of this project. It should be easy to reproduce this design with limited third world technology.

Darrieus Turbine Construction

The construction of the Darrieus turbine was somewhat more complex, due to the precise nature of airfoil construction. The final airfoils were constructed using insulating foam covered in a layer of fiberglass, to ensure that the airfoils would be strong and light.

The shape of the airfoil is based on the NACA 0015 shape. This shape means that there is zero camber to the airfoil. In order to create this shape, a cross section of the specific shape and size of the airfoil was laser cut out of a piece of acrylic.

Figure 31. Acrylic NACA 0015 cross section

These cross sections were carefully attached to an 8 inch wide block of foam and cut with a hot wire cutter. This created an 8 inch section of NACA 0015 airfoil. However, the airfoils needed to be 2 feet long, so three sections were cut and glued together end to end.

In order to prepare the fiberglass, the fiberglass mesh was cut into a size equal to the surface area of the airfoil, with a ¼ inch excess on each side. A section of peel ply was also cut to the same size. Next, the fiberglass resin and the fiberglass hardener were mixed. Once the resin and the hardener were mixed, they needed to be applied quickly or the mixture will harden. A layer of the mixture was applied to the surface of the foam airfoil, after which the layer of fiberglass mesh was applied. All of the air bubbles were removed from the mesh and some more of the resin was applied. In order to soak up the excess resin, a layer of peel ply was wrapped around the outside. This had the added advantage of creating a smooth, uniform outer layer that could be safely placed on a surface to dry. The entire airfoil was placed in a vacuum bag, which prevented air bubbles from forming during the drying process, and left overnight to dry. Once finished, the excess fiberglass was cut off using a bandsaw and the airfoils were ready to be used.

The airfoils were attached to the center shaft using a technique similar to the one used for the Savonius. Angle brackets were attached to both the shaft and airfoils, and connected by a 1 foot aluminium rod. Bolts were used to connect the angle brackets to make it easier to quickly remove the aluminium rods for transportation and storage.

The shaft itself is constructed of 2 inch diameter schedule 40 PVC, into which the angle brackets were affixed using screws. The shaft is held to a base constructed of welded steel, which has a vertical metal shaft bolted onto it. Attached to this shaft are two ball bearing setups, designed to allow the outer PVC shaft to rotate around. The entire configuration can be seen below in **Figure 32**, and the construction guide can be seen in **Appendix B**.

Figure 32. Completed Savonius-Darrieus wind turbine.

Airfoils

First considering the Darrieus, due to its light weight and durability, a design decision was made to create the Darrieus airfoil wings from fiberglass. Fiberglass is easily molded into any desired shape while maintaining a light load and drying into a robust material. The shape of the airfoil was made from Styrofoam insulation using a hot wire cutter. To make certain the shape of the airfoil was cut correctly, a thin cross-section of the airfoil was created in SolidWorks and then laser cut out of acrylic material. This shape was attached to either end of 6 inch by 4 inch foam insulation sections. The hot wire cutter was pulled along the NACA 0015 airfoil shapes until a 8 inch section of the 2 foot airfoil was successfully outlined. Each airfoil consisted of three 8 inch sections glued together and carefully sanded before the fiberglassing process took place. The fiberglass material was in the form of a flexible, white fabric. Prior to mixing the epoxy chemicals, the fiberglass fabric was cut to cover the entire 2 foot airfoil foam with an overhang of ¼ inch extra fabric. After protecting the work area with plastic, the two chemicals of the epoxy were mixed, five parts resin and one part hardener. The epoxy needed to be used within five minutes of mixing. Carefully, the epoxy was spread over the foam with a roller to act as an adhesive for the fiberglass fabric. The fiberglass was then immediately applied over the shape of the airfoil and all air bubbles were brushed out any of the open ends away from the rounded airfoil edge. The wet, fiberglassed airfoil was then left to dry for approximately 24 hours. After the 24 hour drying time period, the excess ¼ inch fiberglass material was carefully cut from the edges leaving a 2 foot NACA 0015 airfoil.

Rope Pump Construction

The rope pump design for this project was based on a document created by a Dutch organization, WOT, which focuses on construction of a low-tech water and energy mechanisms for developing nations (WOT, 2012). Some design modifications were made to yield better lubricated connections as well as weight considerations so that the final design is relatively light and portable. For ease of construction and to keep cost low, most of the rope pump was created out of PVC pipe. PVC is a type of plastic with a friction coefficient of 0.2 when dry and as low as 0.04 when lubricated and functions with high strengths in tension and wear. In tensile strength, PVC can take loads up to 62 megapascals and a bending strength between 69 and 114 megapascals. This material is strong, lightweight, and inexpensive. Additionally, PVC is conveniently found at most commercial building stores since it is the most widely used municipal water supply and sewage material (PVC, 2013).

Figure 33: Final Constructed Rope Pump

For this project, PVC was used for the rotating shaft to support the wheel, the frame to hold the wheel shaft and pipe, as well as the pipe to draw the water from the water source (**Figure 33**). The wheel was made from a spare tire as in the guide. The benefits of using a tire are due to its high friction coefficient (up to 0.9) as well as the small rubber fins protruding from its surface. The high friction coefficient and gripping fins are used to pull the rope and pistons upward through the pipe and faucet as the tire spins (**Figure 34**). Most ropes with high tension properties can be used for this pump; however, the rope needs to be thin enough to tie knots on either side of the discs and not exceed the disc's diameter. For the ½ inch PVC pipe, 1/4M washers were used as pistons to provide minimum clearance; however, the piston discs can be made from metal, plastic, or even excess rubber from the wheel.

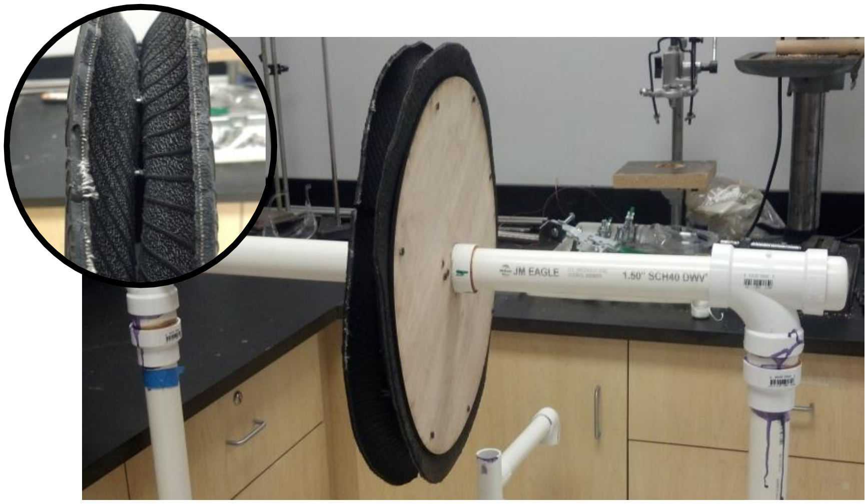


Figure 34: Pump Shaft and Tire Texture

The water is lifted through the pipe by the discs and deposited in a reservoir. Due to the nature of the design, there is no pressure generated by the pump; the weight of the water directly opposes the lifting force generated by the rope pump. Even though the design condition calls for the water to be lifted from 35 feet underground, the narrow pipe diameter means that the weight of the water is fairly low. However, due to the low-tech nature of the pump, there are significant losses due to friction and leaking. A complete rope-pump construction guide is provided in **Appendix B-2**.

Idealized Final Design for Fraserburg, South Africa

Figure 35 displays the desired layout for a Savonius-Darrieus wind pump to be implemented in Fraserburg, South Africa. The combined Savonius-Darrieus wind turbine is elevated to a height of 10 meters in an area with favorable wind characteristics. The turbine will turn the rope pump, which will lift drinking water from deep underground. The lifting force is generated by rotating the wheel using the wind turbine. The axle is attached by belt drive to the rotating shaft which is turned by the turbine. The overall structure will be lightweight, inexpensive, and easy to maintain in a third world country.

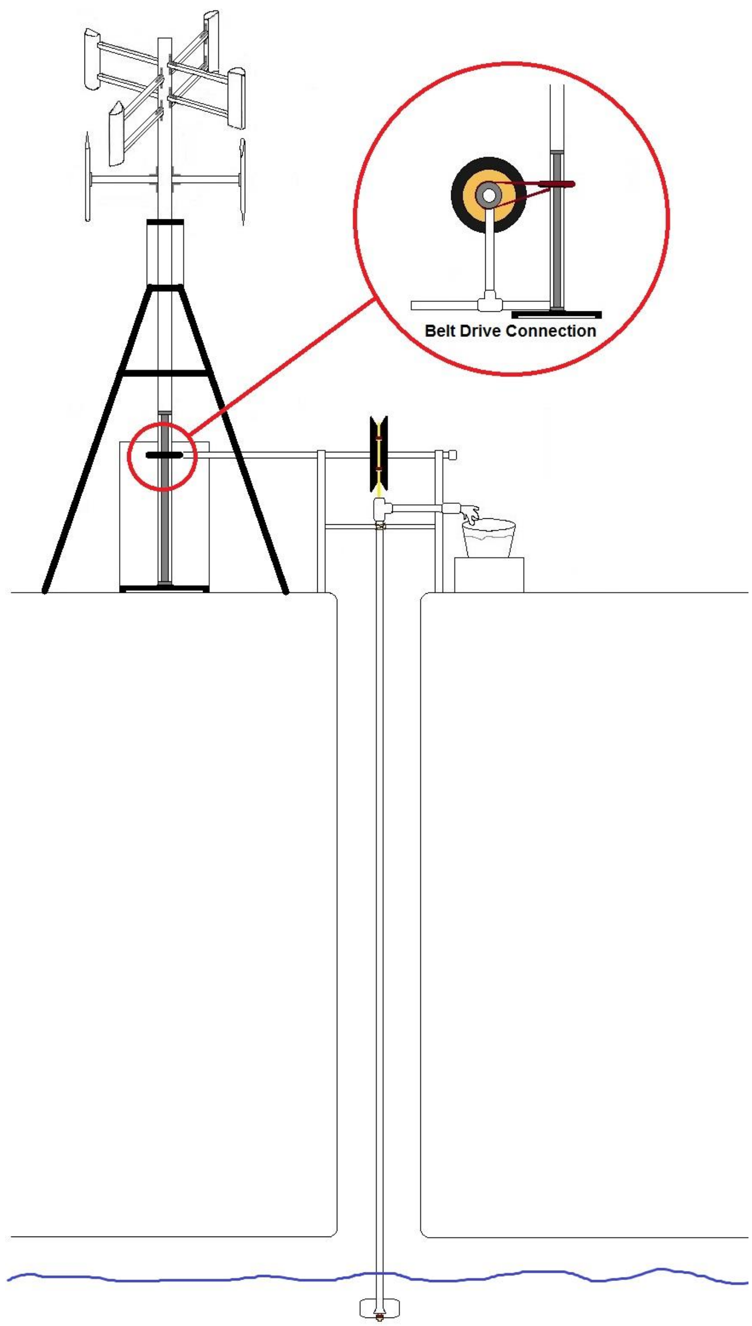


Figure 35: Fraserburg Wind Pump Design.

Due to certain limitations on campus, this project did not have the resources to accurately mirror the exact situation in Fraserburg, South Africa. As such, the design to be tested at WPI will be slightly different (**Figure 36**).

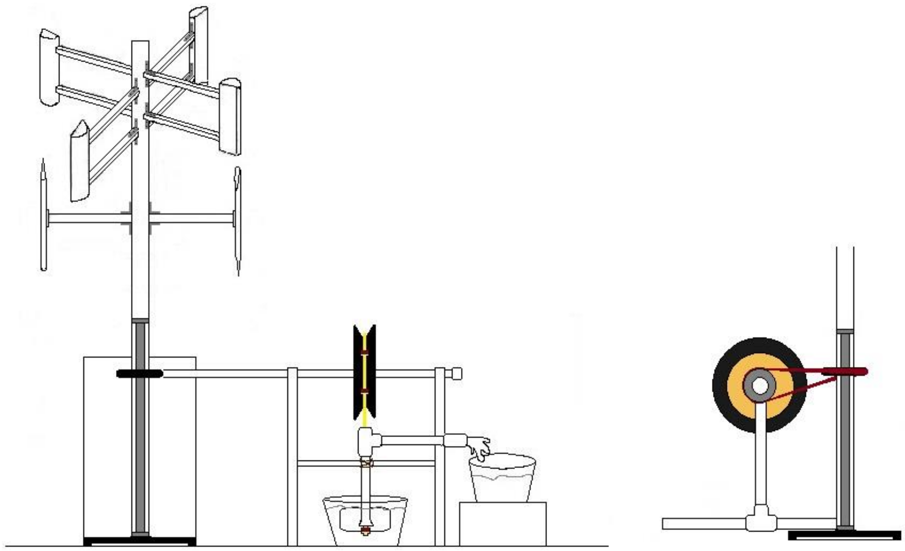


Figure 36: WPI Testing Design

The size of the Darrieus blades and Savonius blades remained the same; however, the entire structure is not as far off the ground. The WPI turbine setup was built on a 10 foot shaft made of 2 inch PVC. Additionally, no well was utilized to test the project. During the process of attempting to emulate the Fraserburg design, no satisfactory method was derived. Instead, the pump was tested to make sure that the device can create a satisfactory flow through the pipe and the amount of torque required to generate this flow was measured.

Material Availability and a Package Concept

For this project there was a large focus on the feasibility of reconstruction in a third world country. When researching available materials, this topic was found highly dependent on the location at hand. Many rural areas in Africa do have access to home-run wood shops, basic tools, and scrap materials (Cole, 2008). Residents of these areas tend to be very creative in how to construct homes, wash areas, and other facilities of need. While some areas do not have access to developed cities in Africa, other are capable of even purchasing basic materials from small construction shops selling tools, wood, nails, and other simple resources. The areas that are less fortunate rely on NGO aid, local innovators, and available scrap (Cole, 2008).

For this project, many of the materials were based on easily obtainable resources. Items such as the tire for the rotating shaft and buckets for the Savonius are likely to be available in many third world areas. If buckets or tires are not available, any light weight material that can be shaped into a semi-cylinder or other rubber material can work to cover the same functions. Many other items for this design can be replaced with other readily available materials as well, provided many of the characteristics remain the same. Additionally, if some of the more difficult materials such as the shape of the Darrieus airfoil, the ball bearings for the shaft, or the fiberglass material is not easily obtained, there is the idea to manufacture a small package in the United States to send a smaller list of materials to areas interested in this wind-pump application. To limit cost, the more complex aspects of this design were limited to minimize the size of the kit that would be provided as construction aid.

Chapter 4: Results and Analysis

The basic requirement for the pump-turbine design was that the system provides an adequate amount of water for a small village: 20 cubic meters of water per day. More generally, the construction and maintenance of the wind pump needed to be possible in a third world country. This provided a set of guidelines around which the prototype pump could be designed. In order to increase pump volume flow for the actual model, the size of the main water pipe would likely be increased. This would allow the pump to bring more water to the surface with every revolution.

The pump needed to pump at least 0.231 liters per second in order to meet the minimum defined requirements. To find the maximum pump flow rate, the pump was powered by hand at varying speeds. A representation of the data points collected can be seen below in **Figure** 37.

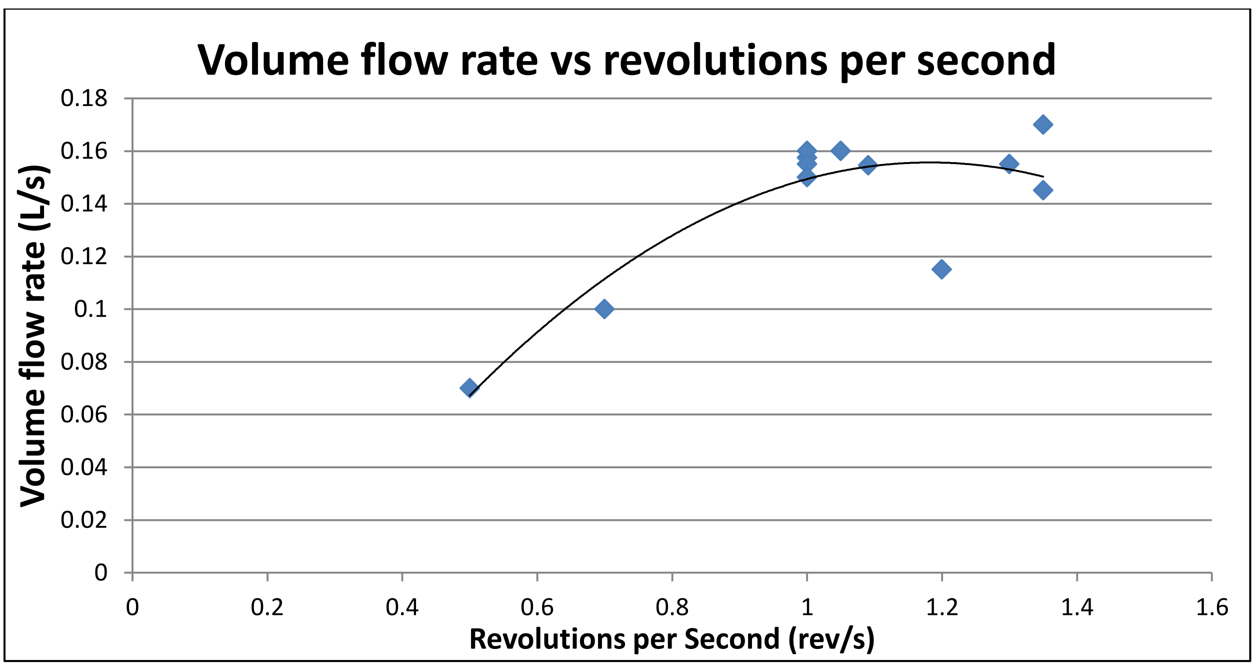
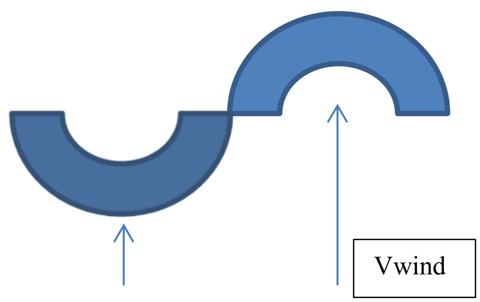


Figure 37. Volume flow versus revolution speed.

It can be seen that there is a maximum flow rate that can be provided by the pump (0.156 liters per second, corresponding to a speed of 1.18 revolutions per second). Rotating the pump any faster resulted in leakage losses due to the design of the pump.

For the combined Savonius-Darrieus, the power generated by the turbines can be estimated by calculating the expected torque. The Savonius turbine relies only on drag to turn. As such, the total turning torque of the mechanism can be approximated by considering the drag force on the “cups” to be applied directly on the middle of each cup. This can be seen here:



The drag force on a surface can be evaluated as:

$$F_d = \frac{1}{2}\rho_{wind} A v_{wind}^2 C_d$$

Where ρ is the density of the surrounding air, A is the cross sectional area, v_{wind} is the wind velocity, and C_d is the coefficient of drag on the surface. For a concave semicircle, the drag coefficient is 2.3, and for a convex semicircle, the drag coefficient is 1.2. By evaluating the above expression using the available parameters, the net drag is evaluated as 2.9 newtons, applied at the middle of the Savonius cup (which is the same as the radius of the Savonius turbine). Using equation 8 above, the torque generated by the Savonius can be estimated to be 1.33 newton-meters.

Another method, which can be used for both the Savonius and Darrieus turbines, is calculated using the following formula:

$$(8) \qquad P_{turbine} = \frac{1}{2} * \rho_{wind} * v_{wind}^3 * A_{cs} * C_p$$

With ρ as air density, v_{wind} as wind velocity, C_p as the coefficient of power, and A_{cs} as cross sectional area. While useful, this equation is very general and cannot be properly calculated without an accurate coefficient of power for the combined Savonius-Darrieus turbine.

Testing and Results

To determine the amount of power required to run the pump, the prototype pump was built and tested in the laboratory. Once functional, a piece of string was affixed at one end and wrapped around the shaft approximately ten times. Weights were then added to the string until the weights were able to pull the string and rotate the shaft at a speed of 1.18 revolutions per second. It was discovered that the weight required to turn the pump at the required speed was 14 pounds, or 62.3 newtons of force on the shaft (which has a radius of 2.4 centimeters). Using this equation for torque:

$$(9) \qquad \tau = F * r$$

this results in a required torque of 1.5 newton-meters on the shaft.

To determine how much torque was generated by the turbine, a rudimentary force gauge was created using a spring affixed to the shaft with a string. The string was affixed to the shaft at one end, and when the turbine turned in the wind, the string wrapped around the shaft and eventually pulled the spring a certain distance, which was recorded. The force generated by the turbine could then be calculated using the spring constant of the spring.

The spring constants of two different springs were calculated by measuring the elongations of the weighted springs. The results of this measurement can be seen in **Figure 38**.

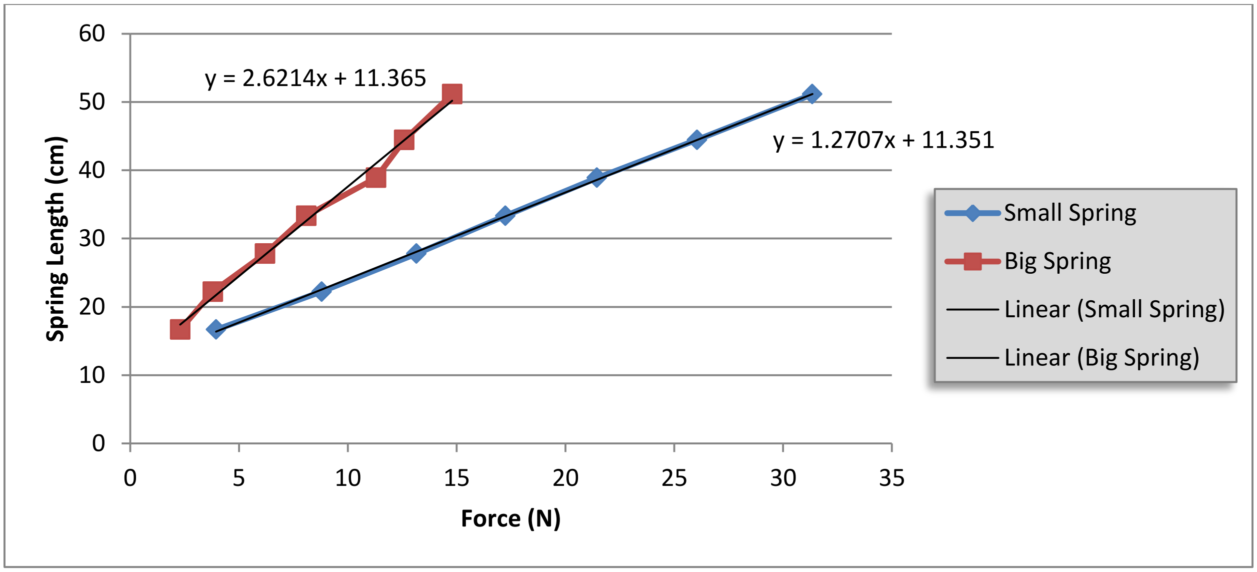


Figure 38. Spring constants.

The small spring was selected for use in the test, which has a spring constant of 1.27 newtons per centimeter.

By attaching the spring to the wind turbine shaft and measuring the elongation of the spring, the force on the spring (and therefore the torque generated by the turbine) was measured. Using a wind speed of 5 miles an hour (or 2.23 meters per second), the spring elongation was measured as 14.9 centimeters. This means that the turbine provided 18.92 newtons of force to the spring. Calculating the torque using equation 9, with a turbine shaft radius of 2.4 centimeters, results in a torque of 0.454 newton meters. This is below the required torque for the pump; however, the wind turbine was tested using a relatively low wind speed, and wind power increases as a function of wind velocity cubed, as seen in equation 8, which is redisplayed below for clarity.

$$(8) \qquad P_{turbine} = \frac{1}{2} * \rho_{wind} * v_{wind}^3 * A_{cs} * C_p$$

$$(10) \qquad P = \tau * \omega$$

Also printed above is an equation that expresses the power, P, as a function of torque (τ) and rotational speed (ω). For the prototype pump, there is a specific optimal rotational speed at 1.18 revolutions per second, as stated above. For the prototype turbine, the rotational speed (and the power) will increase as the wind speed increases, as shown in equation 8. Using this equation, the power generated by the wind turbine can be estimated and matched to the power required by the pump, as calculated using equation 10:

$$P = \tau * \omega = [1.5\ N * m] * \left[1.18 \frac{rev}{s} * 2\pi \frac{rad}{rev}\right] = 11.2\ W$$

Which is displayed below in **Figure 39** by a blue line. The red line is a representation of the power from the turbine using equation 8, using a conservative estimate for the coefficient of power (0.1). It can be seen that the two lines intersect at a wind speed of 6.46 meters per second, just above the estimated wind speed for the region of 6.3 meters per second.

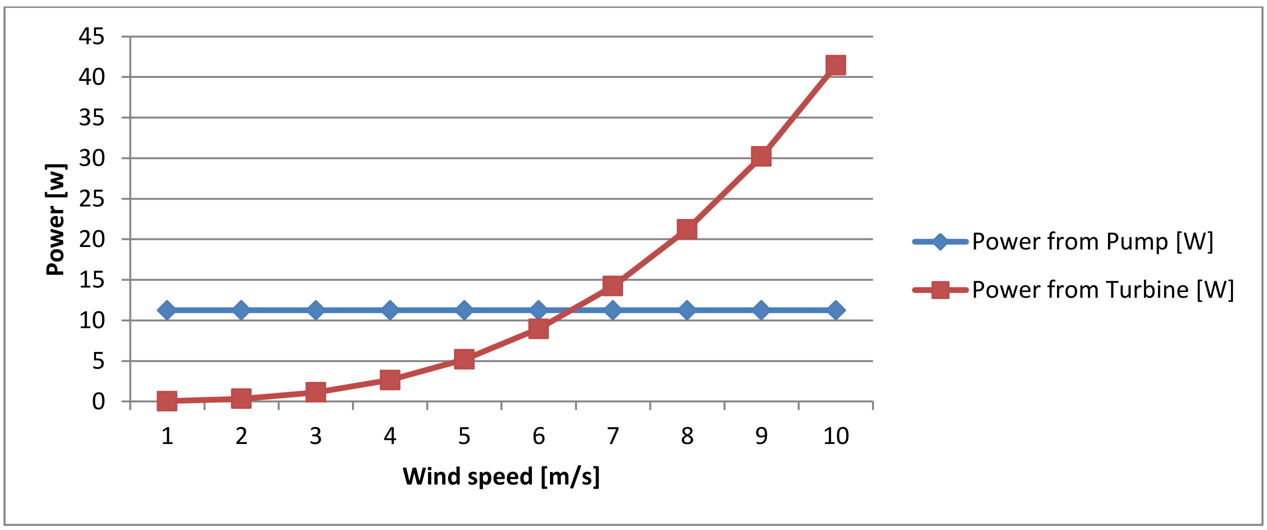


Figure 39. Power as a function of wind speed.

As stated above, the turbine is relatively inefficient at lower wind speeds. However, at the design condition, it can be seen that the turbine should be able to provide enough power to the pump to run it at its optimal speed.

Cost Comparison

Since one of the major aims of this project was to mimic a wind pump feasible for developing nations or a package that could be easily sponsored, the materials need to be fairly inexpensive. The project budget is on a similar level of available funds. The numerous competitive pump devices discussed earlier in the Background are compared in **Table 6**. As shown, there is a wide range in options and product costs from $900 USD to $10000 USD. Since many of the wind pumps currently on the market are electric, there is an added cost for battery and electrical connections.

Table 6: Current costs for wind pump comparison

Company	Product	Electric or Mechanical	Head	Price
WPI	Savonius-Darrieus Rope Pump	Mechanical	30m	**$310**
Survival Unlimited	Hand Pump	Mechanical	60m	$900
TF	Wind Unknown pump	Electric	N/A	$2345
Depon	Wind S.Stage Centrifugal	Electric	118m	$2568
Dahai	Wind Piston Pump	Electric	N/A	$3000
Most Common	Multi-blade Piston Pump	Mechanical	100m	$10000
Material for this table found from: Survival Unlimited, Alibaba				

The most common wind pump design uses mostly steel and can cost upwards of $10000 to build and install. For comparison, a hand-driven mechanical pump is even almost $1000. Working within a small budget, the final design for this project amounted to a total of $350 USD. The WPI prototype cost is based on the expectation that community members would construct the device themselves and thus does not include the cost of manpower. Most of the competitors' pricing does include manpower costs which would still be necessary for the high-technology methods for construction, however, excludes an installation charge which could add significantly to the cost. The WPI prototype competes very well against the options on the market and proves to be a more affordable to fit a third world country's water needs. For reference, the cost breakdown and parts list is included in **Appendix A**.

The affordability of the WPI wind pump design is due to the emphasis placed on the simplicity of the design and the limited budget with which the group worked. Ideally, the low cost of the turbine-pump system would make it more available to individuals or NGO's in third world countries.

Conclusions and Recommendations

This project concluded that a wind turbine of this size could adequately run the hand powered water pump design that was used. However, the flow rate is inadequate compared to the design specifications, with a final maximum flow rate of 1.55 liters per second (or 67.4% of the design condition of 2.3 liters per second). It is believed that, due to the prototype nature of the design, there was a significant amount of energy lost to friction and the low efficiency of the machines. In particular, the water pump experienced significant leakage and water loss during operation. However, even with this kind of flow rate, the pump is still effective at providing water.

The goal of this project was to design and build a turbine-pump system that could be constructed in a third world country. This means that the most significant design restrictions were related to the construction methods instead of the efficiency; as such, the design goal was to create a pump that was inexpensive rather than efficient. In that respect, the project was an absolute success. If this project were to be continued past the current stage, the project goals would likely change to focus more on the effectiveness of the turbine and the pump by improving efficiency and reducing losses present in the current design.

Appendix A: Cost Breakdown

Contained here is a cost breakdown of the list of materials used for construction of the wind turbine and pump prototype designs.

Appendix A-1: Wind-Device Materials

Part #	Part Name	Material	Amount	Price Per	Total Price
1	Rotating Shaft 2" ID x 10'	PVC	1	$ 6.59	$ 6.59
2	1' Darrieus/Savonius Arms	Steel	4 x 3'	$ 5.57	$ 22.28
3	L-brackets	Aluminum	8 x 4pack	$ 4.12	$ 32.96
4	Airfoil Fiberglass Materials: Peel ply Fiberglass Mesh Epoxy Fiberglass Roller	Fiberglass Epoxy	 1 roll 1 roll 1 1	$ 98.34	$ 98.34
5	Airfoil Shape 2'x2'x1"	Insulation Styrofoam	1	$ 4.95	$ 4.95
6	Open Ball Bearing 2"OD 1"ID	Steel	1	$ 11.15	$ 11.15
7	Flanged Open Ball Bearing 2"OD 1"ID	Steel	1	$ 15.08	$ 15.08
8	Fixed shaft support 1"OD x 6'	Aluminum	1	$ 13.13	$ 13.13
9	Savonius Blade Bucket	Plastic	2	$ 2.60	$ 5.20
10	Bucket Lid	Plastic	2	$ 1.28	$ 2.56
11	3' H-frame bars	Steel	4 x 3'	$ 5.51	$ 5.51
12	Drywall Screws		1 pack (1 lb)	$ 6.47	$ 6.47
13	Machine Screw Nut 8/32"	Zinc	1 pack	$ 3.92	$ 3.92
14	Machine Screw 8/32x1.5"	Zinc	1 pack	$ 6.21	$ 6.21
15	Plywood	Wood	8 x [1" x 12"]	-	-
16	Masking Tape	Tape	1 roll	$ 2.27	$ 2.27
17	Sandpaper (120 grit)	Sandpaper	1 pack	$ 7.26	$ 7.26
18	Washers (1 cm)	Aluminum?	1 pack	$ 2.40	$ 2.40
19	Shaft screw base	Steel	1	-	-
				Total:	$ 246.28

Appendix A-2: WPI Testing Rope Pump Materials

Part #	Part Name	Material	Amount	Price Per	Total Price
1	Wheel	Tire	1	Scrap	$ 0
2	Wheel Support: Handypanel	Thin Wood	1	$ 9.37	$ 9.37
3	1 ½ " PVC x 10' Wheel Shaft Faucet Support Frame	Sch. 40 PVC	2	$ 4.97	$ 9.94
4	Faucet 1 ½" PVC 90-Degree Elbow 1 ½" PVC Tee SxSxS 1" PVC 90-Degree Elbow 1"x½" Spigot/Slip Bushing 1" PVC Tee SxSxS 1" x 2' PVC Pipe ½" x 10' PVC Pipe	Sch. 40 PVC	1 2 1 1 1 1 1	$ 1.46 $ 1.87 $ 0.66 $ 0.77 $ 0.86 $ 1.80 $ 1.81	$ 11.10
5	Frame Fixings 1 ½" PVC 90-Degree Elbow 1 ½" – 2" Adapter 2" PVC Tee SxSxS 2" x 2' PVC Pipe 1 ½" PVC Slip Cap	Sch. 40 PVC	4 2 2 1 2	$ 1.46 $ 1.54 $ 2.96 $ 3.97 $ 0.96	$ 20.73
6	Polypropylene Rope 10m	Polypropylene	1	$ 2.24	$ 2.24
7	1/4M Flat Washers (10 pc)	Plastic	2	$ 1.97	$ 3.94
8	PVC Primer and Cement	PVC	1	$ 7.51	$ 7.51
				Total:	$ 64.83

Appendix B: Fabrication Instructions

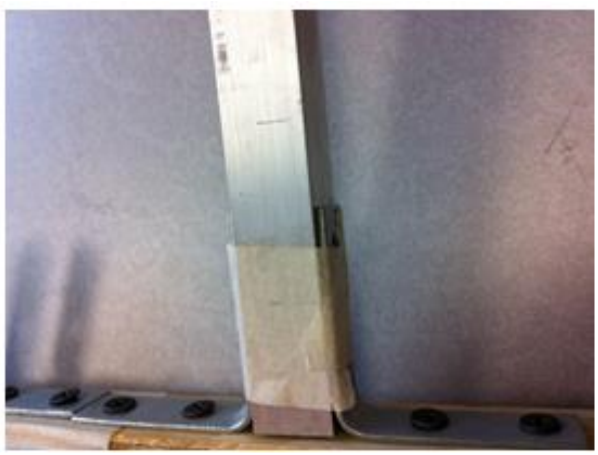
These appendices provide detailed instructions as to the fabrication of the WPI prototype designs of both the Savonius-Darrieus wind turbine and the rope pump.

Appendix B-1: Wind Turbine

Appendix B-1a: Center Shaft

1. Take the 3 foot Darrieus and Savonius arms and cut them into 12 pieces which are each 1 foot in length.

2. Using masking tape, secure four L-brackets [3] to each 1 foot piece of aluminum arm [2]. Ensure that each L-bracket is flush with the end of the aluminum arm.



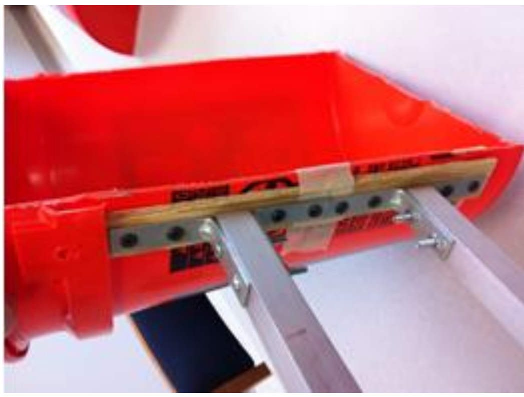
3. Mark the locations of the holes in the L-brackets on the arms.

4. Drill a small hole in each arm (slightly larger than the size of an 8/32" machine screw [14]) at the marked locations.

5. Fasten each L-bracket to the arm using the machine screws [14] and machine screw nuts [15].

6. Take the Savonius bucket [9] and the bucket lid [10] and attach the lid to the top of the bucket, ensuring that the lid is securely attached to the bucket.

7. Cut the bucket and lid in half lengthwise using a saw along its length. The resulting shape should represent the letter D if viewed from the top.
8. Use 4 drywall screws [12] to affix the L-brackets to the edge of the bucket. The screws should be fastened using the plywood [15] on the inside and the outside of the bucket for strength.

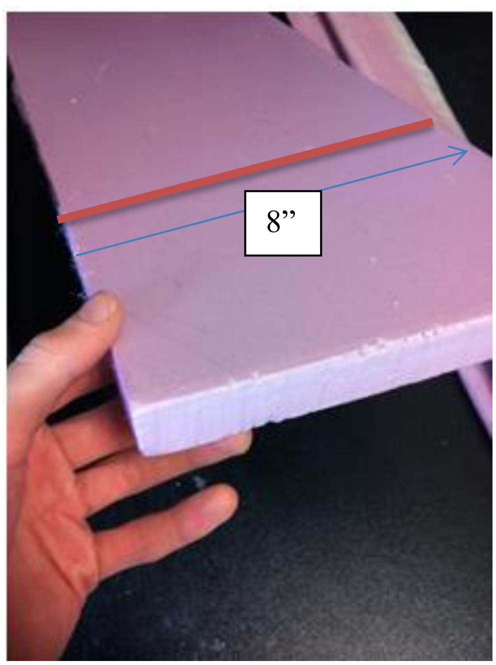


9. Once the arms have been attached to the Savonius turbine, secure the other end of one of the arms to the PVC shaft [1] using masking tape. Mark the locations of these 4 holes.
10. Pre-drill screw holes in the shaft using an 11/64" drill bit (this size matches up with the drywall screw size nicely).
11. Affix the L-brackets to the shaft using drywall screws and the pre-drilled holes. Once this is finished, remove the Savonius turbine by removing the machine screws and nuts from the L-brackets closest to the shaft.
12. Repeat this process for the other 3 Savonius turbines. At this point, the shaft should look as shown.

Appendix B-1b: Fiberglass Darrieus airfoils

1. Cut a cross section of the airfoil blade (for the purposes of this project, a laser cutter was used to cut a piece of acrylic into a NACA 0015 shape with two holes in it for mounting).

2. Cut the insulating Styrofoam [5] into a piece that is 8 inches long and wider than the airfoil cross section.



3. Secure the cross section to the side of the foam piece with screws. This must be able to be removed later.

4. Using a hot wire cutter, cut the foam into the shape of the airfoil. It should end up looking as shown.

5. This process needs to be repeated until there are six 8 inch airfoil sections (three for each blade).
6. Ensure that each section is smooth with no divots or ridges that would interrupt air flow.
7. Gently sand down the surfaces of the airfoils with 120 grit sandpaper [17] to make them smooth for the fiberglass.

8. Glue three of the pieces together, end to end, to form a complete airfoil blade, and wait for the glue to set.
9. Carefully cut a piece of the fiberglass mesh into a piece that is slightly bigger than the airfoil surface area (1/4 inch bigger on all sides). Ensure that the edges are straight and neat. For cutting purposes, a piece of masking tape should be put along the cutting area so that the edges of the mesh do not fray.

10. Cut a piece of peel ply that is slightly bigger than the airfoil mesh (it needs to cover the surface of the mesh while it is drying).
11. Mix the fiberglass resin and the hardener. **Once you reach this point, the fiberglass will begin to set. Be careful that you dispose of the fiberglass properly once it has done so**.
12. Using the fiberglass roller, apply a small amount of the fiberglass resin to the surface of the airfoil evenly along one side of the blade.
13. Apply the fiberglass mesh to the covered surface. The masking tape should not touch the resin part of the airfoil.

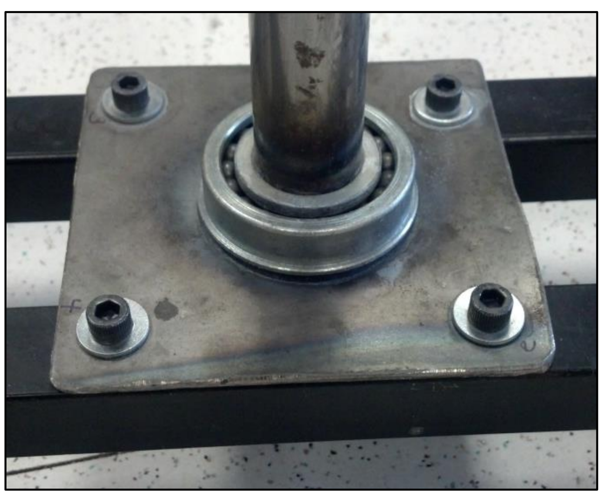
14. Repeat this process along the curved front and the back of the airfoil until the airfoil is completely covered with the mesh.
15. Roll the roller over the surface of the mesh to press it flat across the whole blade. There should be no air bubbles.
16. Repeat this process with the peel ply and set it aside to dry. Suspend it by its ends to ensure that the surface of the blade does not touch anything during drying.

17. Once dried, remove the peel ply and cut off excess fiberglass from the trailing edge and the ends.
18. Fasten two L-brackets to the end of the airfoil with masking tape and mark the holes.
19. Cut four holes in the completed airfoil. These holes should be the same size as the machine screws [14].
20. Glue washers [18] to the holes on one side of the airfoil. The side these are glued to will be on the opposite side from the L-brackets.

21. Attach the L-brackets using machine screws and nuts [14 and 15]. The completed airfoil can then be attached to the shaft using the same process as used for the Savonius arms (steps 2 – 5 and 9 - 11 in the Savonius construction).

Appendix B-1c: Wind turbine base

1. Take the fixed shaft support [8] and weld the shaft screw base [20] to the bottom of it.
2. Weld the flanged ball bearing [7] to the bottom of the shaft, on top of the shaft screw base.



3. Weld the other ball bearing [6] to the very top of the shaft.

4. Weld the H-frame bars [11] together to form the H-frame. The middle two bars of the H-frame should be spaced so that the shaft screw base holes line up with the center of the bars.

5. Mark and drill holes in the H-frame that line up with the shaft screw base.
6. (Optional step) Using pieces of scrap wood, level the 4 outer corners of the H-frame. This can be done by drilling holes through the frame and fixing the wood to the underside using long wood screws.
7. Secure the completed fixed shaft to the completed H-frame. The turbine can now be assembled completely by putting the fixed shaft inside the PVC turbine shaft to form the completed design.

Appendix B-2: Rope Pump

Appendix B-2a: Rope Pump Wheel and Shaft

1. Cut 1½"PVC into two 2' sections.
2. With a 1½" cross PVC fitting, use PVC cement to glue the two 2' PVC pieces into opposite ends. The empty fitting openings are to help attach the wheel to the shaft.
3. Take the scrap tire, dampen, and cut approximately 3" from the inside for the entirety of tire. Do so to both sides to obtain two rubber circles.

WOT, 2012

4. With a thin piece of wood, draw two circles that hang 0.5" past the inside of the tire. This leaves space to attach the wheel support to the wheel itself. Saw the circles.
5. Connect the two rubber tire circles so that the inner edge connects and the outer edges create a "V". Attach at two locations with short nails.

WOT, 2012

6. Place one of the two thin wood circles on one end of the newly constructed tire wheel and nail or screw through all three pieces (rubber–rubber–wood) from the wood side. The gripped texture of the tire should be on the inside to help pull the piston discs and water upward through the pipe.

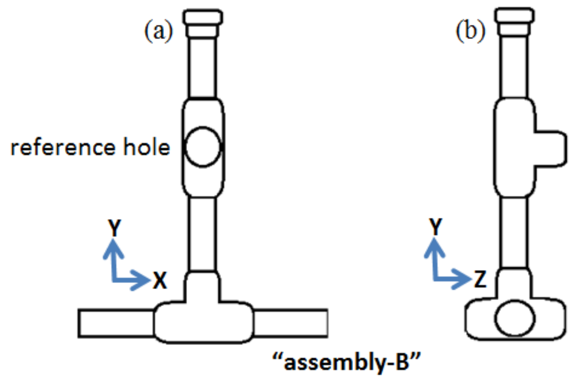
7. Onto the PVC shaft created earlier, slide the unfinished wheel until it hits the cross PVC fitting at its center. Screw or nail the wood piece to the unused openings of the cross PVC fitting.
8. Slide the second wood circle onto the other side of the shaft. Screw or nail through all four wheel pieces (wood–rubber–rubber–wood) starting from the exterior of the newly add wood piece.

Appendix B-2b: Rope Pump Frame

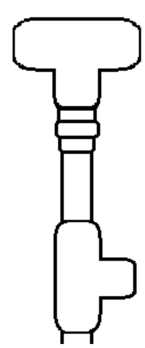
9. Cut 1½" PVC pipe into eight 2' sections.
10. Using a 1½" PVC T-fitting, glue two 2' sections into opposite ends. Using a second, third, and fourth 1½" PVC T-fitting, do the same for the remaining six 2' sections. Try to match these two assemblies as much as possible.

"assembly-A"

11. For two of the four assembly-A, glue a 1½"x 2" adapter on the north end of each. On the south end, glue the unused T-fitting of the remaining two assemblies to create assembly-B. The legs of the newly added assembly-A should be in the x direction (a), whereas the unused T-fitting from the original assembly-A is in the z-direction (b).



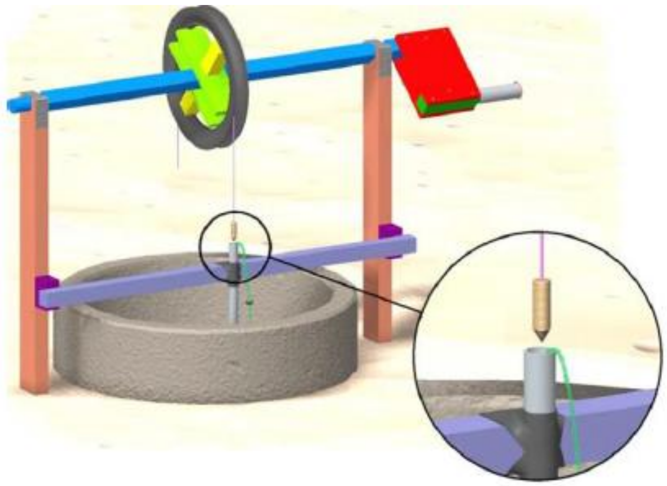
12. Cut 2" PVC into two 3" sections. Glue one of the 3" sections into the adapter on the north end of each assembly-B. To the free end of each 3" section, glue a 2" T-fitting as shown below.



13. Cut 1½" PVC pipe into two 1½' sections.
14. Glue each 1½' section to the opposite ends of a 1 ½" PVC T-fitting (assembly-C).
15. Glue each end of assembly-C to the reference holes of each assembly-B. Make sure the unused opening from assembly-C is facing up.

16. Glue a 4” section of 1½” PVC pipe into the unused opening of assembly-C which should be facing up.

17. Glue a 1½” elbow fitting to the 4” section so that the unused opening faces the opposite (perpendicular) direction of assembly-C.
18. Glue 1½” PVC pipe of approximately 12” in length extending outward from the unused opening of the elbow.
19. Now, sliding the free ends of the wheel shaft into the open 2” T-fittings at the most north end of the frame, adjust the wheel so that it sits directly above the newly added 1½” elbow and pipe.
20. Hang a string or rope with a weight at the end from over the wheel to where it lays on the 12” pipe extension. Mark this location (similar to the image below).



WOT, 2012

21. Cut the 12” PVC extension so that when a 1½” T-fitting is added to its end, the rope and weight fall directly in the middle of the T-fitting’s opening.

Appendix B-2c: Faucet and Rope

22. Cut a 12” section of 1” PVC pipe.
23. To one end, glue a 1” T-fitting and to the other end, glue a 1” elbow fitting. Be sure the unused elbow opening is in the same direction as one of the unused T-fitting openings (“adapter opening”).

24. Glue a 2" section of 1" PVC into the adapter opening.
25. Glue a 1"x ½" PVC adapter fitting to the end of the extending 1" PVC pipe.
26. From the free end of the adapter, the ½" PVC pipe used to deliver water to the surface is glued. The first ½" pipe section to be glued can be an arbitrary length since additional pipe sections will be added.
27. Glue a 6" section of 1" PVC pipe into the free T-fitting opening opposite of the adapter opening. This is used as a water safeguard.
28. Cut a 12" section of ½" PVC pipe. This will be the pipe section that is immersed into the water source. This ends needs to be flared to help catch the discs. Use a heat source and a cone to flare the end.

WOT, 2012

29. With either ¾" or 1" pipe, cut a 5" section. Flare one end of this pipe also (the lead).
30. Using a 5" section of 4" PVC Pipe, attach the two flared pipes to opposite ends (similar to the image below). The idea is that the rope enters the lead, is guided around a circular surface and enters the ½" pipe. This allows the rope to rotate without catching the discs on unwanted edges.

WOT, 2012

31. Finally, sit the faucet into the open T-fitting of the frame as shown below.

32. With couplings, attach the desired depth of ½" PVC pipe to the faucet extension and the flared extension.
33. With a diamond braded rope at the desired length (L_{rope}), slide ¼"M discs onto the rope and tie a knot directly on either side. The discs should be spaced 8"-12" apart.

$$L_{rope} = \frac{1}{2}\pi d_{wheel} + \frac{1}{2}\pi d_{lead} + 2L_{between\ centers} + 8"$$

34. Place the rope and discs around the tire, and through the entire ½” pipe.

35. To attach the ends of the rope together, use an adjustable knot as shown below.

WOT, 2012

Appendix B-2d: Completed Assembly

Appendix C: Mathcad

Appendix C-1: Savonius-Darrieus and Rope Pump Calculations

Required flow for a village is 500 m^3 per day

$$Q_{ideal} := 20\frac{m^3}{24hr} = 0.231\cdot\frac{L}{s}$$

The pipe water has a velocity, determined by how fast our mechanism is turning. This velocity is equal to the tangential velocity of the rotating shaft on the rope pump

$$r_{disc} := \frac{1.5}{2}ft = 0.229\,m$$

$$r_{shaft} := 24mm = 0.024\,m$$

The shaft radius is the same for both the turbine and the pump

$$\omega_{disc} := 1.2\frac{rev}{s}$$

This is the rotational speed for optimum pump operation

$$Q_{actual} := 0.155\frac{L}{s}$$

The torque required to turn the pump was measured using weights

$$m_{onpump} := 14lb = 6.35\cdot kg$$

$$F_{pump} := g\cdot m_{onpump} = 62.275\,N$$

$$\tau_{pump} := F_{pump}\cdot r_{shaft} = 1.495\cdot N\cdot m$$

The torque generated by the pump was measured using a spring turned by the pump

$$k_{smallspring} := 1.2707\frac{N}{cm}$$

$$dx_{smallspring} := 14.9cm$$

$$F_{turbine} := k_{smallspring}\cdot dx_{smallspring} = 18.933\,N$$

$$\tau_{turbine} := F_{turbine}\cdot r_{shaft} = 0.454\,J$$

Now we will calculate the torque generated by a rotating Savonius rotor (using only drag and neglecting friction for this calculation)

First, we calculate the drag forces generated by the Savonius buckets

$$\rho_{air} := 1.225 \frac{kg}{m^3}$$

$$v_{wind} := 6.3 \frac{m}{s}$$ Ambient wind speed for our region

$$r_{sav} := \frac{11.75}{2} in = 0.149\,m$$ The radius and height of a 5 gallon Home Depot bucket

$$h_{sav} := 14.5in = 0.368\,m$$

$$A_{cs.sav} := 2 \cdot r_{sav} \cdot h_{sav} = 0.11\,m^2$$

$$C_{d1} := 2.3$$ Drag coefficient for this shape -->)

$$C_{d2} := 1.2$$ Drag coefficient for this shape --> (

$$F_{drag} := \frac{1}{2} \cdot \rho_{air} \cdot A_{cs.sav} \cdot v_{wind}^2 \left(C_{d1} - C_{d2}\right) = 2.939\,N$$

Our rotors are going to be displaced on arms extending outward to increase the effective torque.

Additional torque is needed to overcome the initial friction and weight of pulling water into the pipe.

$$r_{offset} := 1ft = 0.305\,m$$

Therefore, the torque generated is:

$$\tau_{sav} := F_{drag} \cdot \left(r_{sav} + r_{offset}\right) = 1.335 \cdot N \cdot m$$

An alternative method for calculating the power from a Savonius and a Darrieus
(http://users.xplornet.com/~rmanzer/windmill/rotor_calculator.html#)

An array of efficiencies from 0% to 50%

$$C_p := 0.1$$

The power density is a function of air density and wind speed

$$PD := \frac{1}{2} \cdot \rho_{air} \cdot v_{wind}^3 = 153.154 \cdot \frac{W}{m^2}$$

For the Savonius

$$P_{sav2} := PD \cdot A_{cs.sav} \cdot C_p = 1.683\,W$$

For the Darrieus

$$h_{darrieus} := 2ft = 0.61\,m$$

$$r_{darrieus} := 1ft = 0.305\,m$$

$$A_{cs.dar} := h_{darrieus} \cdot 2 \cdot r_{darrieus} = 0.372\,m^2$$

$$P_{dar2} := PD \cdot A_{cs.dar} \cdot C_p = 5.691\,W$$

Appendix C-2: Piston Pump Calculations

PISTON PUMP

Piston Pump Calculations

Assuming 1 revolution per second, so the pump fills and discharges every second
However, changing ω.pump will modify the Q.pipeflow accordingly

$$\omega_{darrieus} := 0.5 \cdot \frac{1}{s}$$

$$ratio_{gearbox} := \frac{6}{1} = 6$$

$$\omega_{pump} := \omega_{darrieus} \cdot ratio_{gearbox} = 3\,\frac{1}{s}$$

$$Q_{pipeflow} := Q \cdot \omega_{pump} \cdot s = 9 \times 10^{-4}\,\frac{m^3}{s}$$

$$h_{pump} := 10cm$$

This is the pump height, not the head. This is related to the crankshaft length

$$r_{crankshaft} := \frac{h_{pump}}{2} = 5 \cdot cm$$

Because the pump needs to cycle through the entire pump in the whole cycle, the crankshaft needs to be half the length because it will pull it up by its whole length and then push it down by its whole length

$$r_{pump} := \sqrt{\frac{Q_{pipeflow} \cdot s}{\pi \cdot h_{pump}}} = 5.352 \cdot cm$$

$$m_{water} := Q_{pipeflow} \cdot \rho_{water} = 0.9\,\frac{kg}{s}$$

per cycle

$$l_{pipe} := 50m$$

Length of the pipe to the surface

$$r_{pipe} := 1.25in = 3.175 \cdot cm$$

$$V_{pipe} := r_{pipe}^{\,2} \cdot \pi \cdot l_{pipe} = 158.346L$$

$$m_{pipewater} := V_{pipe} \cdot \rho_{water} = 158.346kg$$

Appendix C-3: Multistage Centrifugal Pump Calculations

Rotational Speed and Radius for Centrifugal Pump

$g = 9.807 \frac{m}{s^2}$ acceleration due to gravity

$\pi = 3.142$ pi

$\rho_{water} := 1000 \frac{kg}{m^3}$ Density of water

$\rho_{air} := 1.255 \frac{kg}{m^3}$ Density of air

$h_{pump} := 10cm$ This is the pump height, not the head. This is related to the crankshaft length

$Q_s := 0.0003 \frac{m^3}{s}$ Pipe flow

$l_{pipe} := 50m$

$r_{pipe} := 1.25in = 3.175 \cdot cm$ Length of the pipe to the surface

Pump Blade Theory

$D_p := \frac{1}{2} in = 0.013 m$ Water pipe diameer

$A_p := \left(\frac{D_p}{2}\right)^2 \cdot \pi = 1.267 \times 10^{-4} m^2$

$\varepsilon := .0015$ roughness for PVC

$\frac{\varepsilon}{D_p} = 0.118 \frac{1}{m}$ relative roughness

$\upsilon := 1.004 \cdot 10^{-6} \frac{m^2}{s}$ kinematic viscosity @ 20* C

$Reynolds := \frac{(Q_s \cdot D_p)}{\upsilon \cdot A_p} = 2.996 \times 10^4$

$rough_{unitless} := \frac{\varepsilon \cdot m}{D_p} = 0.118$

$frictionstuff := \left[\left(\frac{6.9}{Reynolds}\right) + \left[\frac{(rough_{unitless})}{3.7}\right]^{1.11}\right] = 0.022$

$f_c := \left[\frac{1}{(-1.8 \log(frictionstuff))}\right]^2 = 0.113$ f as calculated using the Haaland equation

$\omega := 1500 \frac{rev}{min} = 157.08 \frac{1}{s}$ This is just as a reference, a new one is calculated below

$r_1 := 3.75cm$ impeller diameter from center to the inside of the blade

$r_2 := 12cm$ impeller diameter from center to the outside of the blade

$\frac{r_2}{3.2} = 3.75 \cdot cm$ the ratio of the two should be 3.2:1, or 16:5

$b_1 := 30.2$ blade angle in degrees, positive x is right and positive y is up
don't put the units on it in the equation or it will mess it up

$b_2 := 63.11$

30.2 and 63.11

$\beta_1 := \frac{\pi \cdot b_1}{180} = 0.527 \cdot rad$ blade angle (in radians), changeable by changing b1 and b2

$\beta_2 := \frac{\pi \cdot b_2}{180} = 1.101 \cdot rad$

$u_1 := \omega \cdot r_1 = 5.89 \frac{m}{s}$

$u_2 := \omega \cdot r_2 = 18.85 \frac{m}{s}$

For design point, α.1=90 and V.n1 = V.1 (taken from example 11.1, white 766

$V_{n1} := u_1 \cdot \tan(30deg) = 3.401 \frac{m}{s}$

$w_{blade} := \frac{Q_s}{2 \cdot \pi \cdot r_1 \cdot V_{n1}} = 0.374 \cdot mm$ Calculating blade width

$V_{n2} := \frac{Q_s}{2\pi\, r_2 \cdot w_{blade}} = 1.063 \frac{m}{s}$

$V_{t2} := u_2 - V_{n2} \cdot \cot(\beta_2) = 18.311 \frac{m}{s}$

$\alpha_2 := atan\left(\frac{V_{n2}}{V_{t2}}\right) = 3.322 \cdot deg$

Using EQ 11.18 from White (p. 767) to solve for the rotational speed as a function of head

Below is rotational speed solved given an outer radius (r2), head, and flow rate of pump.

$$\omega_{solved} := \left[\sqrt{\frac{\cot(\beta_2)\cdot Q_s^2}{4(2\cdot\pi\cdot r_2\cdot w_{blade})^2} + g\cdot h_{pump}} + \frac{\cot(\beta_2)\cdot Q_s}{2\cdot(2\cdot\pi\cdot r_2\cdot w_{blade})}\right]\cdot\frac{1}{r_2} = 11.08\cdot\frac{1}{sec}$$

Radius solved for given a desired rotational speed.

$$r_{solved} := \sqrt{\frac{h_{pump}\cdot g}{\omega^2} + \frac{\omega\cdot\cot(\beta_2)\cdot Q_s}{2\cdot\pi\cdot w_{blade}\cdot\omega^2}} = 2.125\cdot cm$$

re-check head backwards from r2 and rotational speed (omega).

$$H_{\omega solved} := \frac{(\omega_{solved}\cdot r_2)^2}{g} - \frac{(\omega_{solved}\cdot r_2)\cdot\cot(\beta_2)}{2\cdot\pi\cdot r_2\cdot w_{blade}\cdot g}\cdot Q_s = 0.107\,m$$

$$H_{rsolved} := \frac{(\omega\cdot r_{solved})^2}{g} - \frac{(\omega\cdot r_{solved})\cdot\cot(\beta_2)}{2\cdot\pi\cdot r_{solved}\cdot w_{blade}\cdot g}\cdot Q_s = 0.1\,m$$

$$H_{equal} := \text{if}\left[\left(\frac{H_{\omega solved}}{h_{pump}}\right) - 1 < 0.01, 1, 0\right] = 0$$

1 if true, 0 if false

$$\rho_{air} := 1.255\cdot\frac{kg}{m^3}$$

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