Harnessing Wind Energy with Recyclable Materials

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Team 03

Final Project Report

Document

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TABLE OF CONTENTS

Project Overview

Introduction

The "Harnessing Wind Energy with Recyclable Materials" (H-WERM) design project is a project initiated, and sponsored by Dr. Srinivas Kosaraju, a Mechanical Engineering professor at Northern Arizona University (NAU), located in Flagstaff, Arizona.

Client Identification

The client of this design project cannot be specifically identified as an organization or a corporation: the final project design is intended for individuals who are in need of relatively small quantities of electricity. The energy is intended to be used to provide basic living "luxuries" such as lighting and the use of fan(s).

Needs Identification

People who do not have access to power production facilities or the electrical grid are in need of electricity.

Project Goal and Scope of Project

Goal Statement: Design a home-sized wind turbine system that can be reproduced by individuals in need of electricity.

Scope: Provide an inexpensive, portable wind turbine system to harness wind energy. The wind turbine system will include both a wind turbine to generate electricity, and a means of storing the electricity generated.

Objectives

The project objective is to design a wind turbine system that is portable, easy to assemble, able to withstand high wind speeds, and can store and/or provide 0.5 kWh of electricity per day. This objective was determined by considering the following items:

- Portable: In rural locations, there is limited access to vehicles, fuel, and paved roads. As a result, the wind turbine system must be designed such that a few individuals can transport the system over long distances with varying terrain.
- Easy to build: In rural locations, especially third world countries, there may be limited access to tools, especially tools that require power for operation. Therefore,

the wind turbine system must be designed to be easily assembled and disassembled, using basic tools, by only a few individuals.

- 0.5 kWh of energy generation/storage per day: This objective was determined based upon the use of a 60 W light bulb and a 40 W fan, both running five hours per day.

Constraints

The following constraints were imposed on the H-WERM design project:

- The total budget must not exceed $50.
- The system must generate and store at least 0.5 kWh of electricity per day.
- The system must be built from common materials which are either recycled or otherwise sold at general hardware stores

Research

Horizontal vs. Vertical Axis Turbines

During the initial research period, the team considered designs of both horizontal and vertical axis turbines for the project. The axis alignment refers to the axis about which the turbine blades rotate. Both turbine types were researched and evaluated, and the positive and negative aspects of each were considered.

Since horizontal axis wind turbines mainly rely on airfoil design blades, they are powered by both lift and drag forces taken from the wind flow. This contributes to a higher efficiency, but a rotation system is required to keep the blades pointed into the direction of the wind. In contrast, vertical axis wind turbines can operate in wind coming from any direction, and are available in many different designs. However, they are only powered by drag forces, and not lift, and therefore are not as efficient as horizontal axis turbines. Based on the considerations of efficiency, the team settled on a horizontal wind turbine design for the project.

Horizontal Wind Turbine Analysis

The theoretical amount of power produced by a horizontal axis wind turbine can be calculated using Equation 1:

$$P = \frac{1}{2} C_p \rho v^3 A \tag{1}$$

Where:

- C_p = Coefficient of performance of the turbine
- ρ = Density of air
- v = Velocity of wind
- A = Swept area of the turbine

The coefficient of performance for a wind turbine depends on the turbine type and design, as well as the operating wind speed. The coefficient of performance is unitless and proportional to the following ratio:

$$C_p \propto \frac{kinetic\ energy\ in\ from\ wind}{power\ captured\ from\ turbine\ rotation} \tag{2}$$

Coefficient of Performance

The true C_p of any design is restricted below a maximum theoretical coefficient of performance called the Betz Limit. The Betz Limit is derived from fluid mechanics and conservation of mass and momentum equations. This limit represents an ideal wind turbine, and is similar to the Carnot efficiency of a thermodynamics power system – no experimental turbine can exceed the coefficient of performance limit. The Betz Limit is approximately 0.59, meaning no turbine can capture more than 59% of the incoming kinetic energy of the wind.

Turbine Swept Area

The swept area of a wind turbine is the cross-sectional circular area that the incoming airflow interacts with directly. The turbine blade dimensions dictate this area – the length of each blade provides the radius of the total swept area. To begin the design of the project turbine, the power equation was rearranged as shown in Equation 3:

$$P = \frac{1}{2} C_p \rho v^3 A \ \rightarrow A = \frac{2P}{C_p \rho V^3} \tag{3}$$

This allows for calculation of the necessary swept area of the turbine, based on required power and estimated variables.

Design Assumptions and Calculations

For the engineering analysis, the following assumptions were made:

- Air density: $\rho = 1.2\frac{kg}{m^3}$
- Average wind speed: $v = 5\frac{m}{s}$
- Coefficient of performance: $C_p = 0.40$

Air density was estimated for operation under standard temperature and pressure conditions, average wind speed was estimated from Flagstaff weather data, and the coefficient of performance was estimated based on data for drag-based horizontal turbines. The following given project specifications were also included in the analysis:

- Required power: $P = 55\ Watts$

Based on these values and Equation 3, the required swept area for the turbine is 1.83 m^2. This allows for calculation of the radius of the swept area circle as shown in Equation 4:

$$r = \sqrt{\frac{A}{\pi}} \tag{4}$$

For the required area of 1.83 m^2, a radius of 0.76 m (30 inches) is necessary to obtain the power required for the project. The radius is the length required for each blade, and dictates the design of the turbine.

Final Design

Final Design Concept

Figure 1 contains a CAD drawing of the final wind turbine design concept. The main components of the design include a main rotating shaft, a pulley system, and a V-belt tensioning system. The prototype was constructed using the model as a guide.

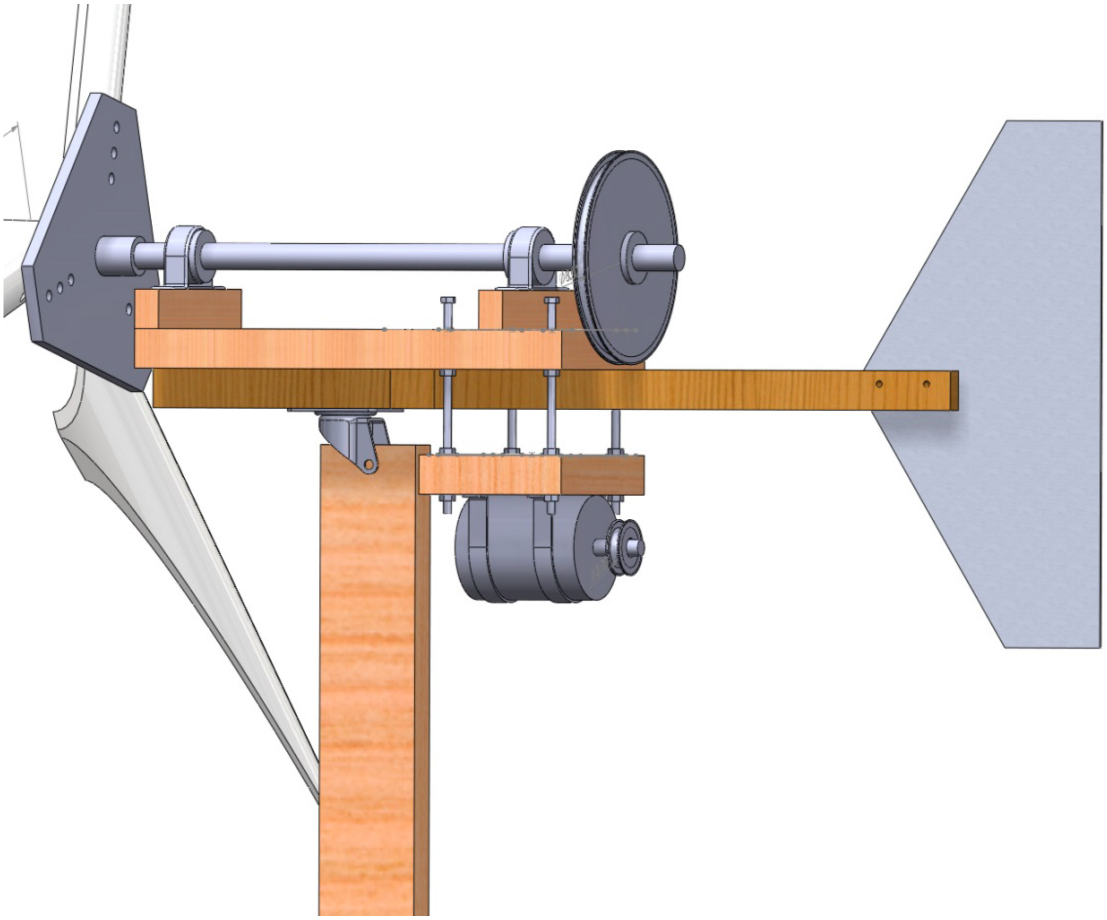

Figure 1 – CAD Model of Final Design Concept

The final design concept has three blades connected to a rotating main shaft. The blades are fashioned from a tube of schedule 40 PVC pipe, 6 inches in diameter. The blades are 30 inches in length, and are cut to roughly resemble an airfoil shape. The blades are mounted to a plate, made from a sheet of ¼ inch scrap steel, by radially spaced holes and scrapped fasteners. The plate is mounted to the main rotating shaft using a setscrew. The main rotating shaft is 1 inch in diameter, and is suspended between two 1-inch pillow block bearings. Two shaft collars, one located on the either side of the bearings, fix the horizontal location of the shaft. The rotating shaft and the pillow block bearings were found at a local hardware store.

A pulley system was included in the design concept due to rpm requirements of the Ametek generator. Through research and testing, the generator output was found to be 12 – 15 V DC when the shaft was rotating at approximately 400 rpms. Since the team could expect the turbine to spin at 100 rpm, for average wind speeds, a pulley system with a gear ratio of 4:1

was implemented in the design. A 2-inch diameter pulley is mounted on the generator shaft, and an 8-inch diameter pulley is mounted on the main rotating shaft. With this pulley system, more torque is required to turn the turbine blades, but the DC generator rotates four times faster than the turbine shaft, increasing the rpm input to the generator and thus the overall power production at lower wind speeds.

Within the pulley system, a V shaped belt is used to transfer the rotational load to the DC generator. This type of belt will operate with a no slip condition, sustaining grip with the least amount of friction. To achieve the no slip condition, a tensioning system was implemented in the design. This tensioning system contains four 8-inch bolts that go through the wooden base and connect to the DC generator plate, as shown in Figure X. These bolts have nuts and washers placed throughout their overall length, allowing the tension of the V belt to be adjusted.

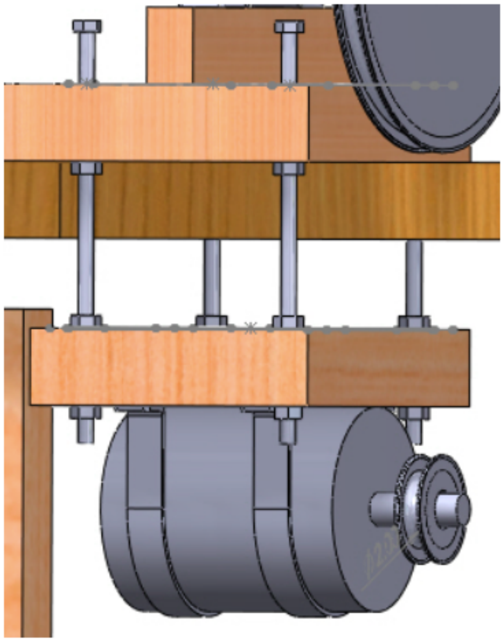

Figure 2 – Tensioning System

A weather vane and a caster wheel allow the turbine to rotate as the wind direction changes, increasing efficiency. As the wind changes direction, the normal force exerted on the weather vane causes the hub to rotate around the caster wheel, mounted between the hub and the post, until the turbine faces into the wind.

Prototype

Figures 3 – 5 are photos of the wind turbine prototype. By comparison of Figures 1 and 3, one can observe slight differences between the model and the prototype. During the manufacturing process, some minor design changes were implemented due to material availability, prototype testing, and to improve function. Major design iterations include the change from a 3-blade design to a 6-blade design, and the addition of both a nosecone and a testing stand. In general, the design modifications either positively or neutrally affected the function of the design.

Figure 3 – Prototype of Final Design

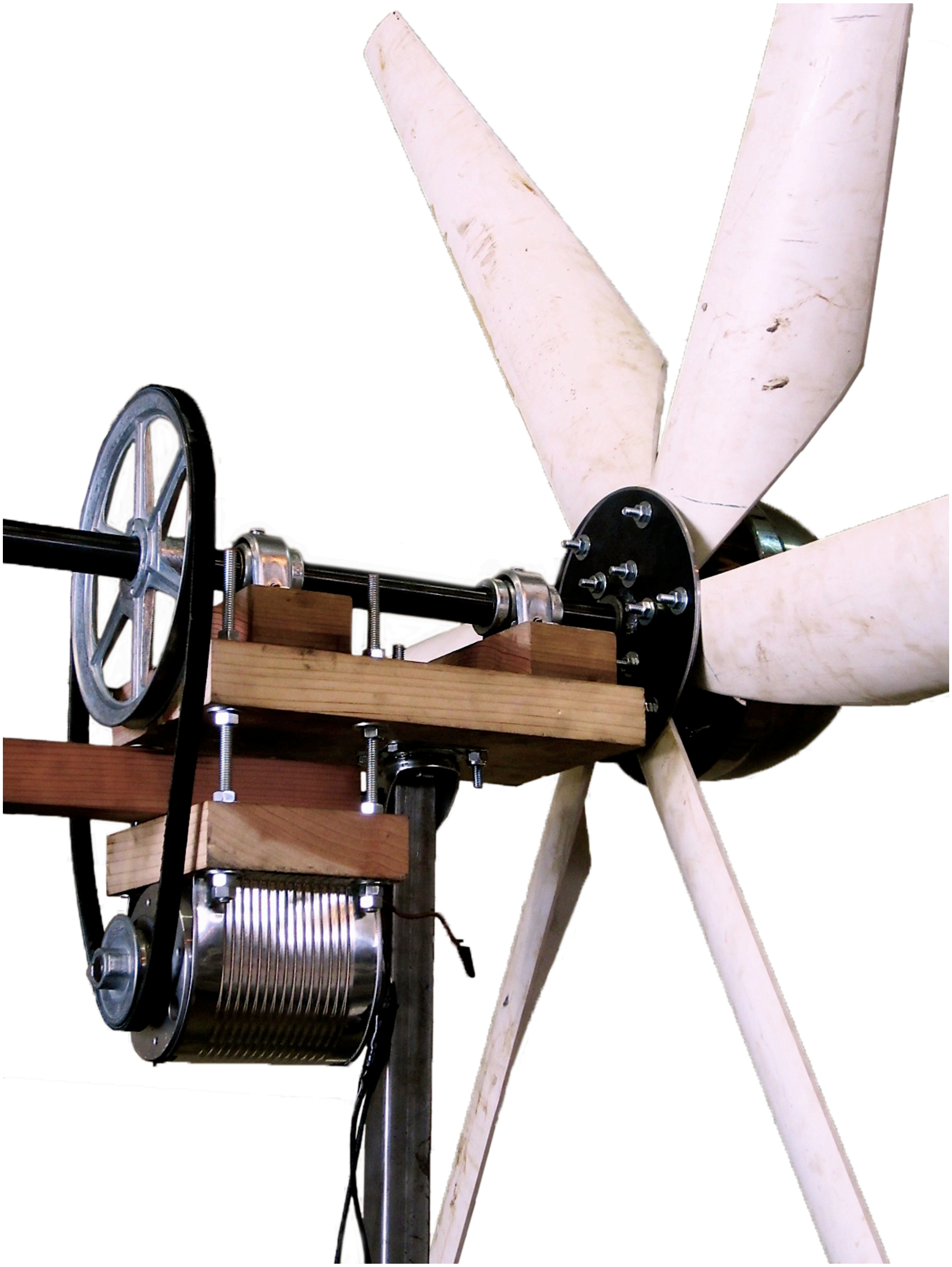

Figure 4 – Close-up View of Prototype Mechanical Components

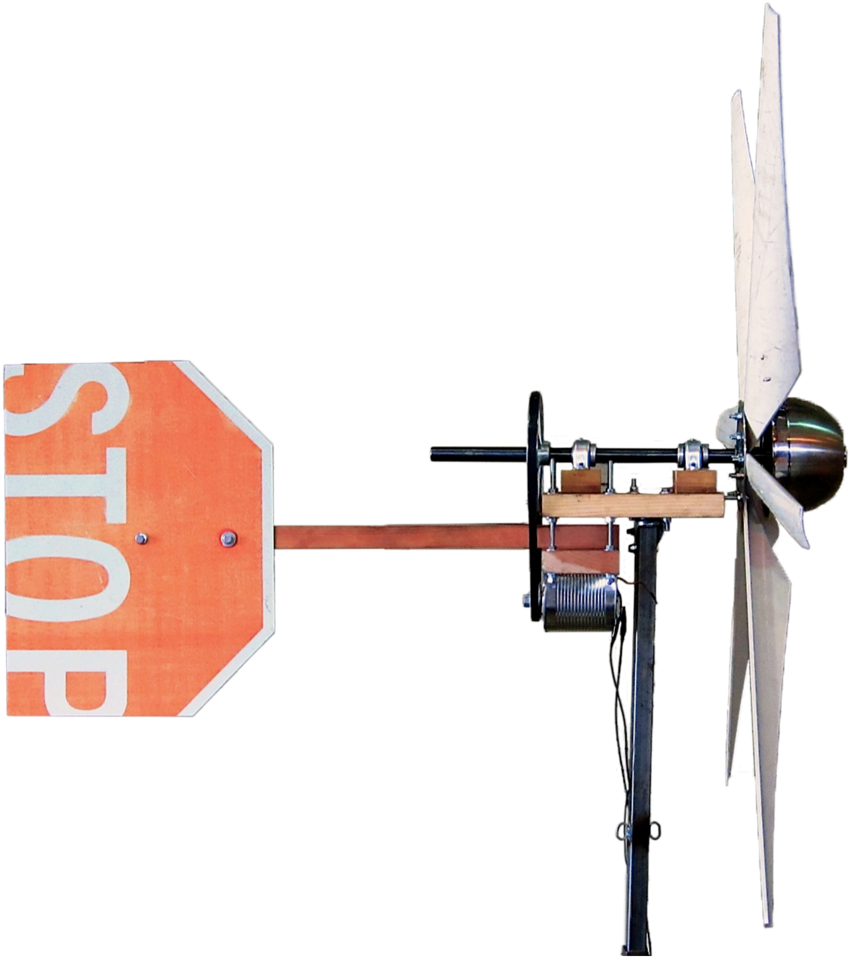

Figure 5 – Side View of Prototype

The prototype contains 6 blades mounted on a circular disk. During fabrication, the team decided to alter the 3-blade design due to starting torque requirements imposed by the pulley system. Increasing the number of blades in this drag-based system allows the blades to generate higher amounts of torque on the main rotating shaft at lower wind speeds.

The vertical orientation of the fasteners was changed several times during the design. Specifically, the orientation of the bolts used in the tensioning system and used to fasten the caster wheel to the wooden turbine base was changed. The tensioning system bolts were changed due to accessibility; it became easier to tighten and loosen nuts on the bolt shafts with the orientation shown in Figure 5. The orientation of the two bolts used to fasten the caster wheel to the wooden base was changed to limit the horizontal rotation of the turbine. This was achieved by flipping the two front bolts so the caster wheel could only rotate 180 degrees.

The central shaft of the wind turbine stands about 5 feet off the ground, to capture optimal wind flow. Since the wind turbine experiences a large moment arm and becomes top heavy, a strong base was built to withstand these forces. A truck wheel with a 6 lug 5.5 pattern was selected to create a base for the wind turbine. A base plate was created from a 1/8 inch steel plate and cut into a circle using a band saw. Three holes were drilled into the plate to match the 5.5 pattern and the plate was fastened using three bolts. A square cutout was created to make a slot for the stand to sit in, as shown in Figure 6. Although the wheel proved strong enough to hold the wind turbine up, it was not enough to withstand the wind forces across the blades.

Figure 6 – Turbine Base

An additional support was created by welding old chain links to the sides of the metal stand. Once the chain links were connected to the stand, ropes fastened from the stand to three 1-foot long stakes. The stakes were positioned about 120 degrees from each other to make a stable support. Combined with the steel base plate fastened to the truck wheel and ropes pulling in a 120º pattern, the wind turbine proved stable in wind up to 20 miles per hour.

Prototype Manufacturing

The team specifically attempted to build the turbine using tools and techniques commonly available to the general population. The purpose of building the turbine this way was to show it is possible to build a turbine using only basic machine shop techniques.

With the exception of one component, the entire system was build using basic tools and techniques. The blades were made by tracing a paper template of the desired blade shape onto the PVC pipe and cutting the pipe with a table saw. The rough edges of the blades were then smoothed using a palm sander. The wooden base pieces were cut with a table saw, and the fastener holes were created using a drill press and/or a hand held power drill. Other small tools such as wrenches, Allen wrenches, and ratchets were used to tighten fasteners and setscrews.

The PVC blades of the system were attached to the central blade hub by 12 bolts. This central blade hub was made from hardened steel. A CNC milling approach was first taken in making the hub, due to the precise process the mill generates. However, the end mill was not able to handle the steel, since it had been heat-treated and hardened. An alternative approach was to circularly cut the piece of metal with the band saw. This was not the most accurate process in obtaining a perfect circle, yet it proved accurate enough for our assembly.

As previously stated, the chain links connected to the side of the metal stand were welded to create added support. Although this process needed welding, chain links are readily available across the world and a few skills are needed to complete this task. In addition to the chain links, a couple shaft collars were welded to the central blade hub, one on each side, for the connection of the hub to shaft. The extra shaft collar added rigidity and increased the factor of safety to insure connection of the two parts.

Prototype Cost and Materials

Table 1 lists the components used to construct the prototype and their associated costs.

Table 1 – Bill of Materials

Component	**Cost**
Generator	$64
Battery	$35
Pulleys	$27
Bearings & Shaft Collars	$25
Nose Cap	$16
Shaft	$10
Epoxy	$9
Electrical wiring components	$5
V-Belt	$4
Caster Wheel	Scrapped
PVC Pipe	Scrapped
Wood	Scrapped
Metal Posts	Scrapped
Sheet Metal	Scrapped
Car Tire	Scrapped
Solder	Scrapped
Total Cost	**$195**

As shown in Table 1, the total cost to construct the prototype was $195, which exceeded our budget of $50. The most expensive components were the generator and battery. These components proved difficult to find salvaged. Other components, including the pulleys, bearings, shaft, and shaft collars were purchased to save time, but could reasonably be found in junkyards.

Prototype Testing

For testing, the turbine system was fastened to the bed of a truck using ratcheted tie down straps, as shown in Figure 7. The truck was driven at various speeds to simulate different wind velocities. The turbine wire leads were attached to a voltmeter and an ammeter to measure the voltage and current produced. Data sets, including current, voltage, and the digital speedometer readings, were recorded for vehicle speeds between 3 to 18 mph.

Figure 7 – Testing Procedure

Results

Figure 8 shows both the measured power output of the wind turbine and the theoretical maximum power output plotted against wind speed.

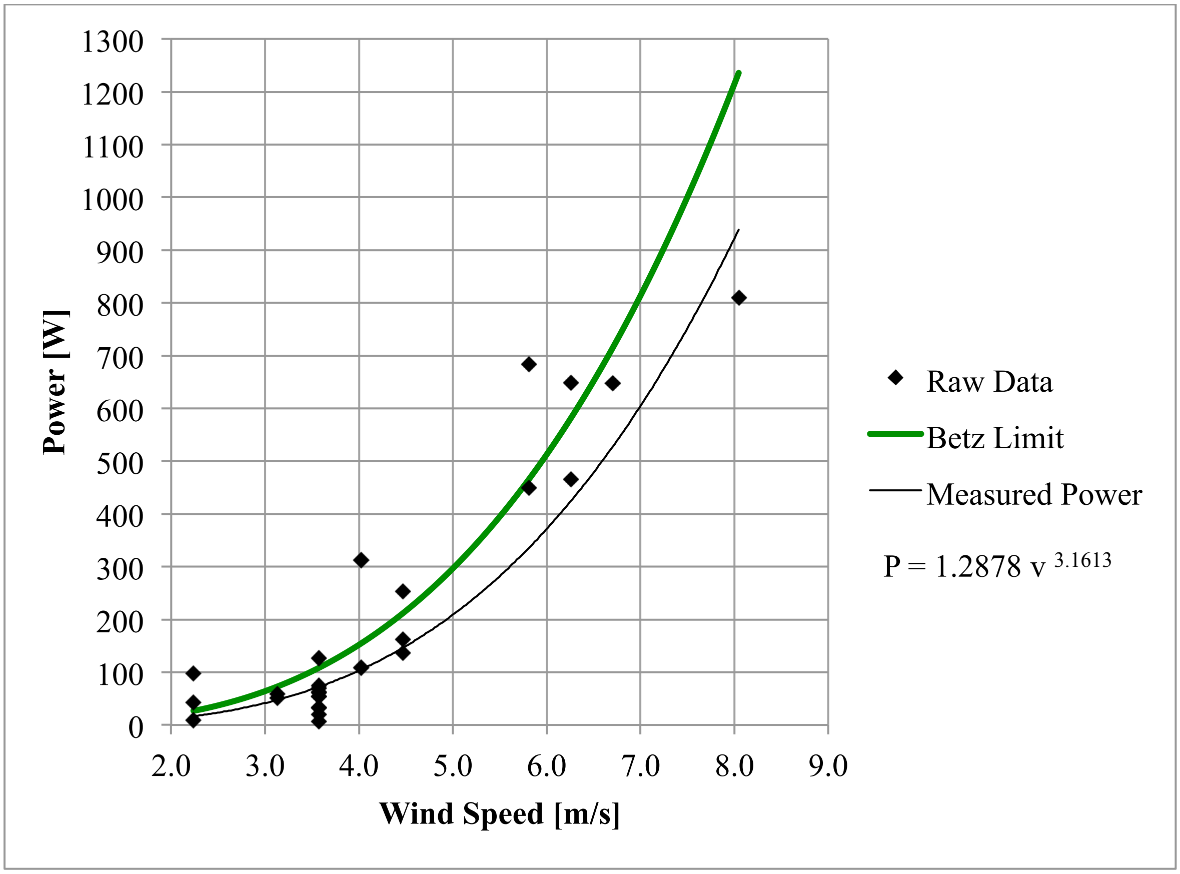

Figure 8 – Power Output vs. Wind Speed

Looking at Figure 1, one can see that the measurements are quite scattered. This is due to wind gusts, which were not accounted for in the wind speed measurements. Since the wind speed was measured as the velocity of the truck, tailwinds subtracted from the measured speed, lowering power output, while headwinds added to the measured speed, increasing power output. This is why there were several instances where the measured power exceeded the Betz limit, as well as several instances where the measured power was very low. Since there were both unusually high and low power readings, a regression analysis was performed on the raw data. The result was a polynomial trend line, with order n = 3.16. This is reasonable, because the theoretical wind power equation involves a cubic relationship between power and wind speed. In addition, the trend line graphically matches expected results, as it is lower than the Betz limit and similar in shape.

Using the equation of the trend line shown in Figure 8, the coefficient of performance (C_p) was calculated for the prototype. Figure 9 shows the calculated C_p plotted against wind velocity.

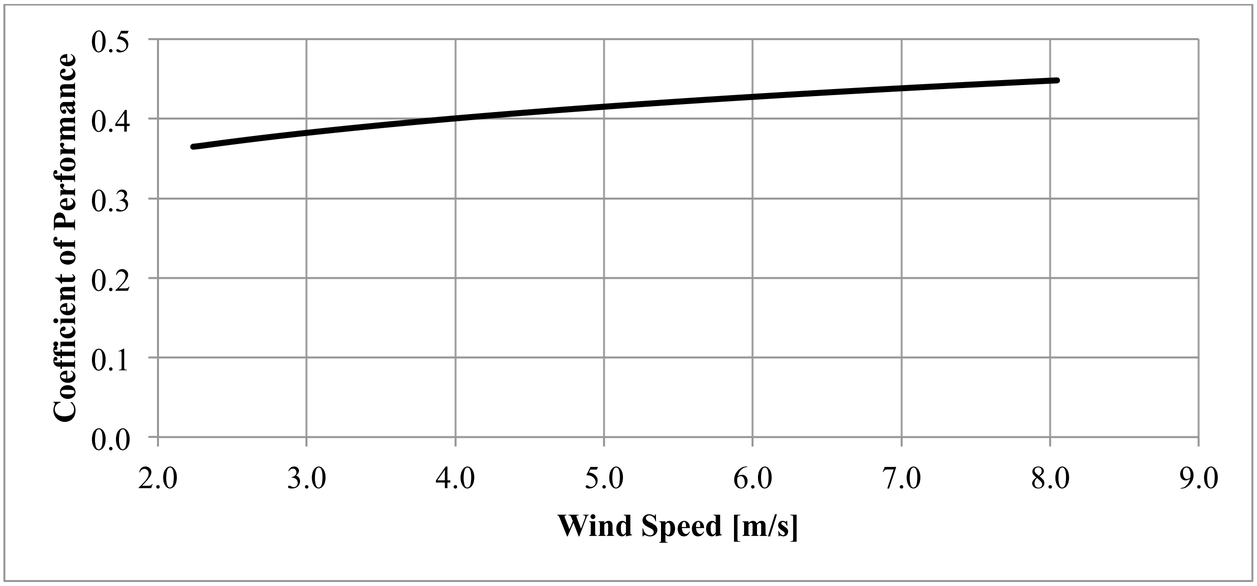

Figure 9 – Coefficient of Performance vs. Wind Speed

As shown in Figure 9, the coefficient of performance for this turbine ranges from 0.35 to 0.45, or an efficiency of 35% to 45%. While this may seem rather low, these efficiencies are actually very good considering the Betz limit is only 59%, and are on par with most commercial wind turbines.

Figure 10 shows the voltage output of the turbine plotted against wind speed.

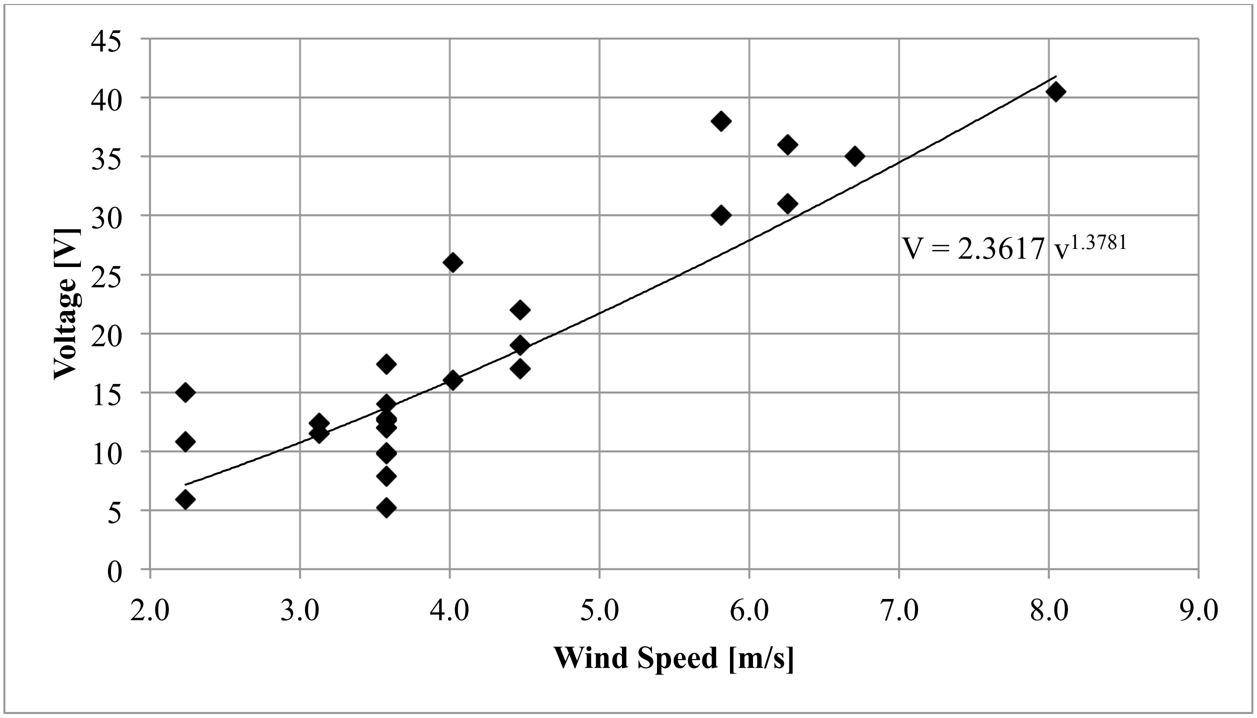

Figure 10 – Voltage Output vs. Wind Speed

To charge the battery chosen for this project (or any 12 V car or motorcycle battery), the required output voltage is 14 V. Based on the regression analysis of the data shown in Figure 10, the wind speed required for this wind turbine to produce 14 V is 8.14 MPH or 3.64 m/s. At this wind speed, 0.5 kWh of power could be charged in approximately 9 to 10 hours.

Conclusion

In conclusion, a portable home-sized wind turbine system was successfully built and tested. Overall, all the project goals were met – the final design can be disassembled into four pieces for ease of transportation, the prototype was constructed using mostly simple tools, and the system can generate 0.5 kWh of electricity per day, if provided with a wind speed of at least 3.64 m/s for 10 hours per day. However, the budget constraint of $50 was not met, due to the difficulty in finding salvaged generators and batteries that were still functional. However, the final cost of $195 is still quite reasonable for building a personal wind turbine.

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