2006-1476: DESIGN AND IMPLEMENTATION OF AN EDUCATIONAL AXIAL FLUX WIND TURBINE/GENERATOR

Recayi Pecen, University of Northern Iowa

Recayi Pecen holds a B.S.E.E. and an M.S. in Controls and Computer Engineering from the Istanbul Technical University, an M.S.E.E. from the University of Colorado at Boulder, and a Ph.D. in Electrical Engineering from the University of Wyoming (UW). He has served as faculty at the UW, and South Dakota State University. He is currently an associate professor and program coordinator of Electrical and Information Engineering Technology program in the Department of Industrial Technology at the University of Northern Iowa. His research interests and publications are in the areas of AC/DC Power System Interactions, power quality, and grid-connected renewable energy applications. He is a member of ASEE, IEEE, Tau Beta Pi National Honor Society, and NAIT. Dr. Pecen was recognized as an Honored Teacher/Researcher in "Who's Who among America's Teachers" in 2004 and 2005. He was also nominated for 2004 UNI Book and Supply Outstanding Teaching Award, March 2004. Dr. Pecen is nominated for 2005 Ross A. Nielsen Professional Service Award at UNI.

Francis Praska, University of Northern Iowa

Francis Praska is currently working towards a B.S. in Electrical and Information Engineering technology from the University of Northern Iowa, an Associate of Science in Electrical Engineering Technology from Northeast Iowa Community College. He holds a B.S. in Computer Science from Bellevue University at Bellevue Nebraska. He also holds an Associate in Applied Science in Information Systems Technology and Aircraft Armament Systems from the Community College of the Air Force. He served for 20 years in the United States Air Force and was honorably discharged in 2001. He is a member of the American Legion. He is married with four children. His interests are in electronics and outdoor activities.

Ashraf Al-Qassab, University of Northern Iowa

Ashraf Al-Qassab is a senior student working towards a B.S. in Electrical and Information Engineering Technology from the University of Northern Iowa. His interests are in electrical machinery, and power systems, electronics, and clean energy technologies. He has an associate degree from Hawkeye Community College (2002). He is working part time for monitoring Energy in Center for Energy and Environmental Education Building at UNI.

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Abstract

Wind turbines capture low and high speed winds throughout the world. This paper presents design and implementation of an educational, small-scale, axial flux wind turbine-generator. An axial wind turbine is easy to build, fun to learn and cost effective system designed using in almost any windy location in the world. Two students at the University of Northern Iowa (UNI) enrolled in a Bachelors of Science in the Electrical and Information Engineering Technology (EIET) major, have spent many hours researching various wind turbines. The subject matter presented in this paper are (1) design and build a cost effective 0.5 kW wind turbine capable of producing 12-48 V direct current (DC), (2) build two wind turbines with different configurations, (3) build a traveling display that can be taken to remote locations and educate anyone with questions, and (4) experiment with variable loads and blade designs. Senior students involved in this project have shown excellent progress by developing their technical and teamwork/social skills as part of the Senior Design I and II core courses and have been successfully completing their course requirements.

I. Introduction and Problem Definition

Worldwide, the need for electrical power has increased exponentially. Energy needs versus climate change relation has been a subject of a significant debate in the world. Recent scientific evidence indicates that global warming is underway [1]. Observed changes show that despite large variations from year to year, the global mean temperature has risen significantly in the last century [1]. Expected future increases in global average temperatures may have adverse, possibly irreversible effects on the climate, including changes in regional temperature patterns, more frequent extreme weather events and a rise in sea levels worldwide. Climate change may affect human life and the ecology of the planet in a variety of ways, including changes in agriculture, water supply and quality, human settlements, and human health, in addition to affecting biodiversity and migratory patterns and causing other eco-system disturbances [1].

In recent years, climate change science has made it clearer than ever before that human-induced global warming is underway. Climate change scenarios prepared by the Intergovernmental Panel on Climate Change (IPCC) show a wide range of possible impacts from global warming in the next century [2]. The observed global warming is largely due to increases in the emissions of greenhouse gases (GHGs) such as CO_2, CH_4, NO_2, HFCs, PFCs and SF_6 from various human and industrial activities. Ice core data show that changes in the atmosphere since pre-industrial times far exceed changes from the preceding 10,000 years [1-2]. Since ice cores trap air bubbles from the atmosphere over time, this provides scientists to measure directly levels of greenhouse gases associated with different times in history [1-2]. These changes are driven by worldwide population and economic growth, and underlying production and consumption of fossil energy, agricultural activity and land use change.

The impact of energy use on the environment is a result of several factors: the mix of fuels used to produce energy; the efficiency of conversion of primary energy into useful energy (including distribution); the technology in use; and the total level of energy used [3]. The use of fossil fuels in the fuel mix for energy with today's technologies continues to pollute the air and emit GHGs, though emissions as a percentage of output are declining. On the other hand, a renewable energy source, hydropower degrades the ecosystem by altering the ecological balance of river basins, with resulting effects on flora and fauna [1-3].

More than 80% of Iowa's current electrical energy demand is largely supplied by coal-fired power plants, that is 30 % more than the national average value of 50% [4]. Coal is slowly becoming a fossilized energy resource that has already been banned in some European countries such as Denmark that is a sample country with a sustainable-energy economy [1, 4-5]. The global warming and the climate change have been established as scientific facts by thousands of scientists worldwide, and the human activities such as the coal-combustion constitutes one of the major contributors to it [5]. Unfortunately there are more coal-fired power plant constructions and projects than any other energy investment in the U.S. today. Carbon emissions from coal-fired power plants are projected to increase by 45% between 2000 and 2025 due to the proposed construction of new plants [5].

Because Iowa generates 80% of its electricity from coal, it emits 86,000 tons of NO_x, and 148,000 tons of SO_x, and 42,069,000 tons of CO_2 according to the Energy Information Administration (EIA) and Department of Energy (DoE) [4, 6]. A new, a 750 MW capacity coal-fired power plant by LS Power Co. of New Jersey, which will cost about $1.2 Billion is planned in Cedar Falls-Waterloo area in Iowa [7-8]. Some of the significant reasons on investing coal-fired power plants are current economical conditions, existence of plenty of cheap coal resources, massive tax breaks, subsidies, incentives, and environmental regulations that are not strengthen enough by recent Administrations [9]. By burning fossil fuels particularly coal, and clear-cutting forests, humans are adding carbon dioxide and other heat-trapping greenhouse gases to the atmosphere at a perilous rate. Thus, the Earth is heating up slowly.

The consequences of global warming are potentially catastrophic. A warming trend in Alaska over the past three decades "higher temperatures that last longer during the year" is evidenced in the melting of the permafrost [10]. This change in habitat means trouble for many animal species because as climate changes, native Arctic wildlife face food shortages. For example, polar bears in the southern range hunting for much of their prey on sea ice, have experienced shorter hunting seasons since sea ice melts earlier in the spring and freezes later in the fall [11]. Global warming also causes a rise in sea levels, that erodes coastlines and destroys ecosystems and habitats for people and animals [12]. According to the Environmental protection Agency (EPA), sea levels along the Florida coast are already rising at rates 6-10 times faster than those over the past three millennia, and are likely to rise as much as 20 inches above their 1990 levels by the year 2100 [13]. The impact of climate change and global warming to countries in Southern Asia has been more serious. Therefore, any small or large projects on non-fossil fuel and clean-energy technologies will reduce the aforementioned environmental impacts of coal-fired power plants and promote more renewable energy applications for our future [14].

Wind power technology has become one of the fastest growing energy technologies in the world increasing an average of 32% annually each year over the past five years. It also constitutes one of the most efficient green power technologies [15-19].

The wind power generation in Iowa is a clean, available, and cost effective alternative source of energy and, better yet, can be readily integrated into both existing and new power grids [4, 19]. While Denmark, a world leader in clean energy generation produces 3,110 MW, Iowa produces only 471 MW (as forth highest in nation), yet Iowa has more wind capacity [20].

Educational institutions particularly universities may play a significant role in promoting wind power technology to the communities. This paper reports how to design and build a 0.5 kW axial flux wind turbine/generator. The skill is to harness the maximum wind power and convert it to electricity. The second task is to build it from materials locally available with minimum cost. The axial flux design used in this project meets these requirements [21-23]. It is highly durable to all extremes of weather and it has low maintenance associated with it.

An idea of small-scale cost effective wind turbine design in Iowa was very attractive for enthusiastic fellow students, family friends, and farmers in the area. As the project was in the research stage, it was immediately evident that anyone who was asked for assistance gave it willingly and asked at least a dozen questions about how wind power systems worked.

The primary questions collected were:

- How much power/voltage/current will this system produce?
- What can you do with the power you produce?
- Isn’t it hard to build?
- Is it expensive?
- Can I come and look at it when it’s finished?

This paper describes detailed design and construction of an axial flux wind turbine/generator. This includes a cost analysis, and pictures of the project phases. Graphs showing wind speed and electrical power data during testing are obtained. A brief layout of the educational module that will be taught with all the information is compiled into a teaching plan. Students involved in the project have gained knowledge and skills in electrical and mechanical areas. They also improved their social and managerial skills since they had to visit many companies getting assistance with various parts of this project.

In the past, a number of small-scale renewable energy projects ranging from 1-5 kW have been completed at UNI campus as well as local parks in Cedar Falls, Waterloo area in Iowa [24-28]. Most of these projects are started, researched and completed as part of an EIET senior design project. Similar to the aforementioned projects, the main objectives of this project are (1) to reduce green house gas emissions, (2) to promote more clean and cost effective renewable energy applications in Iowa, (3) to complete senior design course requirements successfully with an enjoyable project subject, and (4) to promote science, engineering, and technology concepts among high school students through appropriate public relations tools.

II. Building an Axial Flux Wind Turbine

The first step in building an axial flux wind turbine is to determine the load requirements. A feasibility study was conducted to determine what type of cost effective system could be built from scratch, and be educational at the same time. It was decided to build a 0.5 kW, 24 VDC system, a system originally developed by Hugh Piggot [21]. Construction began with the stator; it included 10 coils, of AWG#18 wire wound 150 times. One wire of each coil was soldered together connected all 10 coils while the second wire of each coil would be fitted with an electrical lead so that they could be connected to one of five bridge rectifiers. Students have tested the basic fact that the voltage induction is always in AC and a bridge rectifier would convert the AC voltage to the DC voltage. After the coils were wound and soldered, they were set into a plywood mold and covered with a mixture of fiberglass resin and baby powder to protect the coils as seen in Figure 1. The mold is specifically designed to be attached to a metal frame which is discussed below.

Figure 1. Wound coils in stator mold

Figure 2. Stator after resin poured and dry

The second part of the generator construction consists of attaching magnets to two 13 inch diameter metal disks as seen in Figure 2. The holes in the center of the disk are for the car hub bolts that hold everything together. The wood disk on top of the rotor disk is a spacing mold for the magnets. The Neodymium magnet blocks with a dimension of ½ x 1 x 2 inches were used for this project. A fiberglass resin is poured over the magnets to protect them; super glue is used to ensure the magnets do not shift when the fiberglass resin is poured over them as seen in Figures 3-4. Since the magnet blocks have been known to shift during the curing process, it is very important to perform this work in a well-ventilated area due to the safety concerns.

Building the turbine blades from bass wood required the most attention to detail. Location of the turbine, its height, any disturbances within 300 feet of the turbine were all determining factors of wind speed. The authors utilized an interactive wind speed tool called "Interactive Iowa Annual Wind Resource Map" developed by the Iowa Energy Center (IEC) at the Iowa State University (ISU). The wind data was accurate within a range of $\pm$3%.

Figure 3. Rotor plates with magnet guide

Figure 4. Pouring resin on rotors

The tower would be constructed with a diameter of 2 inches schedule 40 pipe. To prevent movement and provide stability, the tower would be secured with ¼ inch steel cable at 20 feet, 40 feet and 60 feet from the ground. The overall height of the tower is 65 feet with a gin pole and a base designed to tilt offering opportunity to raise and lower the tower for inspections and adjustments as seen in Figure 5.

Figure 5. Pounding in base pivot pin

Figure 6. Tower Crank

The 31 foot gin pole is attached to the base with three guy wires attached from the tower to the end of the gin pole as seen in Figure 7. The guy wires run from the tower to rods cemented in the ground 45 feet from the tower base, the recommendation is the guy wires should terminate 50-70% the height of the tower. A winch taken from an unused silo was secured to a concrete base 60 feet from the front of the tower as seen in Figure 6. A separate cable runs from the winch to the end of the gin pole. This winch can be turned by hand or by using an electric drill.

The tower was raised the first time without any weight at the top. This task was completed so that all guy wires could be properly adjusted as seen in Figure 7, and final adjustments are made using turnbuckles located at the cement rods. The tower was raised and lowered three times during the adjustment phase, the third time a flag was attached to the top of the pole to monitor any possible sway that would be encountered with the turbine attached. An anemometer has also been attached to the pole at the 55 foot mark. The anemometer could not be placed any higher without interfering with the guy wires or the blades of the turbine itself.

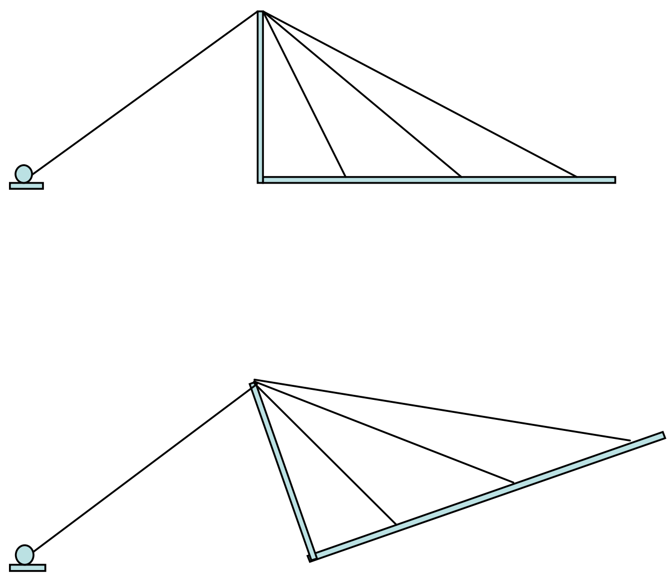

Figure 7. Tower at three points of being raised

The frame for the turbine is designed to slide over the top of the tower, two strands of 10 gage wire is run from the rectifier box at the top of the tower. The cable is run from the tower base to a controller and then into a 24 V battery bank. The battery bank consists of two series connected 12 V deep cycle forklift batteries donated by a local company, YMH Torrence Inc. The controller will automatically monitor the charge into the battery and divert any excess generated electricity to a hot water heating element that serves as an overflow drain.

The most difficult and time consuming construction portion of this project was the blades. The wood blank is divided into 6 sections with specific measuring points to set the thickness and twist of the blade. Hand tools were the preferred choice for this phase of the project. The blade is divided into four reference datum's, leading edge, trailing edge, front and back. We needed to pay particular attention to the grain of the wood, carving the wrong way would dig too deeply into the wood; this mistake resulted in two ruined blades. The primary tools were a drawing knife that had been in the family for over 70 years and a smaller two handled planer that proved to be the best tool for the curved part of the blade near the root. The blades are built for a specific tip speed ratio (TSR). The TSR determines how much twist, similar to an aircraft propeller, is necessary to help the blades to catch the wind in the most efficient manner. The result is a blade that has angles at eight inch intervals starting at 14°, and revolving to 11.7°, 6.8°, 4.3°, 2.5°, and ending at the tip at 1.9°. The end result was a blade that was varied in a thickness from 2 mm at the tip up to 37mm near the root as seen in Figure 8. The last steps of blade construction was two fold; first starting at the center of the blade the trailing edge was tapered that point down to 1mm thick. For aerodynamics reasons, the front of the blade was rounded in a curve starting back 30 percent from the front and slowly working to the front bottom corner. Lastly, all three blades need to have the same weight, if the weight is off the balance of the turbine would be off resulting in excessive vibration. Additional wood can be removed or weights added to get the blades balanced. The final result was three blades ready to be assembled and put in the air.

The assembly stage required spacing the tips of all three blades evenly. The roots were cut at an angle of 120° and the blades were secured together with two 10 inch diameter wood disks and 56 wood screws. After the wood screws were installed, five holes were drilled completely through the blade assembly.

The last crucial stage of the blade assembly was verifying the entire system was balanced. After assembly the entire blade configuration is balanced on a nail at the center of the blades. As before, additional wood can be removed or weights can be added to balance the blades. Our blades needed some minor adjustments so wood screws were added as our weights to even out the weight. We have found out that there are better ways to balance and will check on them the next time we build turbine blades.

Figure 8. Blade assembly for the Axial Flux Wind Turbine

Five bridge rectifiers convert the induced AC voltage into a steady DC voltage. We built our own box for the rectifiers from a piece of metal flashing with a bead of silicon and a weather resistant rubber were used to seal the box from the elements. The box provided an excellent heat exchanger for the rectifiers. Two strands of 10 gauge wire were run from the bridge rectifiers through the tower to the base and then were attached to 10/2 electrical wire to the battery bank. We used a plumbers snake to pull a string through the pipe, then attached the 10 gauge wire to the string and pulled the wire up from the bottom to the top. It was at this stage we realized that the pipe frame by the turbine was almost ¼ inch bigger then the pipe at the top of the tower. We were able to have a local machine shop, the Steel Shop, manufacture a bushing to take care of this problem.

The day to raise the tower finally arrived. The 10 gage wire was fitted with connectors to hook to the rectifiers, the top of the pole was greased, the bolts on the turbine where checked to make sure they were tight. The turbine was put onto the pole and the wind vane was attached. We were using the ½ inch drill to raise the tower. When the turbine was 10 feet off the ground the brushes in the drill went out, we continued to raise the tower turning the crank by hand. After the tower was about half way up, the anemometer that is attached to the tower started to rotate but the tower blades didn't move. We had shorted the terminal ends of the 10 gage wire for electrical braking to make sure the blades did not spin and damage the generator.

With a final crank, the tower came to its full upright position; since the wires from the rectifiers had been shorted before the tower was raised the blades did not turn even though there was a 12 mph wind registering on the anemometer. The guy wires were all secured and checked to make sure they were tight, the bolts at the base of the tower was secured, everything looked good. Our initial load was two car headlights with an inline fuse and toggle switch which had a measured resistance of 3.4 ohms. This configuration would allow us to make two observations, first a shining light was a positive sign electricity was being generated, second with the known load we would be able to take accurate voltage readings and calculate power and current output. When the short was removed the blades began to spin but there was no indication that electricity was being generated, an inspection of the load revealed a lose wire. During the process of fixing the wire one of the headlights burned out, this reduced our load to 2.2 ohms. The initial test, using only one headlight for a load worked for about 15 seconds when that bulb burnt out also. Our second test involved a load of 3.7 ohms comprised of three 60 W bulbs and one 100 W bulb installed in series as seen in Figure 9. Again we used the inline fuse and toggle switch configuration. When the switch was flipped the lights came on, we immediately saw that they were brighter then when we had tested this configuration with a 24 VDC input. We assumed that the turbine must be putting out more then 24 V.

Figure 9. Testing the output through four light bulbs.

We connected a digital multimeter across the load and the reading jumped up to 40 VDC within 15 s. Over the next half hour we saw the meter stay fairly constant around 42 VDC with a peak of 51VDC. By comparing wind speed reading from the anemometer our data showed a 20 mph wind would generate around 42VDC. One area of concern was the tail vane furling system; it did not seem to be operating like it was designed too operate. The design is set to limit the turbine speed rpm by turning the blades away from strong winds and keep the turbine from rotating above specific rpm values.

Using the wind data from the Iowa Energy Center [29] it was determined that we could expect average wind results for our chosen tower location in Northwest Iowa as seen in Table 1:

Table 1. Wind speed data for the turbine location [29].

	Average Speed (mph)	Air Density *	Average Wind Power Density (W/m2)	Capacity Factor (%)	Estimated Output for Period (kWh)
Annual	13.98	1.223	250	30.88	2,708
Jan	14.85	1.280	288	36.11	257
Feb	14.84	1.277	301	36.27	234
Mar	15.36	1.243	313	37.70	276
Apr	15.44	1.211	330	37.32	272
May	14	1.182	240	29.85	230
June	13.28	1.163	200	26.01	197
July	11.97	1.152	137	19.41	154
Aug	11.74	1.157	127	18.20	143
Sep	12.85	1.172	172	23.64	178
Oct	14.04	1.205	228	29.93	226
Nov	14.58	1.242	291	34.28	243
Dec	14.7	1.275	294	35.56	254

Based on this data we built the blades with a TSR of 6, this is the speed the blade tips travel divided by the wind speed at that time. The formula is: RPM = (wind speed x TSR x 60)/(circumference x pi). Our research determined that a TSR of 6 with an average wind speed of 12 mph would result in a shaft speed of 171 rpm within the desired speed range for this system. The car hub used for this project has a built-in sensor from the manufacturer; test wires are connected from the sensor to an oscilloscope, frequency is monitored and appropriate rpm values are verified. When it became too dark to continue we shorted the wires, ensured everything was secure and safe.

The data collected during the course of this project has been consolidated into an educational program. Informative pamphlets are designed; two public lectures are scheduled in March 2006 in coordination with the Center for Energy and Environmental Education (CEEE) at UNI campus. Four other local individuals have contacted us about building a turbine for themselves, information is being passed onto interested people on an almost daily event. This turbine can be taken down, transported and set up for display with minimum effort. The experience of building and facilitating wind power is being passed onto interested individuals. These achievements truly accomplish the project goals.

III. Cost and testing

Construction phase began in September 2005. Materials were purchased from numerous vendors. Some specialty work was required, welding the turbine frame and machining the rotor disks. The following is a breakdown of the major areas and the costs associated with each area:

Testing

When the turbine was built it was brought to the UNI testing lab. Leads were connected directly from the coils of the turbine to an oscilloscope. The oscilloscope was set up to monitor AC voltage and the frequency. By monitoring the frequency we were able to calculate the speed versus voltage ratio as seen in Figure 10. We did not have the bridge rectifiers available so were unable to run a test for DC output. This test was done by free spinning the turbine. Once the turbine is up, we will involve numerous tests such as varying loads, monitoring weather conditions, possibly changing blades and trying different materials.

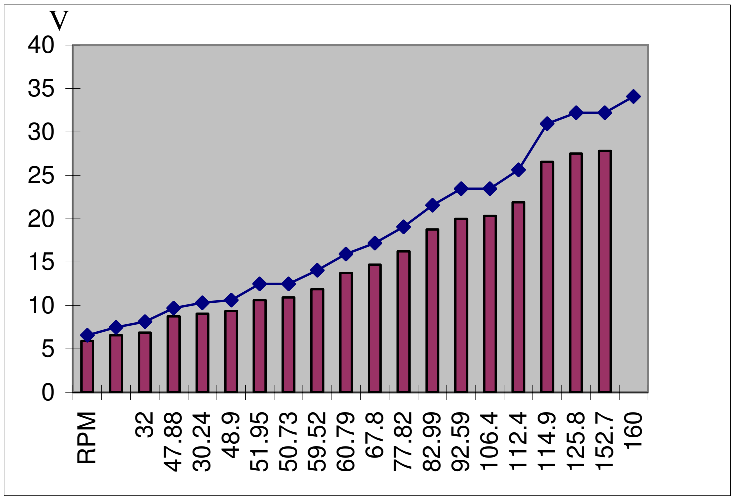

Figure 10. Spin test results, calculated speed (rpm) versus voltage output

Cost Analysis

Table 2 illustrates a cost analysis of the axial flux wind turbine project. The total cost of the project at this time is $1,419. The UNI Scholarship Opportunities for Applied Research (SOAR) grant provided a funding of $500 for this project. Half of the unexpected costs were due to mistakes by the builders such as breaking a blade, needing additional hardware, and other miscellaneous expenses. With the experience gained from this project it is estimated that these mistakes will be avoided and this money could be diverted towards the purchase of additional batteries or other system components.

Were the Challenges Met?

The biggest challenge was the learning curve. We knew all the theory in calculus, physics, electrical and electronics. We had access to all the tools necessary to bring this project to maturity. However, what we lacked was experience. This learning curve proved to be the most time consuming part of this project. We were constantly double checking and rechecking ourselves. Sometimes we over did the checking and other times we ran into situations, especially with the blades, that only experience helped us overcome.

On the day the turbine spun for the first time, the joy of accomplishment was indescribable. We simply took materials and turned them into a very useful clean electricity generating machine. At the time of this final paper submission, there are still a number of load tests need to be performed. When the overall system components begin to run, we expect to see how well the turbine holds up and if the blades and the turbine would handle the vibrations.

Table 2. Cost Analysis for the Project

Wood for Blades	$24.00
Plywood for turbine	$28.00
Steel Pipes for wind turbine	$40.00
Steel Plates for magnet mount	$12.00
Fastenings	$20.00
Car Bearing Hub	$25.00
Fiberglass Res	$40.00
Magnets (NdFeB "Neodymium")	$150.00
Electrical supplies	$110.00
Miscellaneous consumables	$100.00
Guyed tower 2"ID	$300.00
Guy wire	$140.00
Wire from wind turbine to battery	$80.00
Unexpected costs	$350
Total estimated cost:	$1,419.00

IV. Future Goals

The system will be tested under various loads. A second turbine is in the building process. New blades with a different tip speed ratio are being constructed. A new site is being set up for the new turbine. Setting up teaching seminars is being scheduled. A pamphlet was created to give to anyone who asks questions. We have compiled a list of the top questions and the short answers we provided to people about this project.

- Would we build one for them? *No*
- Will you help me build one? *Yes*
- How much power will it generate? *0.5 kW at 24 V*
- Can you connect it to the house? *Not with our current setup, you need an inverter*
- What can you do with the power? *Run lights, a hot water heater, or a hair dryer.*
- Am I asking too many questions? *No.*

We are in the process of compiling all our notes and experiences into one package. We will use this information to teach anyone who wants to learn. We already have one person who wants to build his own turbine, several others who have already been asking questions.

V. Conclusions

This project will not eliminate the need for grid power. It will be a supplement to the power used at a chosen location. Research must be done to determine wind speed data during a year and possible loads. The actual construction of the turbine was not extremely difficult; having access to someone with firsthand experience is immensely valuable. The answers to our questions came from the designer of the turbine Hugh Piggot from the United Kingdom, and Craig and Connie Cook from Canada. We took our time and learned a great many things about wind power systems and our community. We have answered hundreds of questions from the community. By setting up our experience into a traveling, teaching program, we will be answering hundreds more. As seen in pictures there are a few of young people, Francis Praska's children, with ages 9 and 17 all helped with this project. They did not understand all the theory but they were able to help pour the concrete base, pull cable, get tools, set up molds, run the drill to raise the tower, and dozens of other tasks. At the end it was not only an engineering technology senior design project but also it was a family fun with great success.

VI. Acknowledgements

The authors wish to recognize the hard work and skills of the dozens of people who asked questions as this project progressed. Without their questions some details of this project would never have been considered. The authors want to thank Hugh Piggot in Dundonnell, and Rose Shire in UK for the original plans and answers to numerous technical questions, Craig and Connie Cook, Tillsonburg, Ontario, Canada for their advice and encouragement. The authors also appreciate to the main sponsor of this project, UNI College of Natural Sciences for the undergraduate research grant "SOAR" provided, the businesses that helped supply materials or parts for the turbine; Mohawk Electric, Farmland Hardware, Blains Farm & Fleet, Kenny Dyal, Toronto, Ontario, Canada, The Steel Shop, E & E Welding, Croell Readymix, Busti Lumber, and YMH Torrence, Inc.

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