

EFFICIENCIES OF WIND TURBINE DESIGNS



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ABSTRACT

As it becomes clear that change toward renewable energy is necessary, it is also necessary to know the efficiencies of wind turbines, and the design, which determines the efficiency. The purpose of this experiment is to determine the following: the efficiency of the experimental wind turbine designs in a wind tunnel, which of the blade designs tested is most efficient, and the cost-effectiveness of the wind turbine designs. Several different wind turbine designs, varied by number of blades, were tested in a wind tunnel. The power they produced was determined and, when compared to the potential power production, yielded the efficiency rate of each of the designs.

The ten-blade model produced the least power, and had the least efficiency of all the models. The six- and eight-blade models produced efficiencies that were nearly equal, and they had the highest efficiencies among the models tested. With the exception of the ten-blade model, all the models reached maximum efficiencies over thirty percent. This is significant since most wind turbines have efficiencies of thirty-five percent.

INTRODUCTION

Every year, energy consumption rates continue to rise and energy companies must meet the demand. It is expected that energy consumption will increase by sixty percent by the year 2020 (United States Department of Energy, 2002). This means that more and more fossil fuels will be used. Fossil fuels, such as oil, coal, and natural gas, are nonrenewable, which means that they cannot be replaced within a human lifetime. They emit pollutants such as carbon dioxide, a gas that is suspected of being the cause of recent global climate changes; hydrocarbons and nitrogen oxides, which are the causes of ground-level ozone; and nitrogen oxides and sulfur dioxide, the major causes of acid rain.

Power plants are responsible for seventy-two percent of SO₂ emissions and thirty-three percent of all NO_x emissions (Bull et al., 2000).

Renewable energy, such as solar, wind, geothermal, hydroelectric, and biomass energy sources, can be renewed within a human lifetime, and is an alternative to fossil fuels and other non-renewable energy sources. Renewable energy sources tend to be cleaner, and have less environmental impact.

One of the most promising renewable energy sources is wind. Wind energy can reduce pollutants emitted into the atmosphere because it produces no emissions of its own. It also lengthens the time that fossil fuels will last because it provides energy that would otherwise come from the burning of fossil fuels. However, there are also disadvantages of wind power. First, there is the impact of noise. Design changes have reduced the effect of aerodynamic noise, but mechanical noise still remains (American Wind Energy Association, 1999). However, since homes are usually required to be set back away from wind turbines, the effect of noise is small. Another concern is the stability of the tower, which is sometimes undermined by erosion if the tower does not have a good foundation, but the problem can be mitigated through proper installation and landscaping techniques. Yet another concern is the effect of wind turbines on birds. This problem has been most prevalent in the migratory routes of endangered birds, but most wind sites do not have significant problems with birds, and careful planning to stay away from migratory routes can avoid the problem.

As it becomes clear that change toward renewable energy is necessary, it is also necessary to know the efficiencies of wind turbines, and the design which determines the efficiency. The purpose of this experiment is to determine the following: the efficiency of

the experimental wind turbine designs in a wind tunnel, which of the blade designs tested is most efficient, and the cost-effectiveness of the wind turbine designs.

Many past civilizations have realized the possible uses of this resource. The first use of wind energy was powering sailboats. It was first used circa 3200 B.C. when the ancient Egyptians used wind to power their sail boats. It was also used by the Romans to power their navy. In 200 B.C. the Chinese invented the first “windmill” (Wind Power Milestones, 2002). Around the fourteenth century, the Dutch used wind power to solve flooding problems that resulted from the Netherlands’ very low altitude (Wind Power Milestones, 2002). In 1854, windmills were introduced to the United States, and were used to pump water from the ground (Wind Power Milestones, 2002). Denmark pioneered wind power in the 1890s, when 120 wind turbines produced a twenty-five kilowatt system (Wind Power Milestones, 2002). After the oil embargo of 1973, wind energy made large strides (Wind Power Milestones, 2002).

Since 1980, prices of wind energy have fallen sharply to the point that wind energy is now competitive with nonrenewable resources. Modern 1.5-megawatt commercial wind turbines can produce energy at as low as four cents per kilowatt-hour, nearly the same cost as electricity produced by coal. Also, incentives such as the production tax credit, in which the government pays back in the tax return 1.5 cents per kilowatt-hour of the wind energy used (AWEA, 2002), encourage development of wind power by giving tax credits to developers of wind power, and keep \$3 billion worth of proposed wind projects in effect (Wind Energy Outlook, 2002). The production tax credit has recently been extended to December 31, 2003. In addition, most power companies buy excess energy produced by residential wind turbines, paying the customer for any

electricity from the wind turbine that the customer does not use. For example, Allegheny Power pays 1.761 cents per kilowatt-hour, if the excess is between one hundred kilowatts and one megawatt (Allegheny Power, 2000).

A home turbine unit should be able to meet the demands of the house. On average, 1,497 kWh are used per month per home, which equates to a bill of \$120.27 (Laurens Electric Cooperative, 2002). Of course, this varies greatly depending on variables such as geographic location and number of electrical devices being used.

Wind turbines vary in number of blades, length of blades, size, and electrical output. There are two main types of wind turbine designs. First, there is the vertical-axis wind turbine, which has blades that rotate horizontally around a vertical axis. Vertical-axis wind turbines are rarely used, because they can not be placed on top of a high tower, which limits the height that they can be placed. Also, when the turbine needs repair, the design of the vertical-axis wind turbine requires that it be completely dismantled in order to be repaired. The other type of design is the horizontal-axis wind turbine, which has blades that are perpendicular to the wind. This design is the most often used, because it can be placed in higher locations, where the winds are stronger and steadier.

One of the factors in designing a wind turbine is the number of blades. Windmills that were built for pumping water often had many blades, because when pumping water, large amounts of torque, or turning force, is required. However, in generating electricity, not much torque is required, so fewer blades are used. The most commonly used design is the three-blade design. Three blades have better energy output than other designs, but tend to cost and weigh more than two-bladed designs. Two-bladed designs weigh less,

and cost less than three-bladed designs, but tend to be unstable and inefficient, because it is more difficult to keep the weight of the blades balanced (Krohn, 2001).

Another concern in designing a wind turbine is the height of the turbine, and the length of its blades. Wind turbine towers range from twenty-five to eighty meters in height, and can have rotors up to sixty-five meters in diameter. The lengths of the blades need to be as much as possible, since, according to the power equation ($P = \frac{1}{2} \rho A V^3$), as the area swept by the blades increases, so does the output power. However, if the blades are too long, they will be unstable, and will eventually break off.

The location of a wind turbine is of vital importance to how well it will work. First, the proper amount of land is necessary. Residential turbines are not appropriate for urban or suburban homes on a small lot. One acre or more of land is desirable. Larger wind turbines and wind farms require even more land, as much as fifty acres per megawatt installed capacity. Good locations for wind power tend to be at high elevations, and on flat land, where wind flow is largely uninhibited. Also, wind turbines should be at least fifty feet away from any obstructions, such as trees, which could cause turbulence. If the variables of number of blades, length of blades, size of turbine, and electrical output can be properly controlled, then the efficiency of the wind turbine can be improved.

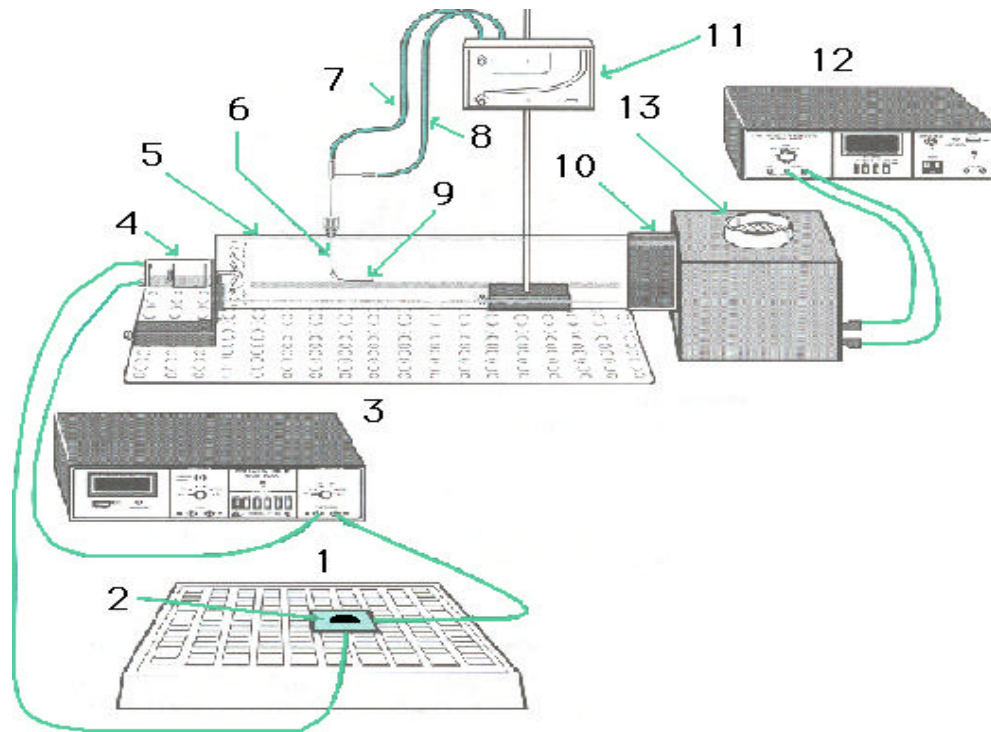
Since the purposes of the experiment include determining efficiency of the model wind turbine and which model is most efficient, the hypotheses are as follows: the ten-blade model was expected to be the most efficient, and the average efficiency was expected to be thirty five percent.

METHODS

In this experiment, wind tunnels are being used to control variables. The reason for using this experimental design is that the variables, especially wind speed, can be controlled. The wind speed, wind direction, and weather are extremely uncontrollable factors out in the field and may cause inconsistencies in the data. In this experiment four groups tested wind turbines following the same procedures as the other groups. This allowed for replication.

The small scaled structure is easy to assemble. Also, the structure creates less hazardous situations (such as falling or disassembling) than with larger scaled turbines. It is also easier to change the number of blades along with the size and shape of each individual blade.

From July 10, 2002 to July 19, 2002 the testing took place at Frostburg State University's Engineering Annex Building in the Physics Laboratory Workshop, Room 103. Each day the testing took place from 9:30 am to 3:30 pm. The setting was used because of the availability of the materials and, more importantly, natural wind and variations in temperature or wind direction cannot affect the data collected. Each group performed the experiment once for each blade and collected data for wind speed, temperature, and output power data.



1-Circuit Panel 2-One Ohm Resistor 3 -Voltmeter 4 -Fan Assembly with DC Generator 5 -Flow Tube 6 and 9 - Pitot Tube-measures the difference in air pressure and impact port 7 and 8 – Connecting tubes 10 -Cap with 2 7/8” hole 11 -Slant Tube Manometer –measures wind speed 12 -Power Supply 13 –Blower
 *4, 6, 8, and 10 bladed turbines (not shown above)

Figure 1- The set up for the experiment.

After the basic set up was constructed (Fig 1), only a few simple steps were needed before the actual testing was done. For one, the power supply was set at 0-24 volts DC (step 1). The digital multimeter was set to measure DC volts (step 2). After all assembly was complete, testing was ready to begin.

The wind speed was measured in four different sections inside the tunnel (Fig 2) (step 3). This was done to get an average wind speed for both the outer and the inner parts of the blades excluding the hub. Then the pitot tube was set to measure the wind at the very top of the wind tunnel, with the pitot tube facing towards the blower assembly (step 4). Next the voltage was adjusted for a slow wind speed setting, 14 volts on the

power supply, and the wind speed was recorded in ft/min at the top of the tube (step 5). Next the output voltage was recorded and the pitot tube was used to measure wind speed at each location (step 6). After that, the pitot tube was removed, and the thermometer was inserted to record the temperature (step 7). The power supply was increased by two volts to get a higher wind speed (step 8) and then, steps three through eight were repeated, increasing the power supply by two volts each time until 24 volts was reached. Finally, the number of blades was changed and steps four through ten were repeated again until finished with the different blade numbers.

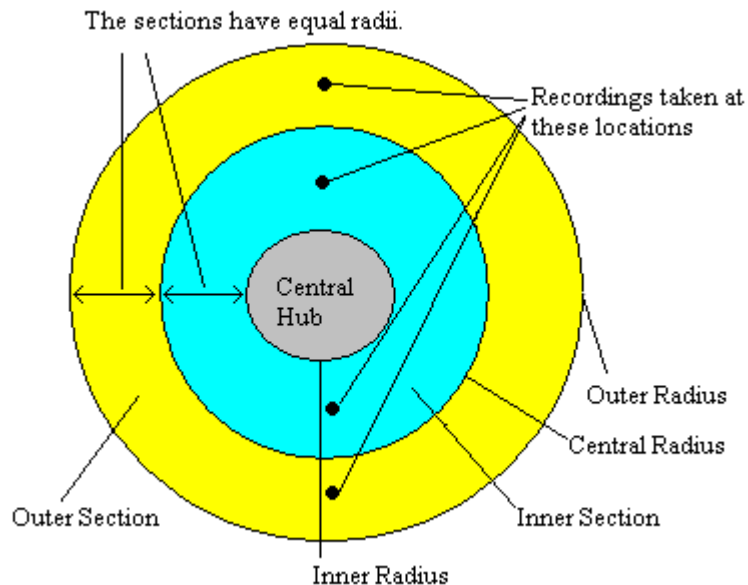


Figure 2- Cross section of the tunnel showing the locations at which the wind speed is measured.

To compare the data that was recorded, calculations need to be made to find the theoretical power in the wind, the actual power produced by the turbine and the efficiency of the turbine. The equation for the theoretical power is $P = \frac{1}{2} \rho A v^3$ (ρ is the air density, A is the area of the blades and v is the velocity of the air). The equation for the actual power produced by the turbine is $P = V^2/R$ (V is the voltage produced and R is the resistance). To find the efficiency of the turbine, the actual power of the turbine was

compared to the theoretical power of the wind. These calculations are needed in order to find the most efficient design and its average efficiency. Two graphs were made to show the correlation of the output power and the wind speed. Two more graphs were made to show the efficiency versus the wind speed. These were made to discover which design is the most efficient. A bar graph was made to show average power for each blade. Finally, another bar graph was made to show the average efficiency for each blade. The average power and efficiencies of each blade were found and compared to see which of the blades was the best.

Another thing that was done for the experiment was site testing. This was to see if any nearby location would be good for a wind turbine. To do this the groups went to different sites and recorded the wind speed, temperature and measured the clear surrounding area. An energy audit was done to find the amount of energy in kilowatt-hours needed for the electricity of a home. This was done to get an idea of how feasible wind energy would be in this area.

RESULTS

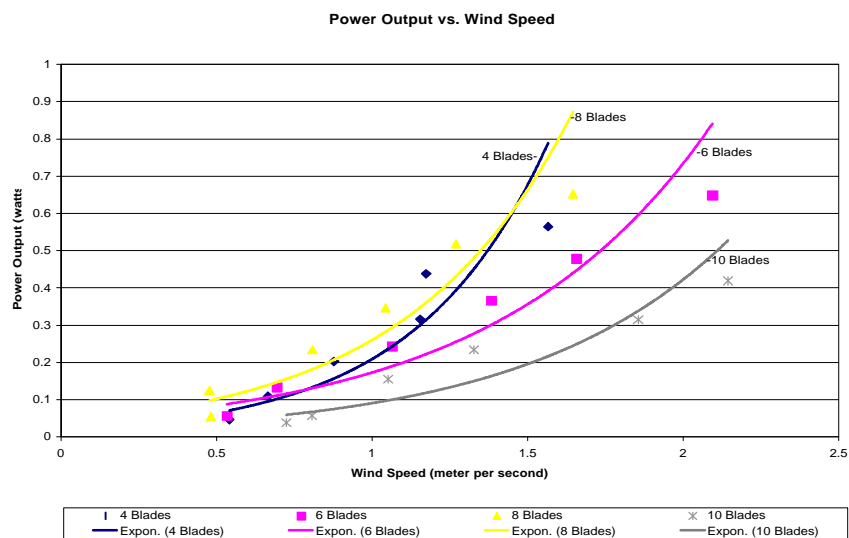


Fig. 3 - A comparison of wind speeds and power output of blade models.

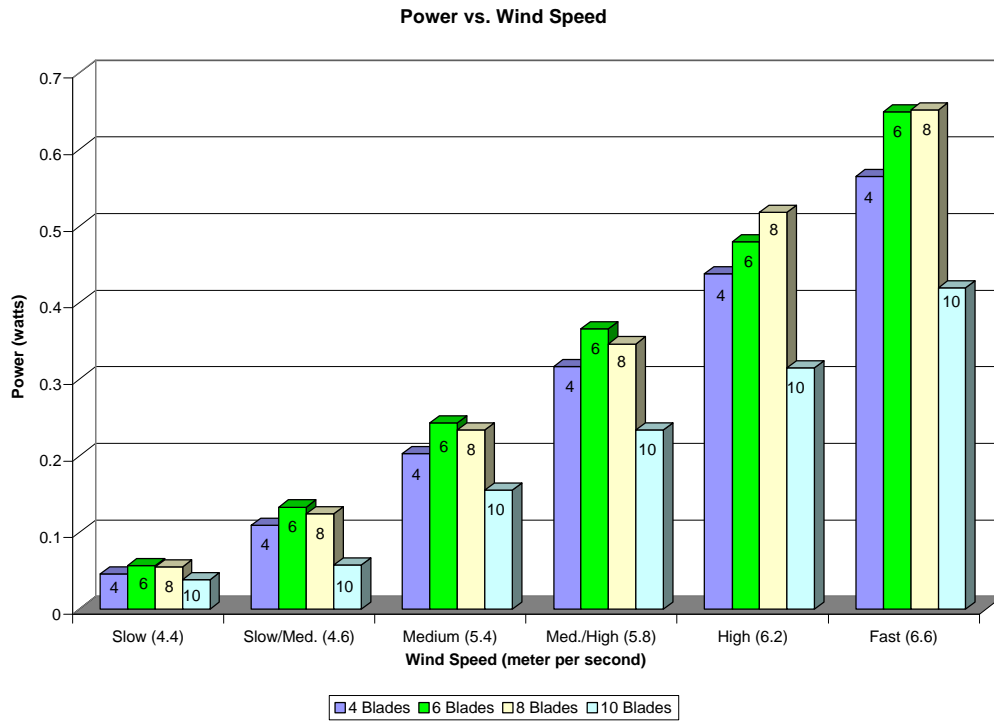


Fig. 4 - A comparison of wind speeds and power output of blades models.

As shown in figure 3, the eight bladed wind turbines produced the most output power compared to the four, six, and ten bladed wind turbines. In figure 4, it showed that the six bladed produced a little bit greater amount of output power compared to the four, eight, and ten bladed for wind speeds at slow, slow/medium, medium, and medium/high wind speeds. But for the high and fast wind speeds the eight bladed wind turbines produced the most output power.

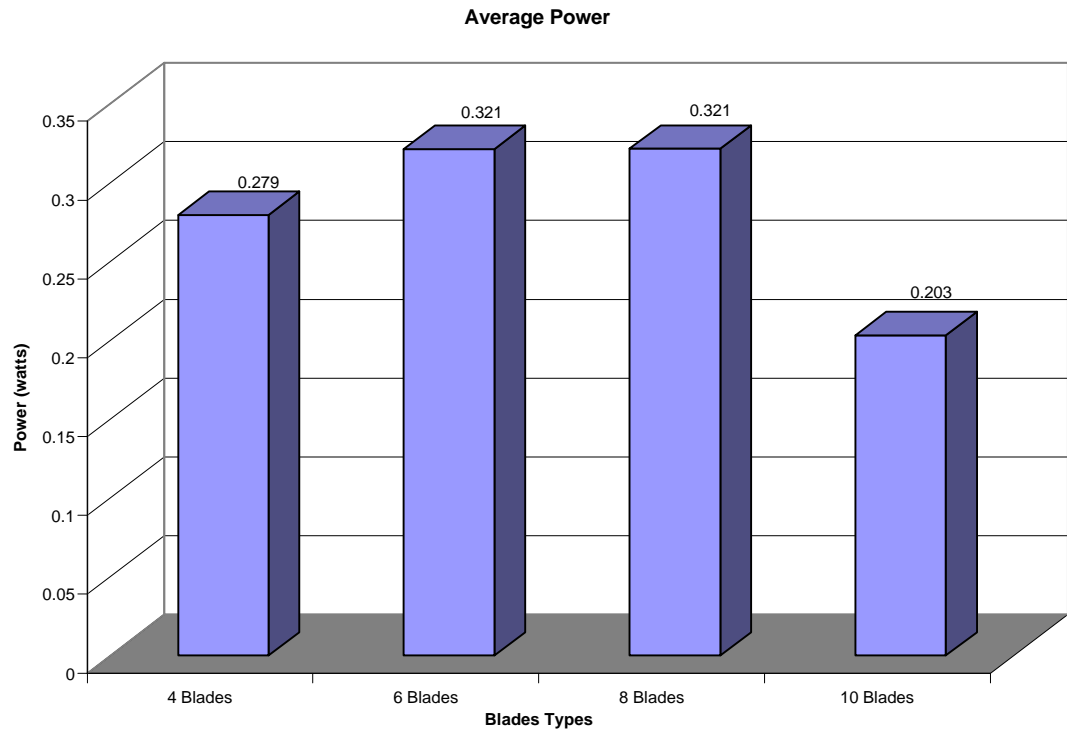


Fig. 5 - The average output power of the different blade models.

In Figure 5, it shows that the eight bladed wind turbines have the overall output power compared to the four, six, and ten blades wind turbines. But the six bladed wind turbine has an average output power of only .00395 watts lower than the eight bladed wind turbines.

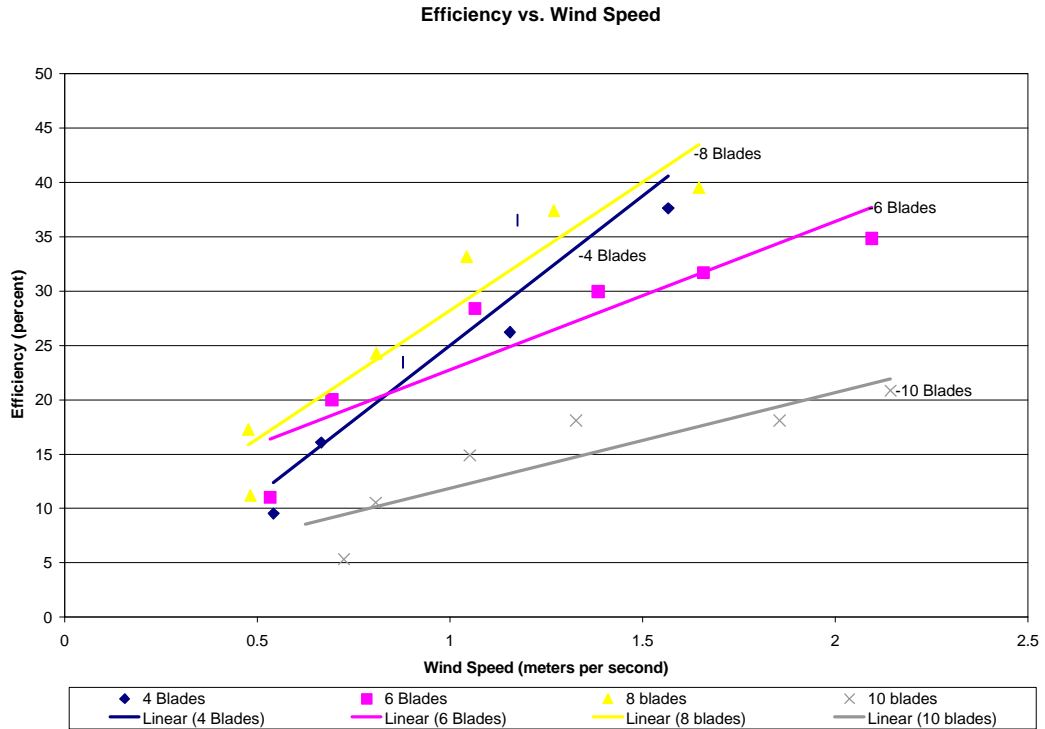


Fig. 6 - A comparison of wind speeds and efficiencies of blade models.

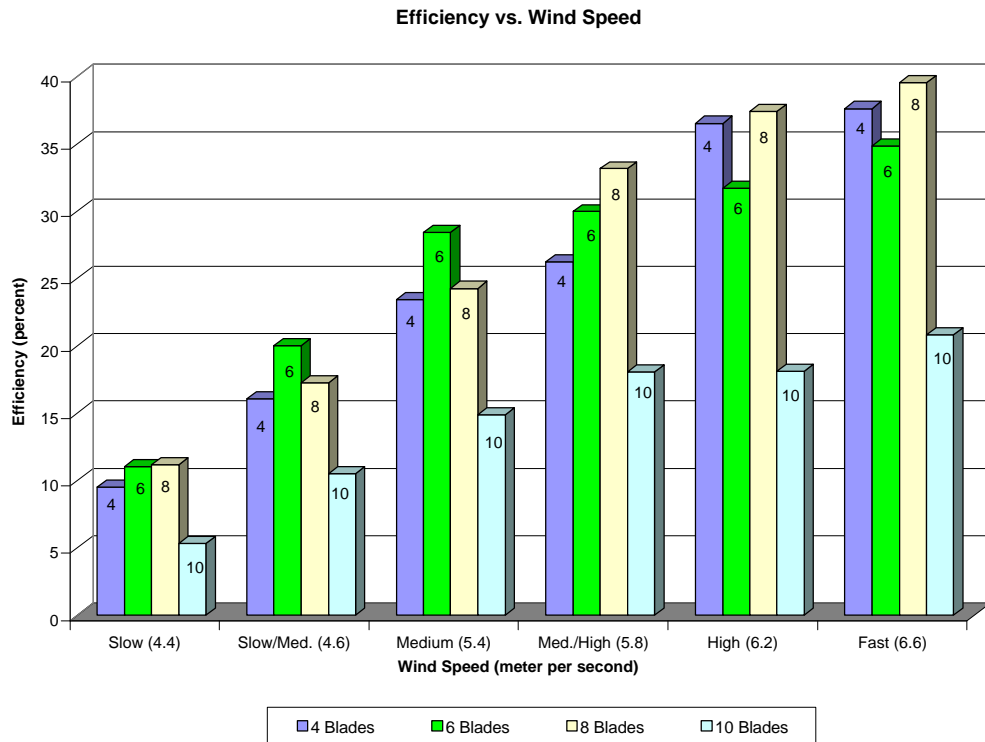


Fig. 7 - A comparison of number of blades and efficiencies of blade models.

Figure 6 shows that the eight bladed wind turbine had the greatest efficiency compared to the four, six, and ten bladed wind turbines. But figure 7 shows that the six bladed wind turbine has the greatest efficiency at the slow/medium and medium wind speeds, but for the other wind speeds; slow, medium/high, high, and fast; the eight bladed wind turbine has the highest efficiency.

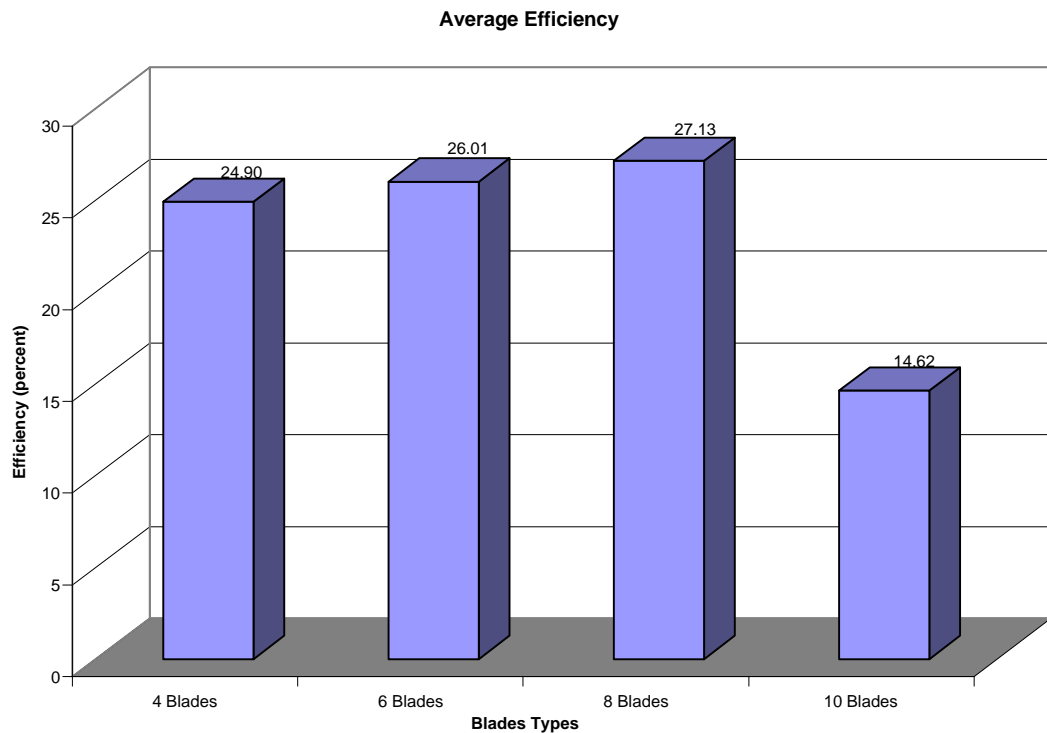


Fig. 9 – The average efficiency of blade models.

Figure 9 shows that the eight bladed wind turbines has the highest efficiency compared to the four, six, and ten bladed wind turbines. The next highest efficiency was the six bladed wind turbine with only and efficiency that is 1.12 percent lower than the eight bladed wind turbine.

T-tests that were performed to showed if two sets of data are statistically different. It was accepted that the two sets of data were statistically different when the p -value is lower than .05 meaning that there is a confidence level higher than 95 percent that the two sets of data were different. The eight to ten bladed wind turbines at the slow wind speed show that the eight bladed wind turbine had a higher efficiency than the ten bladed wind turbine (t-value – 2.46) and it had a p -value of .049 meaning that there's a confidence level of 95.1 percent that they were statistically different. The eight to ten bladed wind turbines at the slow/medium wind speed show that the eight bladed wind turbine had a higher efficiency than the ten bladed wind turbine (t-value – 2.74) and it had a p -value of .041 meaning that there's a confidence level of 95.9 percent that they were statistically different. The eight to ten bladed wind turbines at the medium/high wind speed show that the eight bladed wind turbine had a higher efficiency than the ten bladed wind turbine (t-value – 3.34) and it had a p -value of .021 meaning that there's a confidence level of 97.9 percent that they were statistically different. The four to ten bladed wind turbines at the high wind speed show that the four bladed wind turbine had a higher efficiency than the ten bladed wind turbine (t-value – 3.40) and it had a p -value of .014 meaning that there's a confidence level of 98.6 percent that they were statistically different. The eight to ten bladed wind turbines at the high wind speed show that the eight bladed wind turbine had a higher efficiency than the ten bladed wind turbine (t-value – 5.01) and it had a p -value of .002 meaning that there's a confidence level of 99.8 percent that they were statistically different. The four to ten bladed wind turbines at the fast wind speed show that the four bladed wind turbine had a higher efficiency than the ten bladed wind turbine (t-value – 2.71) and it had a p -value of .035 meaning that there's

a confidence level of 96.5 percent that they were statistically different. Finally the eight to ten bladed wind turbines at the fast wind speed show that the eight bladed wind turbine had a higher efficiency than the ten bladed wind turbine (t-value – 5.44) and it had a *p*-value of .003 meaning that there's a confidence level of 99.7 percent that they were statistically different. This said that the eight compared to the ten bladed wind turbines will be statistically different at all the wind speeds except the medium wind speed. It also said that the four bladed wind turbine will be statistically different at wind speeds of the high and the fast speeds.

DISCUSSION & CONCLUSIONS

The hypothesis that the 10 bladed generators at 4 inches long would be the most efficient was contradicted by the results. The 8 bladed generators had a consistently higher efficiency than the 10 bladed generators. Thus, since the 10 bladed generator was one of the least efficient of those tested, and the most efficient turbine in this experiment was proven to be the 8 bladed generator, the hypothesis was rejected. The hypothesis that the efficiency of the system would be 35% was also rejected.

In Figure 6, the efficiency of the 8 bladed and 4 bladed was the highest when compared to the other two. The eight bladed wind generators had the highest efficiency rate of 39% in high wind speeds. The least performing, according to Figure 7, was the 10 bladed wind generators with an efficiency of 21% for high wind speeds. The 10 bladed generators also stayed consistently at a lower efficiency rate for all the wind speeds. According to Figure 7, the efficiency for the three lower wind speeds was in this order from highest to lowest: 6 bladed, 8 bladed, 4 bladed, 10 bladed. However, the efficiency for the higher wind speeds was in this order: the 8 bladed was most efficient, then the 4

bladed, 6 bladed, and 10 bladed generators. In analyzing this data, the most efficient turbine overall was found to be the 8 bladed generators. For Figure 7 and 8, these trends are also followed for the power output.

The eight and six bladed wind generators were probably the best because we inferred that the wind generator's blades had the optimum amount of space between the blades to catch the most wind for this experiment. The space between the blades allowed wind to move through the blades with less turbulence unlike the ten bladed wind generators. The turbulence causes the wind generator to slow down due to the irregular wind patterns. However, it can be interpreted that the eight bladed wind generators also caught the most wind. It was able produce the most output power because it caught the most wind. In the graphs, a trend that appeared was that the eight and six bladed wind generators produced the greatest efficiency; then it was the four bladed wind generators being third most efficient, and the least efficient was the ten bladed wind generator according to the data.

The t-test tested if there was a ninety five percent confidence between two sets of data. We performed this test between: the 4 and 10, 6 and 10, 8 and 10 for each of the wind speed. The results showed that the eight and ten for all the wind speeds, except for medium were statistically different. This means that the data is statistically different. The data for the 4 and 10 were also statistically different, though only at high and fast wind speeds. They were both respectively lower than the 8 statistically.

After completing the experiment, further research was conducted to compare if a turbine that is 35% efficient would supply a typical house. The reason that 35% was used, instead the 39% average efficiency that this experiment found for the 8 bladed system,

was because it has been further researched in numerous other experiments that turbines are between 30- 40% , or approximately 35% efficient (Roberts, 2000; Gipe, 1999; Elliott & Schwartz, 1993). The class figured the amount of energy needed for an average household (House T) by compiling the data from energy audits done by the class. The amount of energy needed for house T is approximately 1,700 kilowatt hours per month. This is close to the figure posed by Laurens Electric Cooperative (2002) which is 1,497 kilowatt hours per month.

House T uses 1,700 kilowatt hours per month, which is the same as 2.32 kilowatts of power. From a local coal power plan in Maryland, the bill for house T would be \$119.68 per month if the rate was \$0.07 (Allegheny, 2000). For a home built wind generator system, the diameter of the swept area for a turbine to meet house T demands would be 3.4 meters assuming this wind generator is 35 percent efficient. Research on available wind turbines were done since it is more practical to buy from the market. Three wind turbines that met the requirements of house T were found. The first was the Bergey XL.1 Turbines 24V. The Bergey XL.1 Turbines 24V has a diameter of 2.7 meter and this turbine costs \$1,695.00 per wind turbine. The Bergey XL.1 Turbines 24V can produces 1,000 watts, which means three of these turbines, which cost \$5,085.00, will provide for this house T (RENEWABLE ENERGY, 2002). For the wind turbine to pay back itself in the terms of saving on previous electric bill, it would take 56 months or 4 years. Another type of wind turbine is the Southwest Whisper 175. This wind turbine will produce 500 kilowatts hours per month and it cost \$4,990.00 (SOUTHWEST, 2002). So only three wind turbines would be needed to provide for this household energy demand of 1,700 kilowatts hour per month (SOUTHWEST, 2002). The total cost would be

\$15,000.00 (SOUTHWEST, 2002). For this wind turbine to pay back itself, it would take 125 months or 10 years. The most expensive wind turbine is the Bergey Excel wind turbine which cost \$19,500.00. Only one wind turbine would be need because this wind turbine provides 10,000 watts (RENEWBLE ENERGY, 2002). This wind turbine has a diameter of 7.67 meters (RENEWBLE ENERGY, 2002). For the wind turbine to pay back itself, it would take 167 months or 14 years. The money earned from the excess power created by this or any wind turbine is 1.76 cents per kWh if the excess is between 100 kW and 1 MW (Allegheny, 2000) would help to pay the turbine off quickly. Also there is currently a legislative bill that the first year that a home owner buys a wind turbine the turbine owner will receive a proposed 30% refund for their turbine in their taxes. With only needing to use a small portion of land for home units, turbines will be a good renewable resource for the future.

The sites selected for testing were: Miller's construction in Frostburg, MD, and St. John's rock, MD. Of these, the best site was Miller's Construction, and it was considered to be a good site because it was away from obstacles and it was a flat area at the top of the mountain, thus the winds would be higher than the valley and there would be less turbulent. St. John's rock was considered to be a bad site because it was on a ridge, thus a lot of turbulence, and there were a lot of obstacles, such as trees, around. Also the rocky terrain would make it hard to build a turbine there. The optimum site for a wind turbine would be on a large area of flat land, constant wind speeds, and not a lot of turbulence from obstructions. For a home site the best area to have a turbine would be at least 30 feet above anything in a 300 foot radius (Wind System Siting).

Though wind turbines may be a practical resource for the future, the research in finding the most efficient systems must continue. There were several limitations in this experiment. In this experiment there was a major problem with friction. The friction caused any rotor that had less than 4 blades to not turn with the wind speeds that were used. There was too much friction in the generator to allow the rotors to turn, thus no power was created with a 2 or 3 bladed model.

There was also another problem with the generator. The size of the generator compared to that of the turbine's rotor was not at all proportional to life size turbines. The generator had almost, if not over, half of the radius of the turbine's rotor. This was a problem because it may have led to the excessive friction that this experiment encountered.

The material that the blades were made out of also could have created a lower efficiency level. Other materials could have been used and tested in this experiment. Another problem that this experiment encountered was that the blower unit would max out if the power supply was turned to higher than 24v. Other higher wind speeds could have been tested if the power supply was bigger, and perhaps a trend would occur that some blades do better in lower speeds than extremely high ones.

There are a few suggestions for this experiment to make it better in future repetitions. One is that a larger scale turbine should be used with a bigger wind tunnel. This would be beneficial because: wind speeds would be easier to measure because the speeds would not change drastically in a little space; the turbine would be more to scale, and the inner area could possibly contribute a little bit more to the power produced by the system if there is less friction along the edges of the turbine.

Another suggestion is that different materials could be used for the blades. In doing this, an experiment could be conducted to see which blade material works best for each blade number, or even to compare each to rotor size tested. A bigger blower would also assist this experiment. Higher wind speeds could be tested to see if any trends occur.

Another major suggestion would be to use a more proportional generator. For this experiment a smaller generator was attempted, but it was unsuccessful because the small generator would not calculate any current from the system. The small generator was just too small. If a more proportional generator is used (and works), then perhaps the efficiency levels would be different.

The consideration of a pulley system was also brought up in this experiment. As the two and three bladed systems had too much friction to stay running, the pulleys were attempted to reduce the friction, but did not work. A pulley system may produce more power than just the generator and the rotor.

Using a smaller hub might also assist this experiment. The hub in this experiment had .6 inch radius and the rotor itself only had a radius of 4 inches. The portion was too great. Having a smaller hub would allow more air to strike the actual turbine, which may cause more power production. In making the hub smaller, the blades are actually getting longer; the blades could be made a lot longer, and then the power produced would be higher based on the results of this experiment. For a large scale turbine, each additional stable foot of blade length that could be added would have an immense effect on the power produced.

New questions have been raised about this experiment. For one: would using more stable materials really have had a considerable impact on the efficiency results?

Another is: would using a bigger model turbine and wind tunnel have a significant effect on the efficiencies? The next question would be: how big of a difference would there be in using a small, medium, and large proportioned generator with a turbine in respect to its efficiency. The last question would be: would having a smaller hub really have a significant effect on the efficiency of the turbines?

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