4H8110

Wired for Wind

WIND PHYSICS

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4-H Pledge

I pledge my ***head*** *to clearer thinking,*

My ***heart*** *to greater loyalty,*

My ***hands*** *to larger service,*

and my ***health*** *to better living,*

for my ***club****, my* ***community****, my* ***country****, and my* ***world****.*

Author's Note: Wired for Wind – Wind Physics fulfills the following Nebraska State Educational Standards:
12.1.1 – Math in scientific inquiry
12.1.3 – Engineering design, implements solution, evaluate solution, communicate
12.4.3 – Energy sources renewable and non-renewable

Introduction

Wind power is an important renewable resource. The wind industry is growing rapidly and already provides around 6 percent of the electricity used in the United States.

Wind power is produced by turbines. Wind energy is energy in the motion of air molecules (energy of a moving object is called kinetic energy). The wind flows over the turbine blades, causing them to spin. The rotating blades turn a generator that converts the mechanical energy into electrical energy.

There are two types of turbines: vertical axis and horizontal axis turbines. Vertical axis turbines, such as the Savonious and Darrieus models, tend to be less efficient than the more familiar Horizontal axis turbines *(Figure 1)*.

Vertical axis Darrieus turbine: High lift low drag

Horizontal axis wind turbine: High lift low drag

Vertical axis Savonious wind turbine: Low lift mostly drag

Figure 1. Three different configurations of wind turbines.

Wind turbine designs catch wind and utilize a mix of drag and lift forces. Drag forces are the forces of air resistance acting in a direction parallel to the flow direction. Envision air hitting the cupped part of the Savonious turbine, forcing it to spin *(Figure 2)*. Lift forces act perpendicular to the air flow direction. Envision an airplane wing where the wind strikes the front of the wing, flows over creating lift perpendicular to air flow, and causes the wing to rise upward. Horizontal axis and Darrieus turbines have air foil blades that utilize the lift forces more than drag forces *(Figure 3)*.

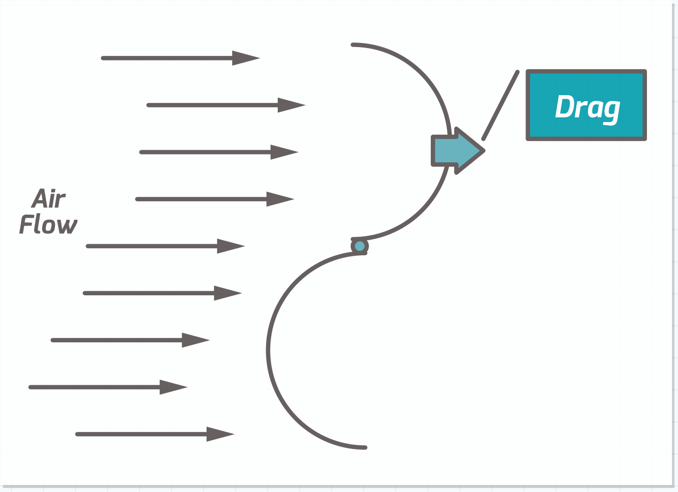


Figure 2. Top view of wind hitting a savonious turbine. Drag forces are greater on concave side than on convex side, causing turbine to spin. Drag force is pushing in the same direction as the wind is blowing.

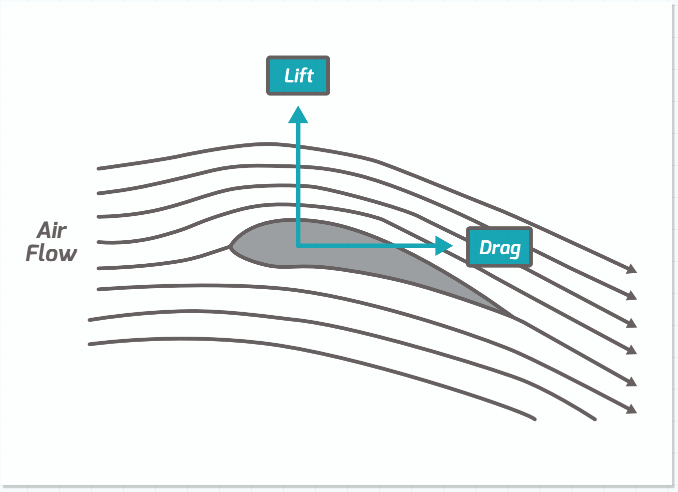


Figure 3. Wind pushing on a horizontal axis or darious blade has both lift and drag. Lift pushing perpendicular, and drag pushing parallel to the flow of the wind.

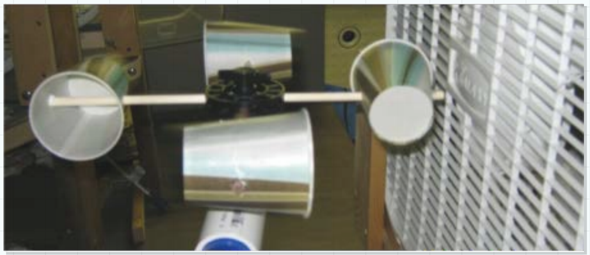


Figure 4. A simple Savonious turbine made from cups.

The purpose of this experiment is to explore the physics of wind energy. Participants will build and test wind turbines. Using the turbine they build, students will calculate the power in the wind, the output power of their turbines, and the efficiency of their turbine in converting wind energy to electrical energy.

What makes a turbine efficient?

Efficiency in this case refers to how much of the energy in the wind is converted into electrical energy. There are two things to know about efficiency:

1. The first law of thermodynamics states energy cannot be created or destroyed. The second law of thermodynamics tells us we cannot make use of all the energy when converting energy from a less useful form to a more useful form (in this case kinetic to mechanical to electrical).

2. Based on the second law of thermodynamics we know that we cannot be 100 percent efficient. How efficient can a wind turbine be? To turn wind into rotational, then electrical energy, a wind turbine must take energy from the wind by slowing it down. There is a theoretical maximum of how much the air can be slowed before the slow-air molecules obstruct the new fast-air molecules. There is a theoretical limit to how much wind energy a turbine can catch and convert into rotational energy. It's called the Betz Limit, and it states that the theoretical maximum efficiency for a turbine is 59.3 percent. In reality turbines operate at much lower efficiencies. (See fun fact below to find out why.)

FUN FACT

The Betz limit is a theoretical maximum efficiency and is calculated assuming the air molecules hitting the turbine blades will simply impart their energy to the blades, which slows the air molecule. In reality the spinning motion of the blades will push the slowed air, making it spin behind the turbine. The energy spent spinning the air behind the turbine reduces the amount captured by the turbine; thus real wind turbines are always lower than 59.3 percent efficient. Albert Betz (1885-1968) was a German physicist whose work on the efficiency of wind turbines led to the calculations of the maximum efficiency of an ideal wind turbine, regardless of design.

Up to this point we have been using the term "energy," which is the ability to do work. For our experiment we will use the term "power," which is the rate at which the work could be done. Efficiencies can be calculated using either power in and power out, or energy in and energy out.

NOTE

Many power plants use thermal energy for making electricity. They include coal, natural gas, biomass, and nuclear power. Efficiency for thermal electric facilities is usually around 35 percent. Combined cycle natural gas facilities use some waste heat to make more electricity, increasing their efficiency to 45-50 percent.

A turbine's efficiency can be determined by the following equation:

$$\text{Percent Efficiency} = \frac{\text{power out}}{\text{power in}} * 100 = \frac{\text{measured power of turbine}}{\text{calculated power hitting the turbine}} * 100$$

Beyond the efficiency we will explore the Coefficient of Performance (CoP) of our turbines. The CoP compares turbine performance to the ideal turbine. By dividing power out (P_{out}) by the theoretical maximum power, we can determine the CoP.

Another term sometimes seen in relation to wind turbines, which we will not deal with in this curriculum, is the term *capacity factor*. Capacity factor is commonly used to describe power stations and wind farms as a way to compare them. Capacity factor basically describes how much of the time they are running. Capacity factor is defined as actual production over maximum production. The capacity factor of a wind farm is influenced by the amount of wind it experiences or the quality of the site, maintenance, and breakdowns. A good capacity factor for a wind farm is 30-55 percent. Capacity factor is not efficiency.

For best results, wind turbines should always be placed in a proper location. The best turbine placement is up high and away from other tall objects such as buildings or trees. It's better to not have a turbine bolted directly to the roof of your house; houses are too low and turbines also cause annoying vibrations *(Figure 5)*.

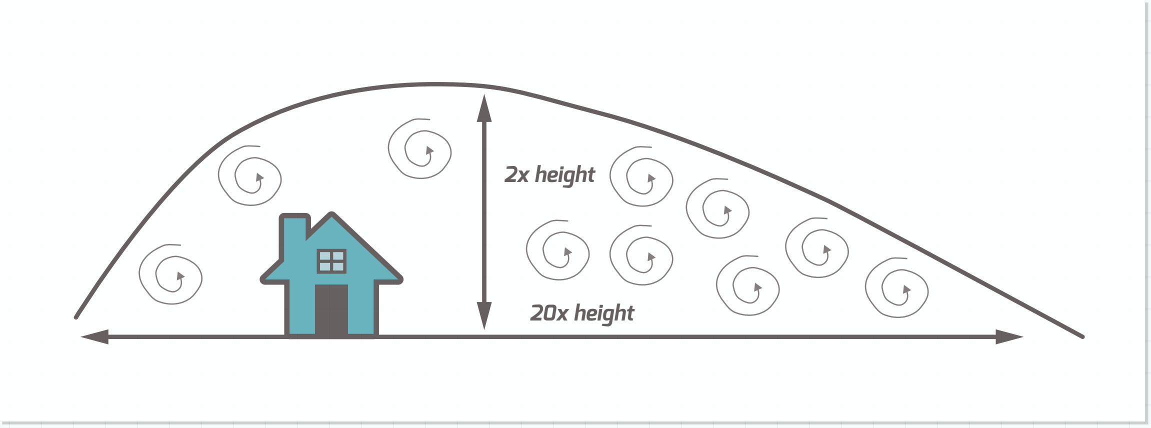


Figure 5. Turbulent winds slow wind speeds and can damage turbines. Avoid placing wind turbines in a zone two times the height and at a distance of 20 times the height of an obstacle like a house, tree, or building.

Finding "power in"

"Power in" is the kinetic energy of the wind that is available to do work on a turbine. It can be calculated using the following equation:

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

- The Greek letter rho *(ρ)* stands for air density. We can say that it is approximately equal to 1.0 for inland sites and 1.2 near sea level.
- Area (A) is the swept area of a turbine that can be found using $A=\pi r^2$ where "r" is the radius of the turbine, or the length of one blade.
- Wind velocity (v) is the measured wind speed.

- P_{in} is given in watts.
- Area in square meters (A in m^2) radius in meters (r in m).
- Velocity in meters per second (v in m/s).

Practice Question

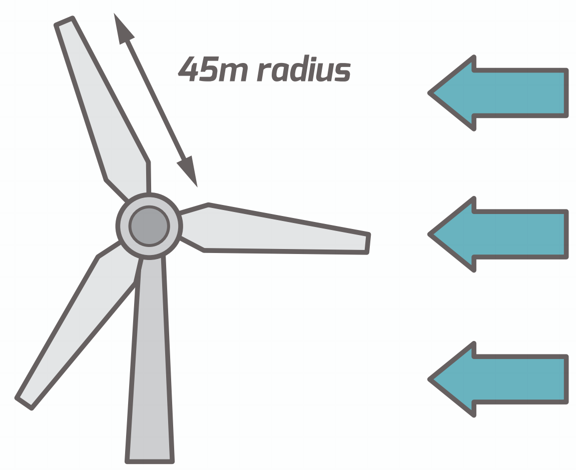
A wind turbine with a 90-meter diameter is placed in a location with an average wind speed of 7 meters per second. How much power is hitting the turbine when the wind speed is 7 m/s?

Answer

$P_{in} = \frac{1}{2}(\rho)(\pi r^2)(v^3)$

$P_{in} = (0.5)(1)(3.14 \times 45^2)(7^3)$

P_{in} = 1,090,482 Watts or 1,090 megawatts



NOTE

The P_{in} for the turbines built for this experiment will be much lower in the range of 2-10 watts.

Finding "power out"

"Power out" is the power that the turbine actually produces as electricity. Using a multimeter and a resistor, the amount of electricity produced can be measured as a voltage (volts), or an electric potential difference. Power out can then be found using the following equation:

$$P_{out} = \frac{V^2}{R}$$

- Where V is the voltage in volts (V)
- R is the resistance in ohms (Ω).

The resistor acts as a load such as a light bulb, computer, or other electrical device. The resistor turns a known amount of electricity into heat.

NOTE

The P_{out} for the turbines built for this experiment will be very low in the range of 0.001 to 0.1 Watts.

Finding turbine efficiency

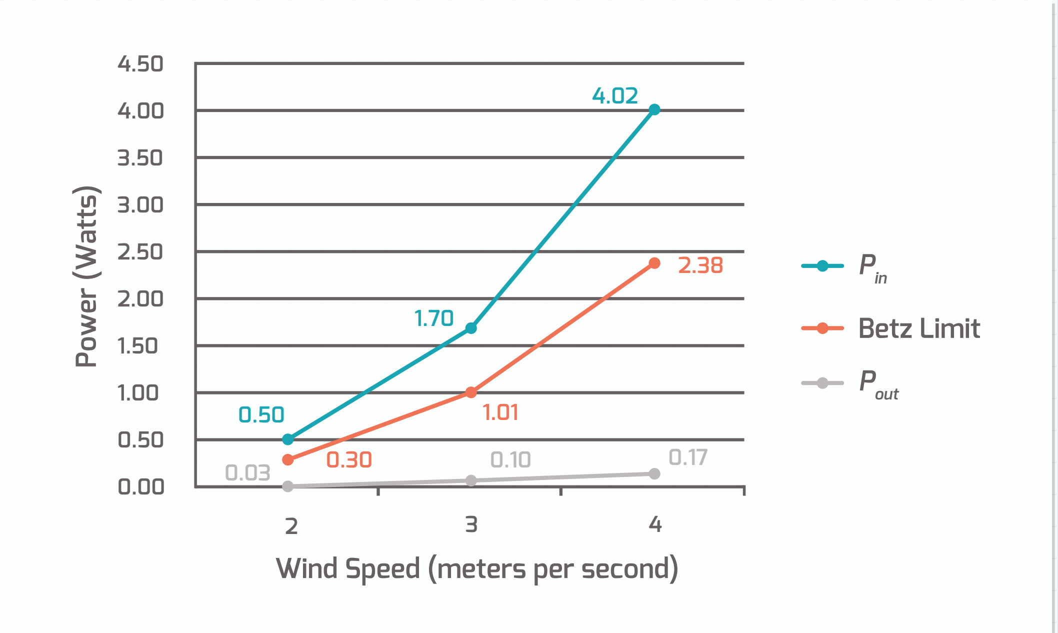
The efficiency of the turbine is power out divided by power in. To get that number as a percent, multiply by 100.

$$\text{Percent Efficiency} = \frac{\text{power out}}{\text{power in}} * 100 = \frac{\text{measured power of turbine}}{\text{calculated power hitting the turbine}} * 100$$

Finding turbine coefficient of performance

$$\text{Coefficient of Performance} = \frac{\text{power out}}{\text{power in} * 0.593} * 100 = \frac{\text{measured power of turbine}}{\text{theoretical maximum power available}} * 100$$

Envisioning Efficiency and CoP



In the graph above the efficiency of the turbine at 4 meters per second would be (0.17/4.02)*100 = 4.2 percent; the Coefficient of performance would be (0.17/2.38)*100 = 7.1 percent.

Experiment Instructions

Supplies needed

- Scissors
- Hot glue gun (with glue)
- Cardboard
- Sticks
- Turbine
- Multi-meter
- Resistors
- Breadboard
- Lead wires
- Alligator clips
- LED lights (optional)

Step 1: Design and Build a Turbine

For this step you are an engineer designing and building a prototype wind turbine. Follow the engineering design process. The process will lead to better results and then just “winging it.”

Engineering Design Process

1. **Identify the problem.** Determine what constraints (or drawbacks) limit your choices in solving this problem. An example constraint: blade materials. Your blades must be made from the materials you have available.
2. **Generate ideas.** Brainstorm possible solutions that might address the problem.
3. **Evaluate and compare possible solutions.** Decide which of the possible solutions are the most logical or make the most sense.
4. **Build a prototype.** A prototype is a first attempt at a design.
5. **Test the prototype.** Conduct a series of experiments to see if your prototype works.
6. **Tell your story.** Record your data and share what you learn with others.
7. **Refine your design.** Explore how you can use what you’ve learned to improve or change your design. If you have time, build a second prototype. Additional versions are sometimes called iterations (first, second, third iteration).

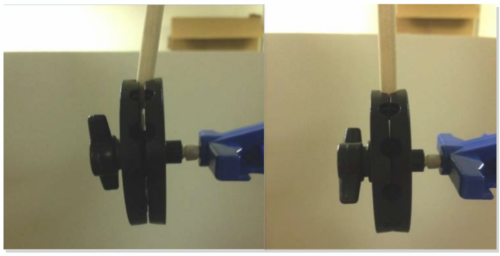
Draw Your Turbine

a. **Cut out blades. When finished they may look like this:**

(These are only examples. Use your imagination and test to determine the best design.)

b. **Attach the blades to sticks using a hot glue gun.**

c. **Secure the blades inside turbine hub.**



BLADE PITCH ANGLE:

It's important to tilt the turbine blades so they can better catch the wind (the angle the blades are tilted is called the blade pitch). Make sure they are all tilted in the same direction. Turbines that require more torque will need a larger angle. Blades are generally tilted between 10 and 30 degrees (Figure 6).

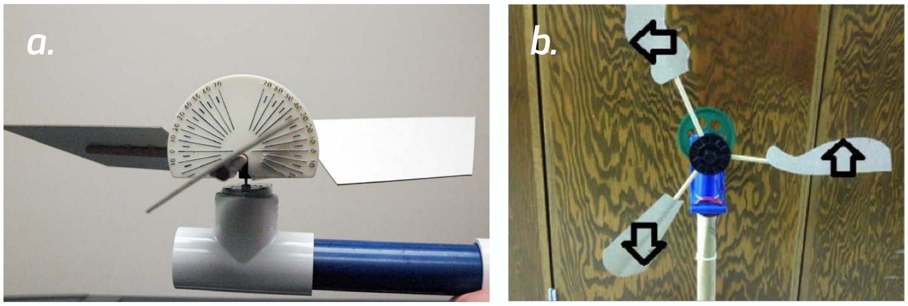


Figure 6. The blade pitch angle of the turbine above is set to 30 degrees (a). To make sure everything is correct, observe that all your blades are set to the same blade pitch in the same direction, making sure all the blades spin in the same direction (b).

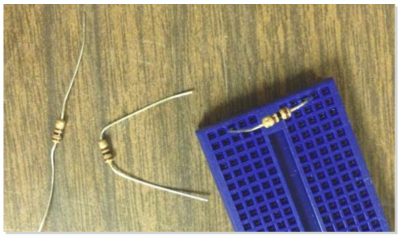
Step 2: Test the Turbine

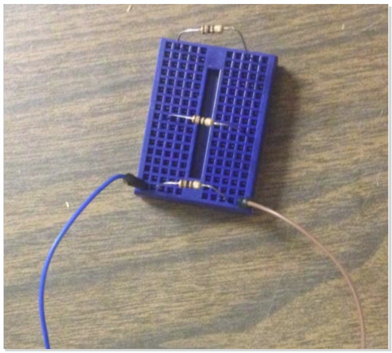
a. Measure wind speed

- Use a wind measurement device. Set device to measure in meters per second (m/s),
- Using the fan set to high speed, record the wind every 2-3 seconds until you have 10 readings and have filled up *Table 1* of the "Wind Physics Database Sheet." Then calculate the average wind speed. (To find the average, add all 10 numbers together then divide by 10.)

b. Prepare your resistors.

- Use three resistors (30 ohm, 51 ohm, and 100 ohm)
- Place resistors in breadboard. (If you don't have a breadbord, simply put resistors in the circuit with alligator clip wires or other connectors.)
- Space them out evenly (you will have three)
- Add jump wires on either side of the first resistor. Once you're finished testing the first resistor, move the jump wires to the second one. Although they're all on the same breadboard, only the resistor with the lead wires on either side of it is in the circuit.

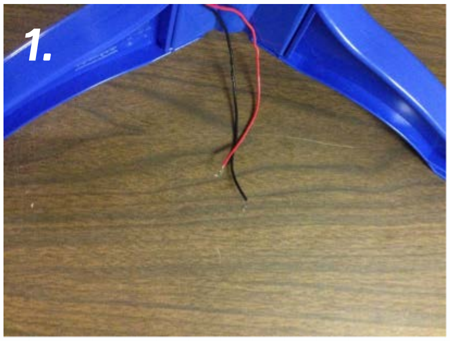


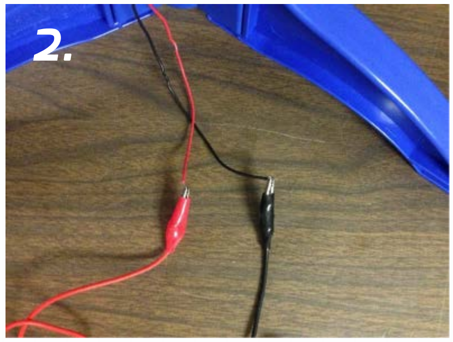


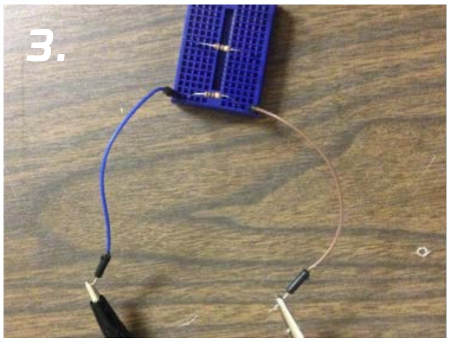
c. Position turbine in front of fan

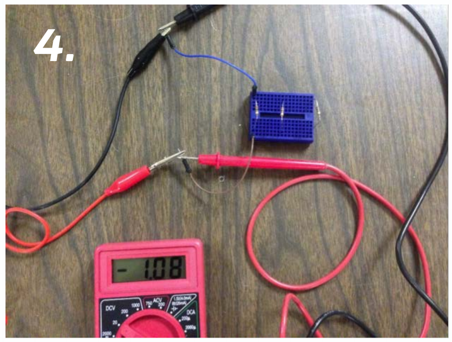
- Make sure that it isn't too far away and is in roughly the same spot where you measured the wind speed.

d. Create the circuit. Attach turbine wires to the first resistor and multimeter.



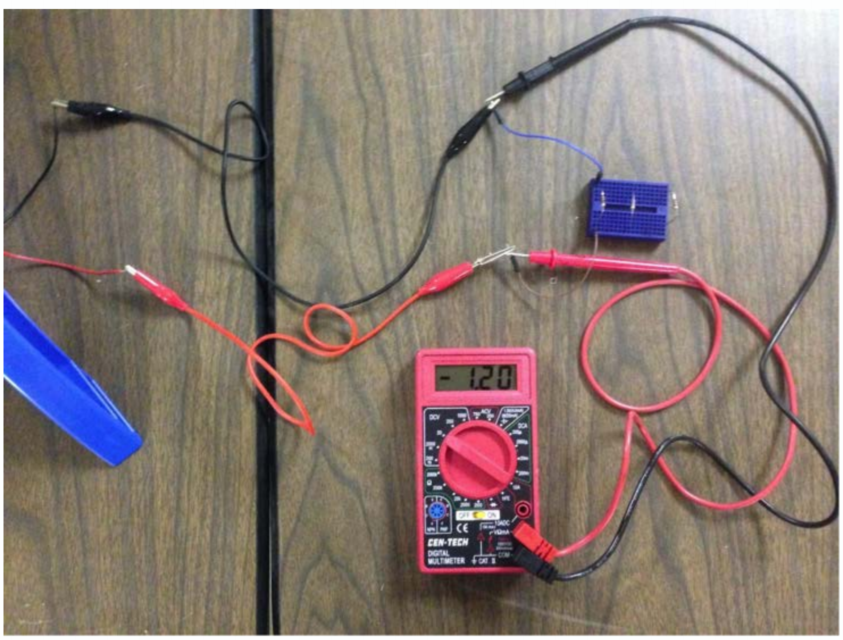






1. There should be two wires coming from the turbine.
2. Attach alligator clips to these wires.
3. Attach the other end of the alligator clips to the jump wires on your breadboard. The circuit is now complete.
4. To test for the voltage running through the circuit, place the two probes from the multimeter on the exposed metal of the lead wires/ alligator clips. A reading should appear.

The entire setup should look something like this:



Make sure that the multimeter is set to DCV 20.

e. **Record the voltage produced**

- There are three resistors to test: 30, 51, and 100 ohm.
- For each resistor, record the voltage every 5 seconds for a total of five measurements. Then calculate the average.
- Whether the voltage is negative or positive doesn't matter, the negative sign only indicates the direction of electric current, magnitude will be the same.

f. **Repeat for all three resistors. *Table 2* in "Wind Physics Database Sheet" should be filled in.**

Step 3: Determine Efficiency

a. **Calculate P_{in}**

b. **Calculate P_{out}**

c. **Calculate Percent Efficiency for each resistor load using the equation $\frac{P_{out}}{P_{in}} * 100$.**

- The efficiencies found will likely be quite low. This is due to the simple nature of these small turbines. Larger turbines with higher tolerance and better materials can produce as high as 40-50 percent efficiency.

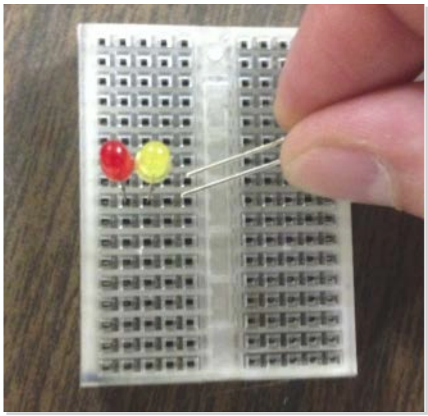
d. **Calculate Coefficient of Performance for each resistor load using the equation $\frac{P_{out}}{P_{in} * 0.593} * 100$.**

e. **The results must be filled up in *Table 3* and *Table 4* in "Wind Physics Database Sheet."**

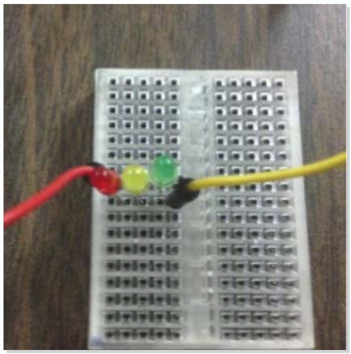
Further Activities and Information

- Compare your efficiency with the efficiency of other groups; or alter your blade design and complete efficiency test for alternate designs to find out which design has the highest efficiency. Record your observations about each to help analyze the differences between them.
- Create different circuits to test using lights and breadboards.

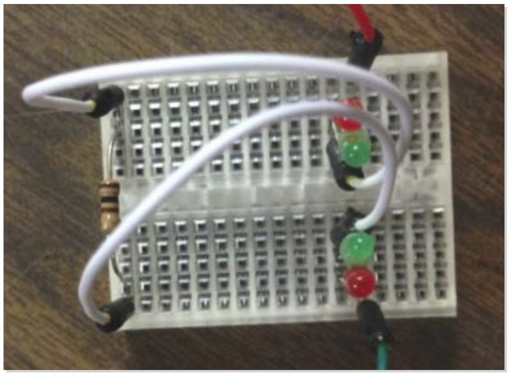
The longer end is positive. The shorter end is negative.



When placing LED bulbs into the breadboard, make sure that all of the positive (and negative) ends are in the same row.



Use lead wires to attach the lights to your turbine and create a circuit. In the picture above the yellow wire is on the positive side and the red wire is negative. How many lights can your turbine light up?

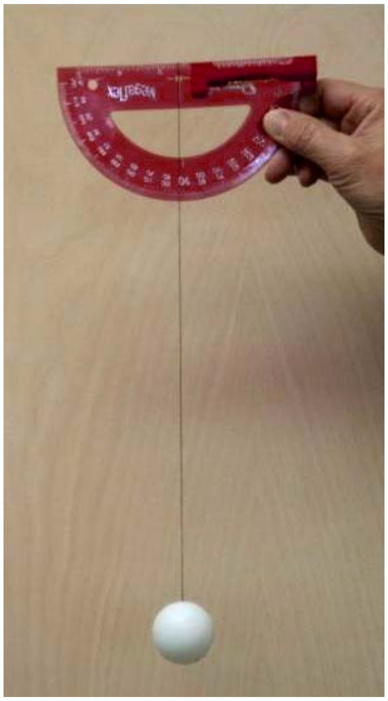


You can even make more complicated things like this, using another set of lead wires and a resistor. The device above will light up only red or only green, depending on the direction of current. Plus there is a 100 ohm resistor in the circuit.

Wind Measuring Devices

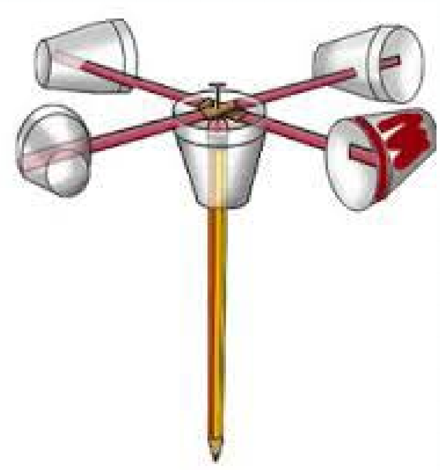
Common wind measuring devices are cup anemometers and other hand-held wind measuring devices that can be made or purchased.

- Make your own:



Protractor Anemometer

lhs2fp.lhs.berkeley.edu/record/1758



Homemade Cup Anemometer

sercc.com/education_files/anemometer.pdf

- Purchase one: $13-$100 (search "Anemometer" on sites such as Amazon):

Cup Anemometer

Handheld Anemometer

Wind Physics Database Sheet

Equations

$A = \pi r^2$

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

$P_{out} = \frac{V^2}{R}$

$Average = \frac{\Sigma}{n}$

$Efficiency = \frac{P_{out}}{P_{in}} * 100$

$\text{Coefficient of Performance} = \frac{P_{out}}{P_{in} * 0.593} * 100$

Table 1

	Wind velocity (v)(m/s)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
Average	

Table 2

	30 ohm	51 ohm	100 ohm
Voltage 1			
Voltage 2			
Voltage 3			
Voltage 4			
Voltage 5			
Average Voltage			

P_{in} = ____________

Table 3

	30 ohm	51 ohm	100 ohm
P_{out}			

$$\text{Percent Efficiency} = \frac{\text{power out}}{\text{power in}} * 100 = \frac{\text{measured power of turbine}}{\text{calculated power hitting the turbine}} * 100$$

Table 4

	30 ohm	51 ohm	100 ohm
Efficiency			

$$\text{Coefficient of Performance} = \frac{\text{power out}}{\text{power in} * 0.593} * 100 = \frac{\text{measured power of turbine}}{\text{theoretical maximum power available}} * 100$$

Table 5

	30 ohm	51 ohm	100 ohm
CoP			

Glossary

1 Watt = 1 joule/second. The “watt” is the standard unit for power in the SI system (International System of Units).

1 Joule = 1 Newton meter. The joule is the work done in applying a force of one newton through a distance of one meter (Newton meter). The joule is the standard unit for energy in the SI system.

Kilowatt-hour is the amount of work done equal to one kilowatt for one hour. Kilowatt-hours are the units used for measuring the amount of electricity your house uses. In the U.S. electricity is worth about 6-20 cents per kWh.

Energy is the amount of work (energy is power over a period of time).
Unite of Energy (joule, watthour, kilowatt-hour, horsepowerhour, calorie, British thermal unit).

Power is the rate work is performed.
Units of Power (joule/second, watt, kilowatt, horsepower).

Coefficient of Performance is similar to efficiency yet instead of dividing by the total power in the wind, the P_{out} is divided by the maximum available (Betz limit = 59.3% of the total power in the wind). The CoP takes into account that a wind turbine cannot extract 100% of the energy from the wind. Thus CoP compares a turbine to the ideal turbine (ideal turbine refers to a turbine which performs at the Betz limit). The CoP is equal to power produced by the turbine divided by 59.3% of the power in the wind

Unit Conversions

1 inch = 0.0254 meters
1 cm = 0.01 meters
1 mph = 0.447 m/s
1 kilowatt (kW) = 1,000 watts
1 megawatt (MW) = 1,000 kilowatts (kW) = 1,000,000 watts

Math Problems

1. What is the swept area of a wind turbine with a diameter of 30 meters?

2. What is the swept area of a wind turbine with four blades each 40 meters long?

3. How much power is in the wind blowing at 5 m/s hitting a wind turbine that has blades 2.5 meters long?

4. A wind turbine produces 10 kilowatts at a wind speed of 13 m/s. How much energy would the turbine generate if the wind was constantly 13 m/s for an entire year?

5. A wind turbine with 45 meter blades in a 7 m/s wind is being struck with 1,090,482 watts of wind power. What is the maximum amount of power a turbine could convert into rotational energy?

Answers

1. Area = πr^2=(3.14)(15^2) = **706.5 m²**

2. Area = πr^2=(3.14)(40^2) = **5024 m²**

3. Power(W)= 1/2 ρAV^3 = 0.5(1)((3.14)(2.5^2))(5^3) = **62.5 watts**

4. 10 kW (24 hours a day)(365 days a year) = **87,600 kWh**

5. 1,090,482 watts (59.3%) = 1,090,482 (0.593) = **646,655 watts**

Summary

Wind turbines are fascinating as they turn the motion of wind into valuable electricity. To do this a wind turbine must be designed, built, tested, and redesigned. Engineers follow the engineering design process and students can, too. Students will use their imagination to design a turbine prototype, then use their math skills to quantify their turbine's performance. Using basic low-cost materials, Wired for Wind – Wind Physics will teach students about engineering design, wind power physics, physic equations, and renewable energy.

Wired for Wind – Wind Physics Equation Sheet

Radius (meters) =

Area (square meters) = $\prod r^2$ =

Wind Speed (meters/second) =

Voltage (volts) =

Resistance (ohms) =

Air Density - ρ (rho)(kg/m^2)= 1.0

$$Energy_{in} = {}^{1}/_{2} \times \rho \times A \times V(wind\ speed)^3$$

ρ (air density) A (area) V (wind speed) V (wind speed) V (wind speed)

$$E_{in}\ \boxed{} = \frac{1}{2} \times \boxed{1.0} \times \boxed{} \times \boxed{} \times \boxed{} \times \boxed{}$$

$$Energy_{out} = {}^{v(volts)^2}/_{Resistance}$$

V (volts) V (volts)

$$E_{out}\ \boxed{} = \frac{\boxed{} \times \boxed{}}{\boxed{}}$$

R (Resistance)

$$Efficiency = \frac{Energy_{out}}{Energy_{in}} \times 100 = \boxed{}\ \%$$