The 162 megawatt Colorado Green Wind Farm, dedicated on May 14, 2004, It is expected to produce enough electricity to power some 52,000 homes.

Wind Power Curves

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The production of the kits and other materials related to wind energy have been generously supported by these agencies.

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Lesson Zap! - Analyzing Wind Power Curves

Background

This lesson has students analyze and understand a variety of curves that describe the power extracted from the wind. Extensions include generating your own wind power curves using the small wind turbines that your students have constructed.

Objectives:

Students will be introduced to:

- Important parts of a wind power curve
- Analyzing data, tables and graphs
- How to compare a variety of wind turbines based on their power output curves
- Important variables in how much power we can extract from the wind.

Suggested Level

Middle & High School

Time Required

1-2 Class Periods

Materials Required

- Worksheet Handouts
- Images of Wind Turbines
- If you would like to generate your own wind power curves you will need to build some small wind turbines, multimeters, graph paper & rulers.

Doing the Activity

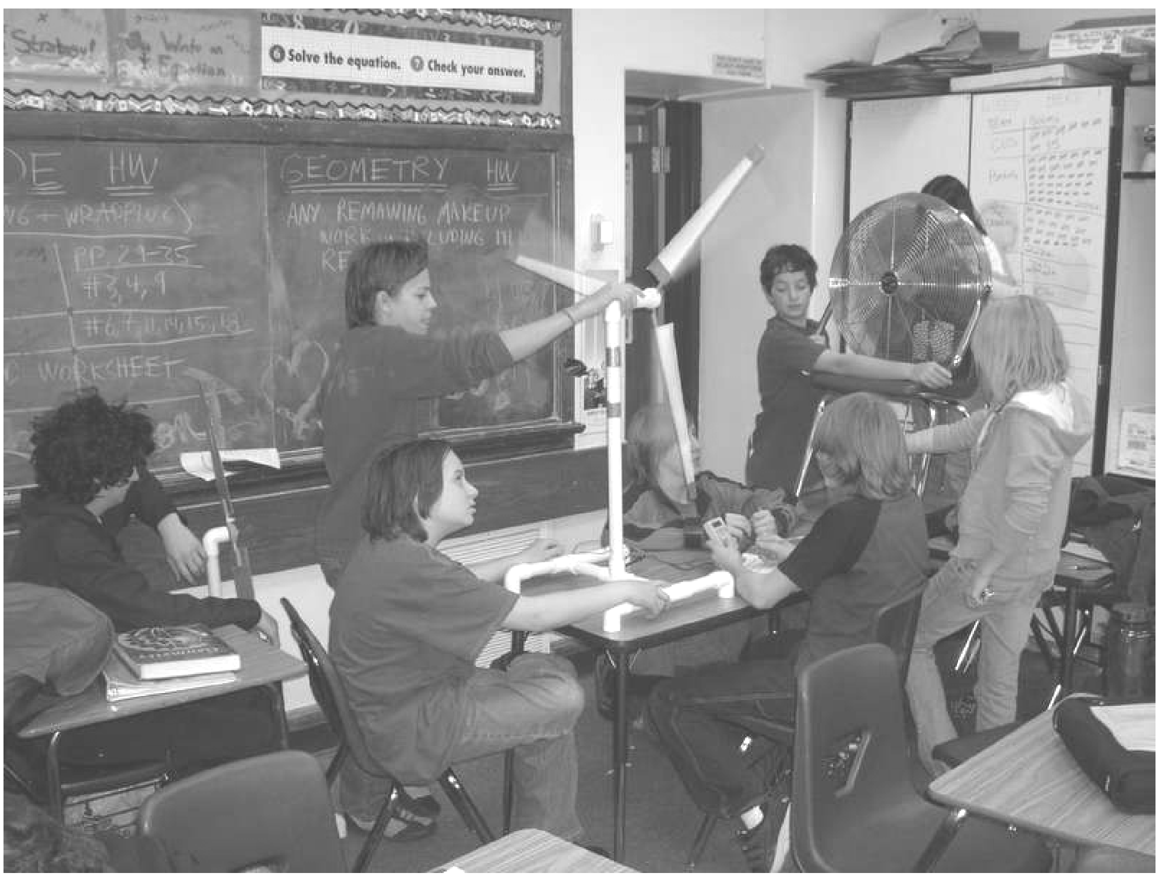
Preparation

I recommend doing this lesson once your students have had a significant introduction to wind energy. The best time would be after they have built and tested their own small wind turbines and done some power output testing. See **KidWind's Blade Design Lesson** to get an idea about constructing your own turbines and running some experiments like this.

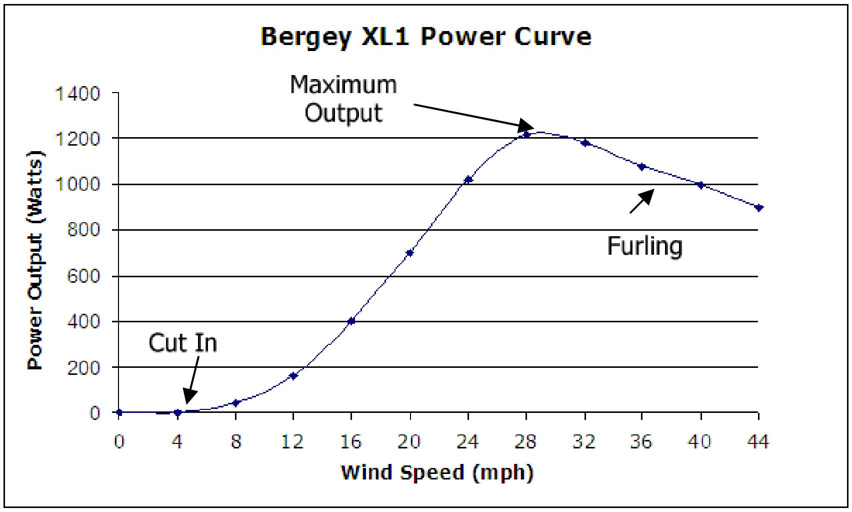
If you try to use this lesson without students doing a blade design experiment it will lose its value because the students cannot place these theories into any context.

If students have done testing of their turbines I would spend about 20 minutes giving them a lecture on what a wind power curve is and about 20 minutes trying to work through the questions.

After they understand commercial wind power curves they can create their own wind power output curves using their model turbines.



Students testing their blades on a PVC wind turbine. Now they can generate their own wind power output curves for their site conditions.



Bergey XL1
Source http://www.bergey.com

Wind Power Curves in a Nutshell

This is a quick look at the basics behind a wind power output curve. For a deeper analysis you can examine some of the documents in the resource section.

Wind power curves describe how much power a particular wind turbine can extract from the wind at a variety of different wind speeds. While these curves have a similar shape, they are specific to a particular turbine and offer insights when choosing a wind turbine for an individual location.

Above is a basic wind power output curve for a Bergey XL 1 small wind turbine. From these types of curves you can tell a great deal about the characteristics of a particular turbine such as when it will start making power, the maximum power output, and in what type of wind regime it will comfortably generate power.

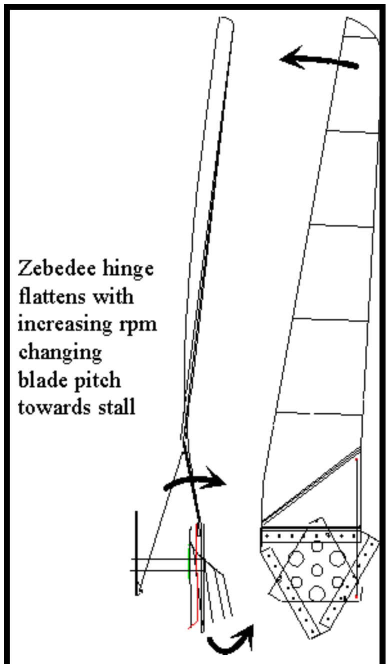
Cut In Speed – This is the wind speed where the wind transfers enough force to the blades to rotate the generator shaft. This number takes into account how smoothly the generator operates, blade design and number, and if there are any gears or other friction elements in the drive train.

Start Up Wind Speed – At the start up wind speed the wind turbine blades are moving fast enough and with enough torque that the turbine will start to generate electricity. While these numbers are pretty close to the cut in speed they are not the same. On a Bergey XL1 the cut in speed is around 5.5 MPH, but the start up wind speed is a little over 6.5 MPH. While the wind turbine may be generating some electricity at 5.5 MPH it may not be enough, or it may not be even enough, to charge batteries or a sustain a connection to the electrical grid.

Maximum Power Output –The maximum amount of power the turbine can produce. This is the peaking part of the curve. On this turbine the maximum amount of power it can produce around 1200 watts (1.2 kW) at about 29 MPH. The **Rated Power** (or Name Plate Output) for this turbine is 1000 watts (1 kW) and as you can see from the graph this happens at around 24 MPH.

Why are these different? I can't exactly say, although I would guess that the rated power is where the turbine is optimally functional and while it could generate higher output it may be cause stress on the components if sustained for a long periods of time.

Furling Speed – Small wind turbines cannot actively slow themselves by changing blade pitch or using brakes. This can be a problem in winds that are extreme (40+MPH). At these speeds the generator may spin too fast and can cause electrical or mechanical problems. To combat this problem small wind turbine manufacturers have developed a number of methods to "dump off" excess wind or govern their rotational speed. Some turbines have designed blades to change shape in high winds to cause blade stall, others are designed with the entire generator on a spring that moves up or to the side as wind speeds go over a predetermined velocity.



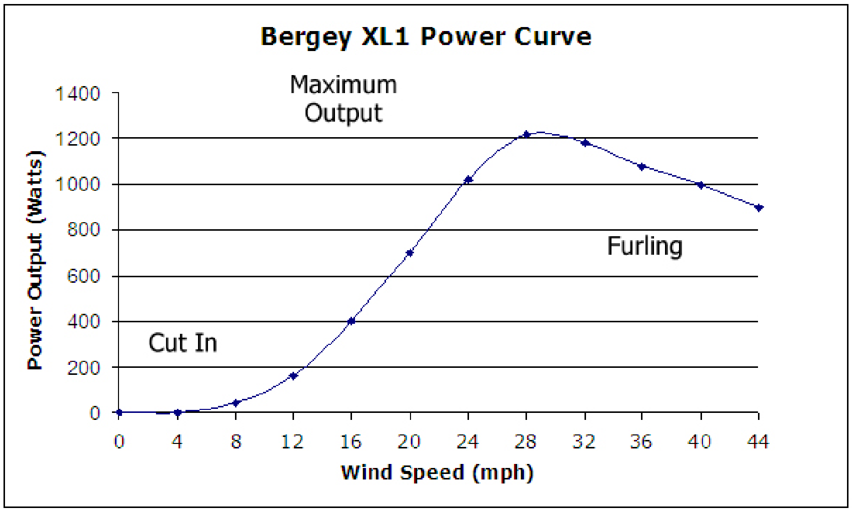
PROVEN wind turbines use flexible blades to "spill" air, stall and reduce speeds in high winds. Image from Proven website

Southwest Wind H40 Furling

On the Bergey XL1 the tail vane slowly starts to move perpendicular to the wind as the speed moves above around 29 MPH. You can tell when a turbine has reached its limit on the wind power curve because the power output starts to decrease or flattens out after this point. This is due to the fact that blades are starting to move "out" of a direct path with the wind.

What else can you see?

Wind power curves also show how important wind speed is when deciding on where to place your wind turbine. At low wind speeds you generate very little power, but also notice how quickly power output ramps up as wind speeds move above 16 MPH.



A simple equation for the ***Power in the Wind*** is described below.

$$P = 1/2 \, \rho \, \Pi \, r^2 \, V^3$$

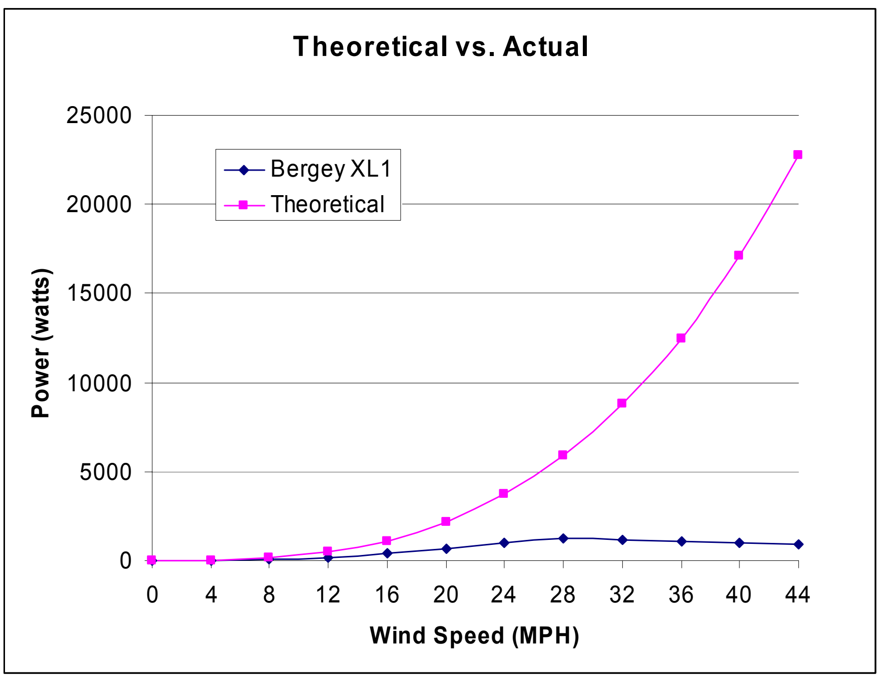
ρ = Density of the Air
r = Radius of your swept area
V = Wind Velocity

You can see from this equation that power output relies on how big your turbine is and it is very dependent on how fast the wind is blowing!

You may have heard that if you double your wind speed your power output will increases eight times as much. The simple math below, and the wind power curve also show that this is true. Due to this incredible increase in power by increasing wind speed you can see why people like to site wind turbines in the windiest locations possible.

$$2^3 = 8 \qquad\qquad 4^3 = 64$$

On the previous curve the Bergey XL1 makes around 50 watts at 8MPH. At 16MPH it is generating around 400 watts (8x as much power with a 2x the wind speed!)



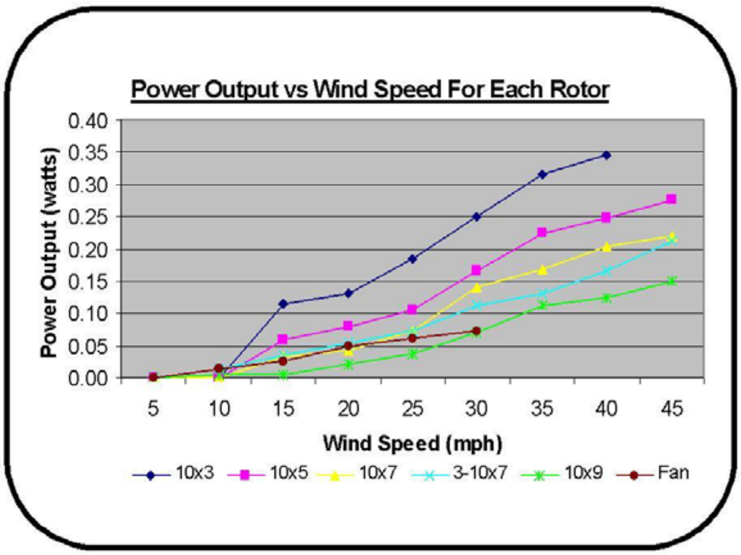
<u>Theoretical vs. Actual</u>
As we all know there is theory and then there is practice. Well the same is true for wind turbines. The equation described above tells you how much power you could get from a cylinder of wind a particular size. Can we build a wind turbine to extract 100% of that resource. We can't and if we did we would have something less like a wind turbine an more like a wall!

The above curve has two lines. One shows how much power would be found in a cylinder of wind 2.5 meters in diameter at a variety of wind speeds. The other you are already familiar with, it is shows much power is generated by the Bergey XL1. The XL1 curve looks flatter because the scale on the Y–axis has changed.

> **What is the Betz Limit?**
>
> In 1926 Albert Betz calculated that we can theoretically extract 59% of the power from moving wind – and this is if we do things perfectly which we rarely can. In reality modern turbines extract around 20-40% of the power in the wind.

Notice how different they are, especially at high wind speeds. What is going on here!? Well due to a number of factors such as the Betz limit, generator and blade efficiencies and other losses we can at best extract 20%-40% of the power in the wind.

That is even with a bunch of PhDs locked in room full of computers doing some fancy math and engineering.



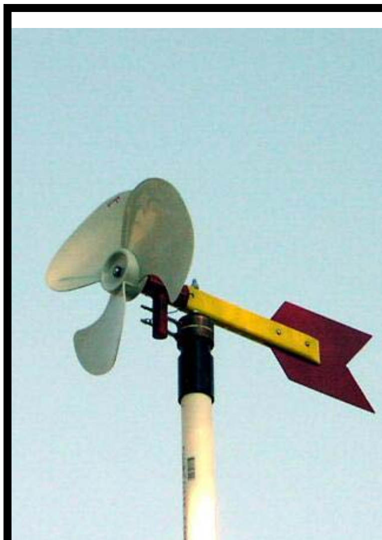
*Kathryn's blade test results. The second number is the pitch of the blade the smaller the **pitch** the "flatter" the blade.*

Wind Power Curve Lesson Extensions

If you have already built or are planning to build and test you own small wind turbines you can generate your own wind power curves and see if they look similar to a commercially made wind power curve.

You need to record a variety of different voltage and amperage readings for a variety of wind speeds and plot on this data on a graph. The graph to the left was generated by a 5th grade student named Kathryn who built and tested a pretty astounding small wind turbine.

"My project was to find if different rotors make a difference and if so which rotors worked best. I used airplane propellers mounted backwards. I compared several pitches of two blade props, one three blade prop, and one blade from a desk fan. I used a hobby motor from Radio Shack for the generator. We tested it by mounting it out in front of my dad's car."



Kathryn's hopped up turbine!

You'll notice right away that Kathryn's curves do not look like the ones we have analyzed. This is due to the fact that she was using a hobby motor and even though she tested in some pretty high winds we probably have not reached peak RPM— small DC motors like RPMs in the 1000s. Her curves are starting to flatten out and maybe if she went up to 60 or 70 MPH we would see some changes…but then on the other hand we might start to see structural failures in other parts of the turbine!

Additional Resources

Additional resources for this lesson can be found on the KidWind website.
http://www.kidwind.org/materials/Lessons/curves/powercurves.html

http://www.windpower.org/en/tour/wres/pwr.htm
More information on analyzing wind power curves. Detailed with a number of tips at looking at wind curve power data.

http://www.inl.gov/wind/software/
Software and power curve files in Excel format for a number of turbine manufacturers. Neat data — but this is definitely for HS and college students.

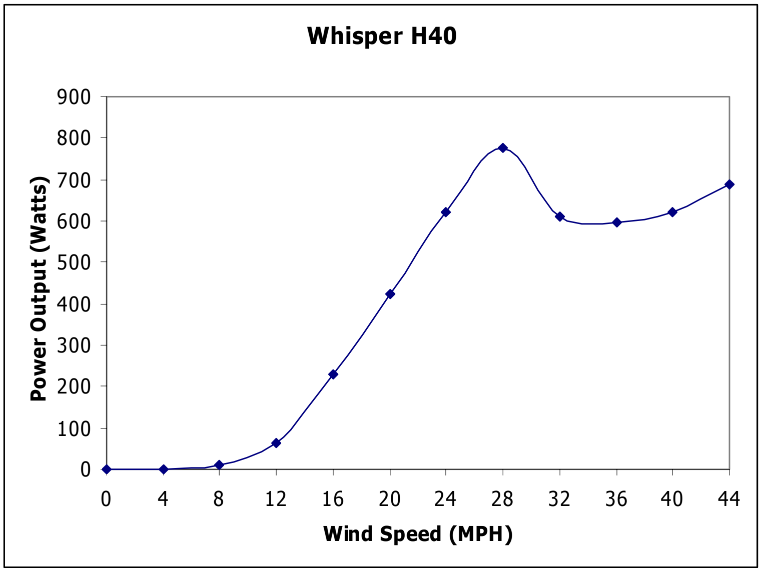
Turbine Manufacturer Data

These links will take you to some specification sheets from a variety of small turbine manufactures. You can examine their output curves and read more about the characteristics of small wind turbines. Some major manufacturers of small and large wind turbines include:

Bergey Windpower
http://www.bergey.com/
Southwest Windpower
http://www.windenergy.com/
Proven Windpower
http://www.provenenergy.co.uk/
GE Windpower
http://www.gepower.com/businesses/ge_wind_energy/en/index.htm
Vestas
http://www.vestas.com/uk/Home/index.asp
Suzlon
http://www.suzlon.com/
Gamesa
http://www.gamesa.es/gamesa/index.html

These are some direct links to spec sheets
http://www.kidwind.org/pdfiles/XL1.Spec.pdf
http://www.kidwind.org/pdfiles/Excel.Spec.Frt.pdf
http://www.kidwind.org/pdfiles/proven.pdf
http://www.windenergy.com/PRODUCTS/whisperh40.html

Name ___________________________________ Wind Power Curve Analysis



The above power curve is for a Southwest Wind Whisper H40. The data used to generate this graph were obtained on Paul Gipe's wind energy website. Use the graph above to answer these questions.

1. What is the cut in speed? ________________

2. At what speed does this turbine have its maximum output? ____________

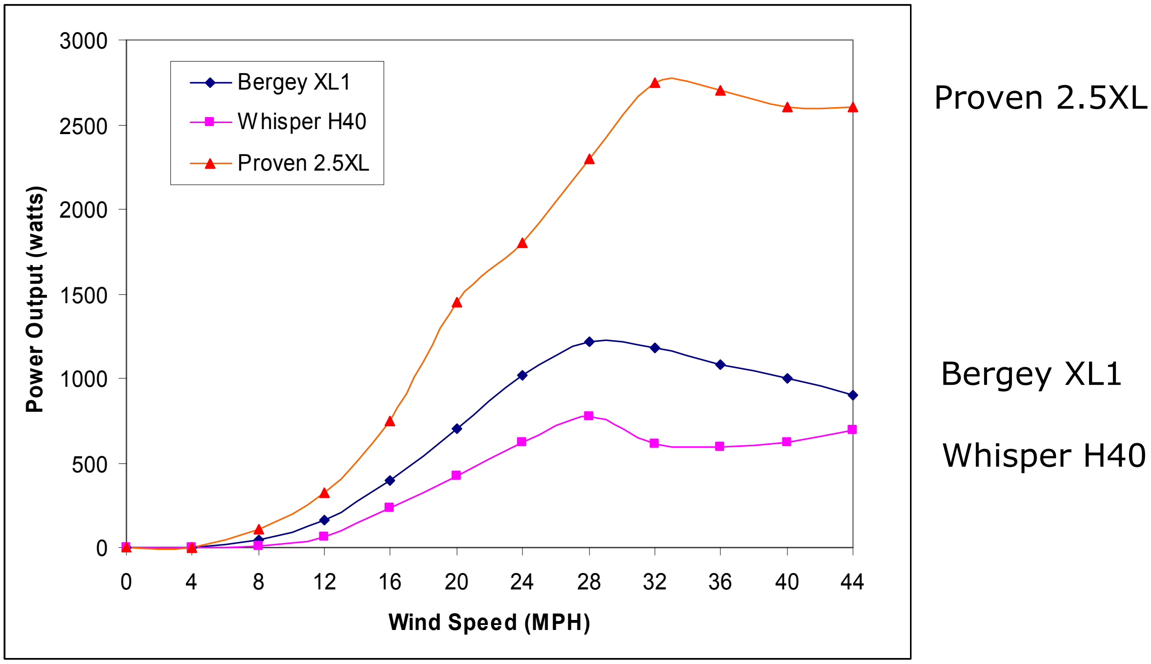
3. Why does the output decrease after 28 MPH?

4. Why might it dip at 36 MPH and increase after that?

Wind Speed (MPH)	Power Output (watts)
0	0
4	10
8	400
12	1200
16	1600
20	1900
24	1700
28	1650
32	1640
36	1500
40	1200

Below is some data that we observed for a Kid-Wind18 Turbine. On a separate piece of graph paper use this data to make you own wind power curve.

1. What is the cut in speed of this turbine?
2. What is the maximum output of this turbine?
3. At what wind speed does the turbine start to furl?
4. How many watts does this turbine make at 14 MPH?
5. How many watts does this turbine make at 30 MPH?
6. Compare this to the curve above. Does it look right?



This graph shows power curves for three different turbines. Answer these questions based on the data shown above.

Which turbine has the lowest cut-in speed? How can you tell?

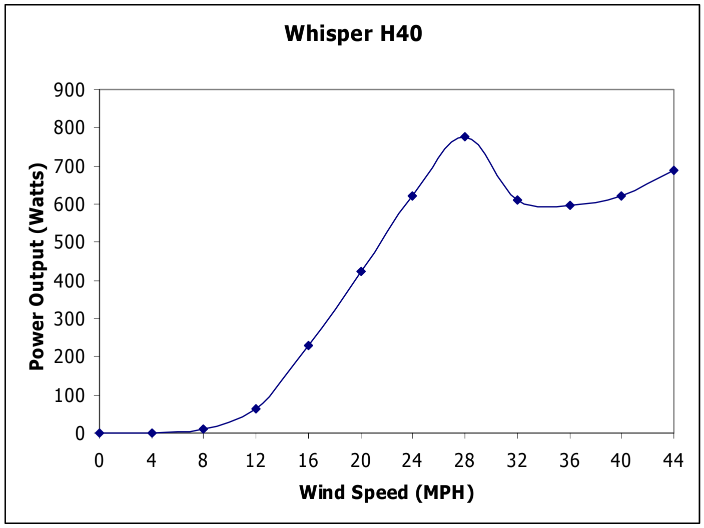
Which turbine has the highest maximum power output overall?

Which one these turbines do you think has the largest diameter blades? Why?

Which turbine would have the least amount of power output loss when it started to furl out of the wind or reduces its wind speed?

Why do all the curves peak then move downward? I thought more wind means more power?

If you had a limited amount of money and needed a turbine that produced a maximum of 1000 – 1200 watts which turbine would you choose?



The above power curve is for a Southwest Wind Whisper H40. The data used to generate this graph were obtained on Paul Gipe's wind energy website. Use the graph above to answer these questions.

1. What is the cut in speed? **Between 4 – 8 MPH**

2. At what speed does this turbine have its maximum output? **28 MPH**

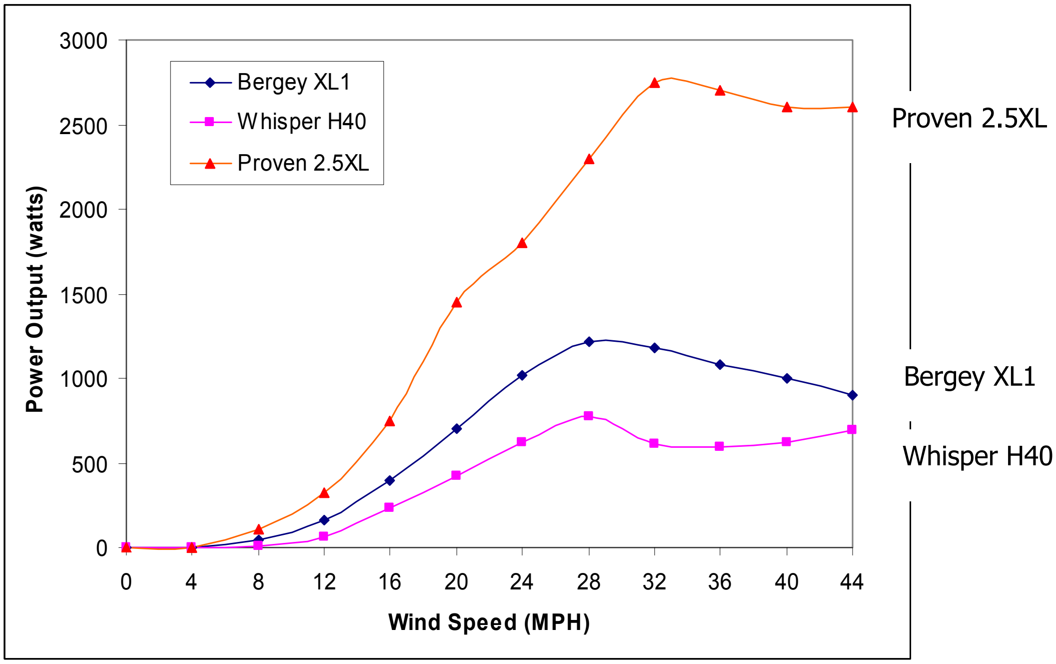
3. Why does the output decrease after 28 MPH?
The output decreases because the wind turbine is starting to furl out of the wind.

4. Why might it dip at 36 MPH and increase after that?
Tough question…maybe the increased wind speed is overcoming the effect of the furl.

Below is some data that we observed for a KidWind18 Turbine. On a separate piece of graph paper generate use this data to make you own wind power curve.

Wind Speed (MPH)	Power Output (watts)
0	0
4	10
8	400
12	1200
16	1600
20	1900
24	1700
28	1650
32	1640
36	1500
40	1200

1. What is the cut in speed of this turbine? 0-4 MPH
2. What is the maximum output of this turbine? 1900 watts
3. At what wind speed does the turbine start to furl? 1900+
4. How many watts does this turbine make at 14 MPH? 1400
5. How many watts does this turbine make at 30MPH? 1650
6. Compare this to the curve above. Does it look right? This curve rises too fast…does not seem to follow the cube law for velocity.



This graph shows power curves for three different turbines. Answer these questions based on the data shown above.

Which turbine has the lowest cut-in speed? How can you tell?

They all seem to cut in between 4-8 MPH so it is hard to tell…if we could see closer up or see actual data then we could better tell.

Which turbine has the highest maximum power output overall?

The Proven 2.5XL

Which one these turbines do you think has the largest diameter blades? Why?

The power equation has two main variable wind velocity and blade area. If a turbine makes more power than another at the same wind velocity then it probably is bigger. Other things may come into effect like blade design or generator efficacy so this is not always true.

Which turbine would have the least amount of power output loss when it started to furl out of the wind or reduces its wind speed?

It looks like the either the Whisper H40 actually increases in output after the furl. The Proven curve looks pretty flat after it start to self govern as well.

Why do all the curves peak then move downward? I thought more wind means more power? The turbines begin to govern themselves by furling or other means.

If you had a limited amount of money and needed a turbine that produced a maximum of 1000 – 1200 watts which turbine would you choose?

I'd probably pick the Bergey XL1 as it makes just enough, but not too much. Don't pay for more than you need.