Siting Wind Power: Wind Power Curves & Community Considerations
(Teacher Notes)
(Assessing the Feasibility of Wind Power for Pennsylvania)

Notes on Part 1

A Beaufort scale is included on the next page that may be copied onto transparency film to be used as an overhead, or the electronic version may be found at: http://www.mountwashington.org/discovery/arcade/wind/beaufort.html. Students have a copy on page 1 of the student handout.

Notes on Part 2

The power curves section of this lesson comes recommended by the designer at KidWind for students who have had a significant introduction to wind energy. The ideal circumstance would be after they have built and tested their own small wind turbines and done some power output testing. See KidWind Blade Design Lesson (www.kidwind.org) to get an idea about constructing your own turbines and running some experiments like this.

The following section helps to describe the purpose of the wind power curve activity and was accessed from the American Wind Energy Association's website: http://www.awea.org.

How Does A Wind Turbine's Energy Production Differ from Its Power Production?[1]

While wind turbines are most commonly classified by their rated power at a certain rated wind speed, annual energy output is actually a more important measure for evaluating a wind turbine's value at a given site.

Energy = Power x Time

This means that the amount of time a wind turbine produces a given power output is just as important as the level of power output itself. And wind turbine operators don't get paid for producing a large amount of power for a few minutes (except in rare circumstances.) They get paid by the number of kilowatt-hours (kWh) their turbines produce in a given time period.

The best crude indication of a wind turbine's energy production capabilities is its rotor diameter--which determines its swept area, also called the capture area. A wind turbine may have an impressive "rated power" of 100 kW, but if its rotor diameter is so small that it can't capture that power until the wind speed reaches 40 mph (18 m/s), the wind turbine won't rack up enough time at high power output to produce a reasonable annual energy output.

[1] American Wind Energy Association. http://www.awea.org/faq/basicen.html, accessed 8 July 2005.

Expected energy output per year can be reliably calculated when the wind turbine's ***capacity factor*** at a given average annual wind speed is known. The capacity factor is simply the wind turbine's actual energy output for the year divided by the energy output if the machine operated at its rated power output for the entire year. A reasonable capacity factor would be 0.25 to 0.30. A very good capacity factor would be 0.40.

NOTE: Capacity factor is very sensitive to the average wind speed. When using the capacity factor to calculate estimated annual energy output, it is extremely important to know the capacity factor at the average wind speed of the intended site.

Lacking a calculated capacity factor, the machine's power curve can actually provide a crude indication of the annual energy output of any wind turbine. Using the power curve, one can find the predicted power output at the average wind speed at the wind turbine site. By calculating the percentage of the rated power (RP) produced at the average wind speed, one can arrive at a ***rough capacity factor*** (RCF) for the wind turbine at that site. And by multiplying the rated power output by the rough capacity factor by the number of hours in a year, (8,760), a very crude annual energy production can be estimated. For example, for a 100 kW turbine producing 20 kW at an average wind speed of 15 mph, the calculation would be:

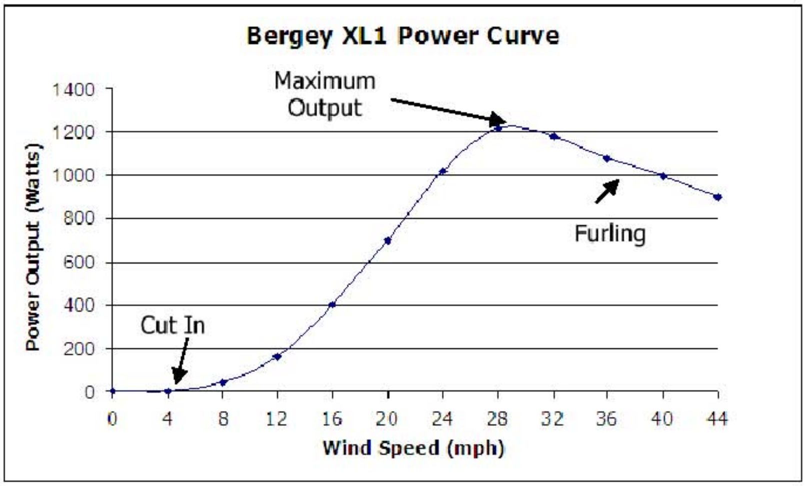
100 kW (RP) x .20 (RCF) = 20 kW x 8760 hours = 175,200 kWh

Actually, because of the effect of the cubic power law, the annual energy output will probably be somewhat higher than this figure at most windy sites. This is determined by the ***wind power distribution,*** which shows the percentage of time the wind blows at various wind speeds over the course of an average year. Lacking precise data on a given site, there are two common wind distributions used to make energy calculations for wind turbines: the ***Weibull distribution*** and a variant of the Weibull called the ***Rayleigh distribution*** that is thought to be more accurate at sites with high average wind speeds.

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 and take a peek at the PowerPoint presentation put together by Walt Musial, a senior engineer.

Wind power curves describe how much power a particular wind turbine can extract from the wind at a variety of different wind speeds and regimes. 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.



Bergey XL1

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.

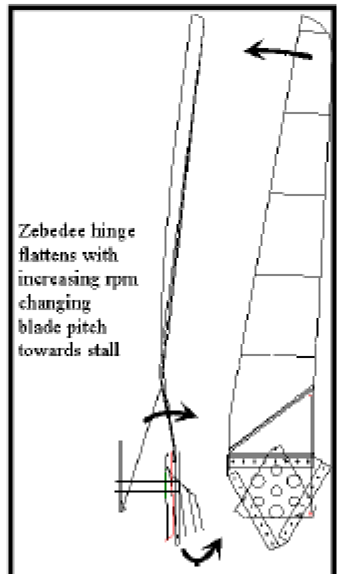
Cut In Speed – This is the wind speed where the wind transfers enough force to the blades to rotate the generator shaft. This number takes into account how smoothly the generator operates, blade design and number and if there are any gears or other friction in the drive shaft.

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 charging batteries or to 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 time.

Southwest Wind H40 Furling

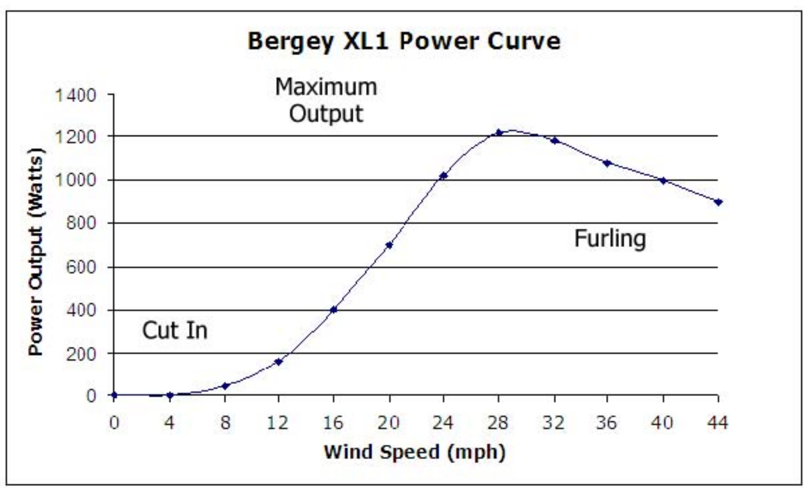


PROVEN wind turbines use flexible blades to "spill" air, stall and reduce speeds in high winds. Image from Proven website

<u>Furling Speed</u> – Small wind turbines cannot actively slow themselves down by actively changing blade pitches 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 particular velocity.

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.

<u>What else can you see?</u>
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.

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

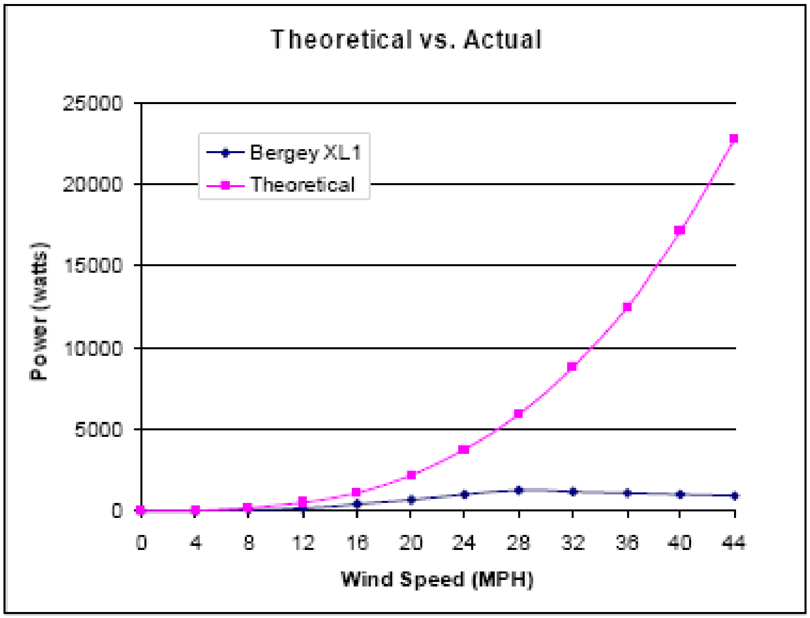
ρ = Density of the Air
r = Radius of your swept area
V = Wind Velocity

You can see from this equation that while power output relies on how big your turbine is and 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 curve above 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 the wind if you built a turbine to extract 100% of that resource. Do you think we can do that? 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.

What is the Betz Limit?

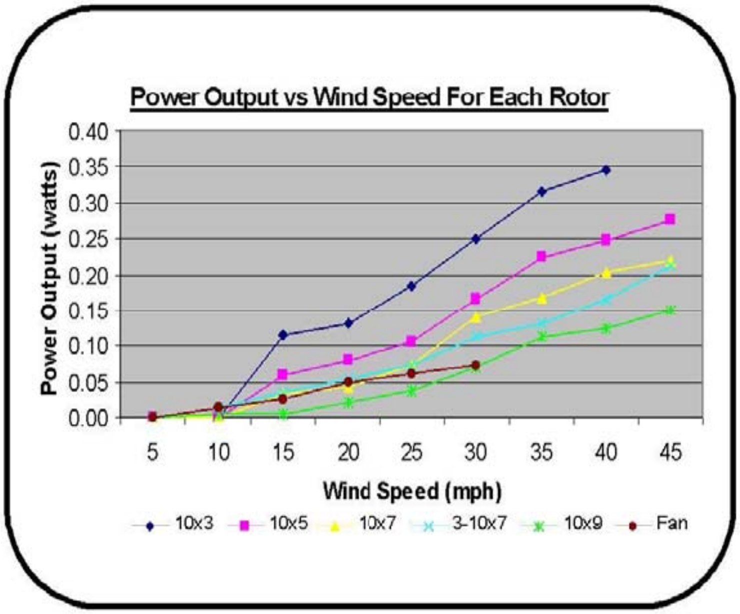
Based on mathematics Betz calculated that we can theoretically extract 59% of the power from moving wind – and this is if we do things perfectly which we rarely can. In reality modern turbines extract around 30-40% of the power in the wind.

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 efficiency 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.

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.



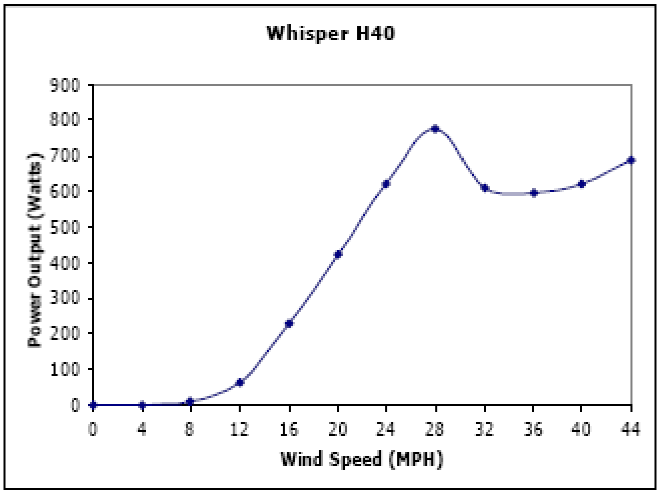
You need to record a variety of different voltage and amperage readings for a variety of wind speeds and plot on this data on a graph. The graph to the right was generated by a 5th grade student named Kathryn who built and tested a pretty astounding small wind turbine.

Kathryn's hopped up 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."

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. Her curves are starting to flatten out and maybe if she went up to 60 or 70 MPH we would see changes…but then on the other hand we might start to see structural failures in other parts of the turbine!

Part 2: Wind Power Curve Answer Key



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.

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

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

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

d. 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

e. What is the cut in speed of this turbine? 0-4 MPH

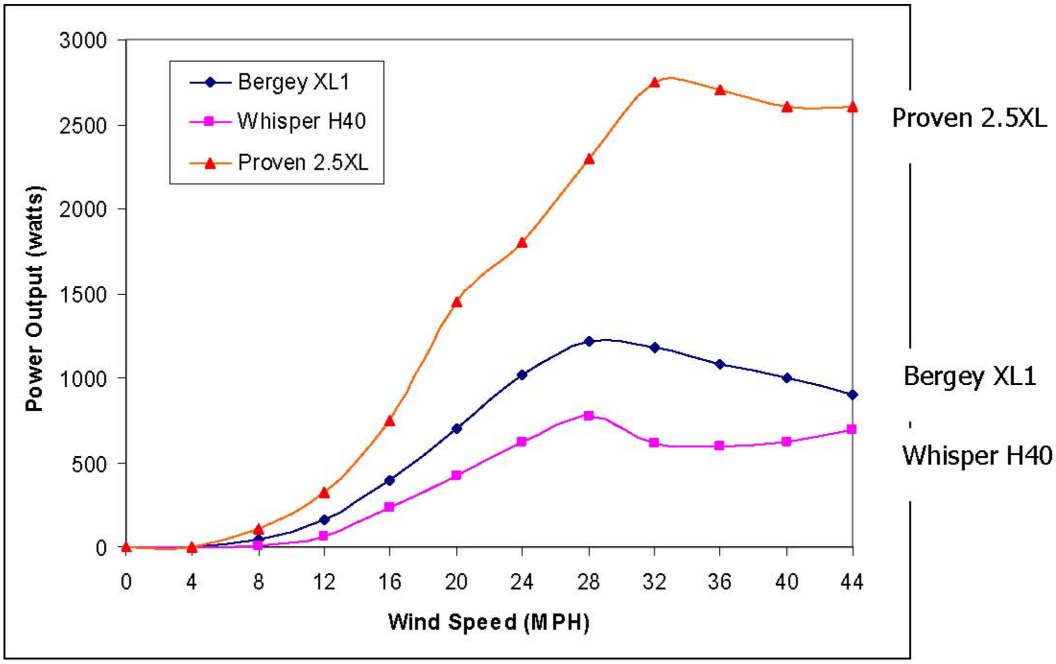
f. What is the maximum output of this turbine?
1900 watts

g. At what wind speed does the turbine start to furl?
1900+

h. How many watts does this turbine make at 14 MPH?
1400

i. How many watts does this turbine make at 30MPH?
1650

10. 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.



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

a. 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.

b. Which turbine has the highest maximum power output overall?
The Proven 2.5XL

c. 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.

d. 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.

e. 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.

f. 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.

Notes on Part 3

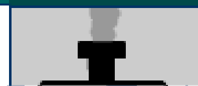
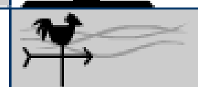
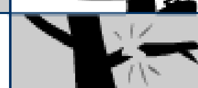
There are a number of factors that go into siting large wind farms and small wind turbines. Some major factors include:

- Wind Speed
- Wind Direction
- Wind Turbulence
- Proximity to Power Lines, Houses and Load
- Type of Turbine
- State and Federal Incentives
- Local Zoning Codes & Ordinances

The following PowerPoint presentations are great resources available as multimedia objects to build a lecture that suits the needs of your students.

- KidWind Basic Wind
- Power in the Wind
- Siting Activities

Beaufort Scale

Beaufort number	Wind Speed (mph)	Seaman's term		Effects on Land
0	Under 1	Calm		Calm; smoke rises vertically.
1	1-3	Light Air		Smoke drift indicates wind direction; vanes do not move.
2	4-7	Light Breeze		Wind felt on face; leaves rustle; vanes begin to move.
3	8-12	Gentle Breeze		Leaves, small twigs in constant motion; light flags extended.
4	13-18	Moderate Breeze		Dust, leaves and loose paper raised up; small branches move.
5	19-24	Fresh Breeze		Small trees begin to sway.
6	25-31	Strong Breeze		Large branches of trees in motion; whistling heard in wires.
7	32-38	Moderate Gale		Whole trees in motion; resistance felt in walking against the wind.
8	39-46	Fresh Gale		Twigs and small branches broken off trees.
9	47-54	Strong Gale		Slight structural damage occurs; slate blown from roofs.
10	55-63	Whole Gale		Seldom experienced on land; trees broken; structural damage occurs.
11	64-72	Storm		Very rarely experienced on land; usually with widespread damage.
12	73 or higher	Hurricane Force		Violence and destruction.

Source: http://www.mountwashington.org/discovery/arcade/wind/beaufort.htm

Additional Resources
Websites:

- 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 the data.
- 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 the data.
- http://www.inl.gov/wind/software/
  Software and power curve files for excel for a number of turbine manufacturers. (Neat data for HS students).

Glossary:

- http://www.horizonwind.com/forteacherskidsconsumers.asp?id=8

Turbine Manufacturer Data:

(These links have been compiled by the designer at KidWind and will take you to some specification sheets from a variety of small turbine manufacturers. 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 (The turbines featured in the Bear Creek videos are manufactured by this company).
  http://www.gamesa.es/gamesa/index.html

These are some direct links to specification sheets from KidWind:

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