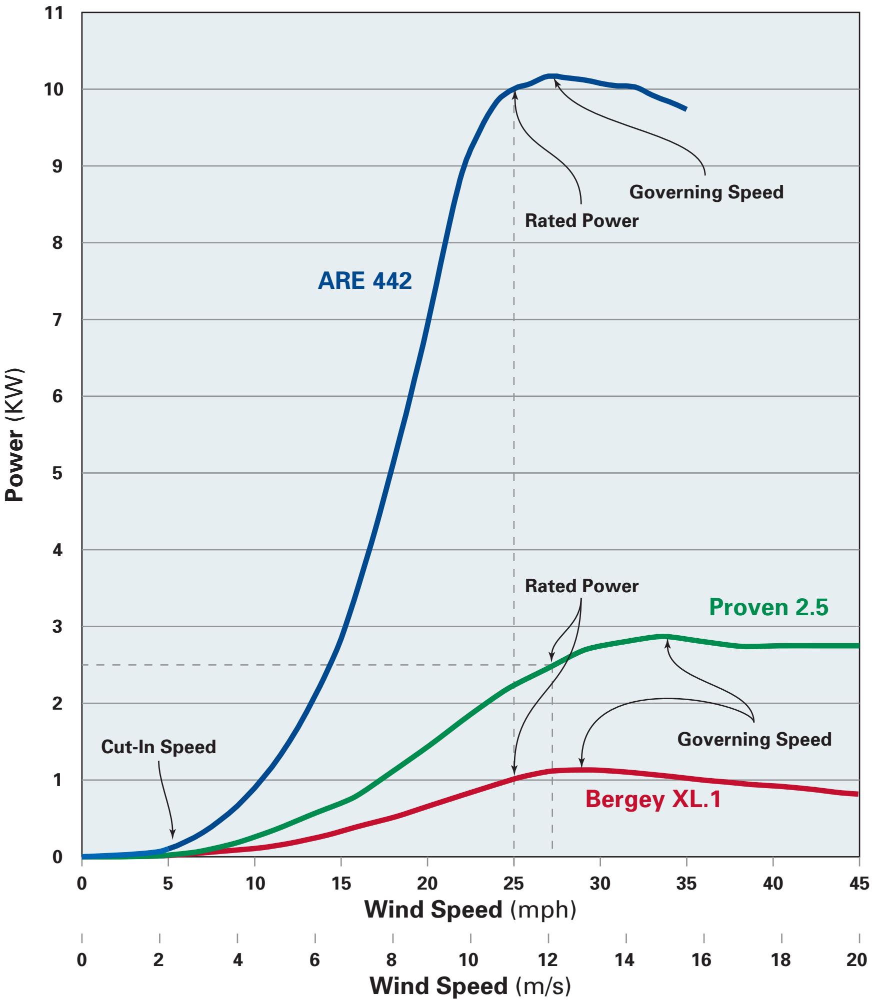
# Wind Power Curves

## *What's Wrong, What's Better*

**by Ian Woofenden**

If you're baffled by a wind turbine's power curve, here's how to interpret wind generator manufacturers' data to choose a turbine that will give you the best performance at your site.

Power Curves for Three Turbines



Power curves are frequently presented by turbine manufacturers in their marketing literature, and interpreting these curves is at best a complicated exercise even for the mathematically inclined. Few wind turbine buyers know how to use this information to determine what they really need to know—how much energy a wind generator will produce at a given site. Let's look at why power curves are not a useful tool for most of us, and what to use instead.

## What's the Curve?

Any alternator or generator produces electricity at varying levels, depending on its rotational speed (rpm). When we plot the output against the speed, we get a curve. If the original motive force is wind, we can plot the generator output against wind speed, which gives us what is typically called a "power curve" for the wind generator (see the "Power Curves" graph). It shows wind speed in miles per hour (mph) or meters per second (m/s), and power in kilowatts (KW).

It's important to remember that power in its technical sense means "watts." This is an instantaneous measure of the rate of electricity generation (or transfer or use), and *not* a measure of energy (watt-hours), a quantity.

## What's Wrong with the Curve?

Misinterpreting wind generator power curves is common and can happen in a variety of ways. First, the untrained eye is naturally drawn to the top of the curve—the peak power. If we were looking at a gasoline-powered generator, this would be useful information. As long as it's supplied with gasoline and a load, it continues to produce at or near its rated output.

Peak power for a wind generator is very different—at most sites, the wind speed at which a turbine generates its peak power occurs only a very small percentage of the time. So focusing on the peak may lead you to wildly exaggerated energy expectations.

Trying to compare one wind generator to another using power curves is another common mistake. While there is some useful comparative information in the curves, it's not a simple comparison, and people too often scrutinize turbines poorly, looking primarily at the peak. For example, I've lived with two turbines that shared about the same peak on their power curves—yet one produced 2.3 times more energy than the other in similar conditions.

*If* (and that's a big "if") power curves accurately predicted energy production, it might make sense to compare turbines by looking at the *low* end of the curve. Good performance at low wind speeds is most important in a wind turbine, since that is where it will spend most of its time (see "Wind Speed Distribution" graph).

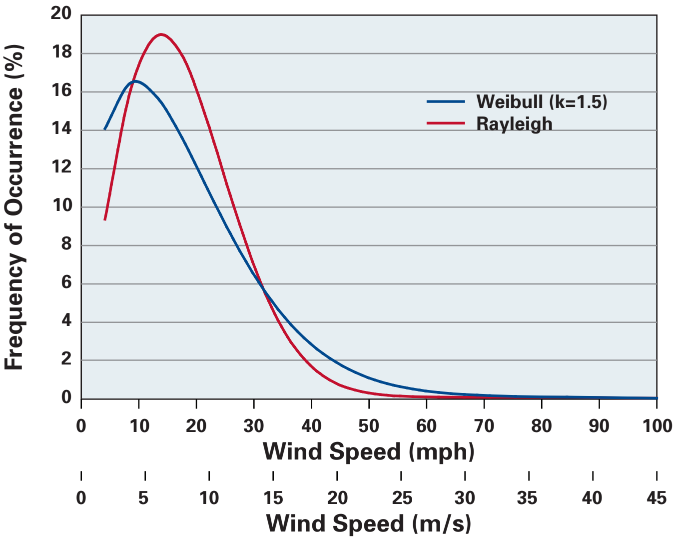
> "Instantaneous power means nothing for wind energy.
>
> —Mike Klemen

Next, applying an average wind speed to a power curve can be an impossible and illogical task. A power curve demonstrates instantaneous production (watts), while a focus on average wind speed points toward overall energy potential (watt-hours).

All these misconceptions or misunderstandings of power curves become clearer as we look at the physics of wind and the reality of how wind works at a typical site.

## Velocity Cubed

Wind is variable. This we know intuitively. We feel it blow lightly on our face one moment, not at all the next moment, and maybe a few minutes later it'll be blowing us down the street. Wind is rarely constant, and it's a myth that there are sites where "it always blows at 15 mph." When you start looking at measured wind data, it's hard to find groups of consecutive data points that are the same in one minute, let alone for hours.



Wind Speed Distribution

The most crucial fact to understand about wind energy is that *the power available in the wind is related to the cube of the wind speed*. Humans are fairly comfortable with linear functions: Spend twice as much money and you'll get twice as much coal; double the rainfall will result in doubling the catchment water into your tank.

Cubic functions are not as intuitive. You might think that when you double the wind speed (velocity, or V), you double the power. But in fact, doubling the wind speed gives eight times the power (2V x 2V x 2V = 8V). A 20 mph wind has eight times the energy (20 x 20 x 20 = 8,000) of a 10 mph wind (10 x 10 x 10 = 1,000). It doesn't always play out precisely this way with wind energy *capture*, since different turbines have different efficiencies. But the principle remains vital to understanding wind electricity.

The $V^3$ law can be worked both ways—up and down the power curve. If a "perfect" turbine produces 100 watts at 10 mph, it has the potential to produce 800 watts at 20 mph. If the machine produces 1,000 watts at 24 mph, it will produce 125 watts or less in a 12 mph wind. Understanding the $V^3$ law helps you look at power curves—and wind energy—differently.

## Wind Distribution

The other major factor that comes into play is wind distribution. When we start to study the way the wind varies, we find out that every site has a different wind distribution profile. A wind "distribution" plots the frequency of each wind speed. Typically, it's shown in a wind distribution curve (see "Distribution" graph). For example, one site may experience 15 mph winds 4% of the time, and another site may see winds of 15 mph only 3% of the time. The distribution curve shows what percentage a given site experiences at each wind speed.

Because of the $V^3$ law, the specific wind distribution can theoretically have a pronounced effect on energy capture at a particular site. To cite an extreme and theoretical example, let's examine two sites: one that experienced 10 mph winds for four weeks straight, and another site that had 40 mph winds for one week and no winds (0 mph) for three weeks.

Both of these fictional sites have a 10 mph average, but the wind distribution is very different indeed. If we apply the $V^3$ law, the first site has 10 x 10 x 10 = 1,000 units x 4 weeks, or 4,000 units. The second site has 40 x 40 x 40 = 64,000 x 1 week plus 0 x 0 x 0 = 0 units x 3 weeks, for a grand total of 64,000 units. What a difference! What good is an average wind speed on its own, if the distribution makes the available energy vary that much?

In the real world, wind distributions don't vary as widely as this extreme example, and in fact tend to be quite similar in most locations where we site wind turbines. In North America and Europe, there's a fairly predictable wind distribution. Standardized distributions (such as the Rayleigh in the Weibull family of distributions; see graph) correspond fairly well with the reality on these continents. Utility-scale wind farm developers rely on very detailed distribution profiles for each site. For home-scale wind-electric systems in most places, it's safe to use the standard distributions that turbine manufacturers assume in their energy predictions. Energy availability doesn't typically vary more than about 25% from site to site.

## Value of Power Curves

Power curves do have a couple of concrete applications. First and foremost is that they show you at what wind speed a turbine will govern. "Governing" is the means of controlling the machine in high winds. According to the cube law, the forces on a wind generator in storm winds are enormous and potentially destructive, and the last thing you want your wind turbine to do is to try to capture them! For instance, an 80 mph wind would equal 512,000 units (80 x

## Perfect Turbine or Pipe Dream?

Wind turbines operate within the limits of Betz' Law. Simply put, if you try to capture 100% of the energy available in the wind, the wind is stopped—it cannot move the blades. On the opposite end of the scale, the wind just goes around a fixed obstruction. In either case, the result is the same—no energy is extracted.

The Betz limit says that capturing 59.6% of the energy in the wind is the best compromise between stopping the air and letting it pass through the turbine unaffected. Maintaining the flow of air is the compromise any wind machine must make, whether it is a horizontal-axis (a traditional-style turbine) or a vertical-axis turbine; with many blades or few. All turbines are subject to the Betz limit.

The "Energy Output" table shows the amount of energy you can reasonably capture per rotor swept area at several average wind speeds. You can multiply by the swept area of the turbine you're considering to see if the manufacturer's claims are even possible!

However, comparing the "model" wind turbine columns with manufacturers' claimed production data from four reputable manufacturers' turbines, none are as good as claimed. Numbers in the "Model Turbine" column are based on an average efficiency of 35%. It is not terribly likely that you'll find a wind turbine that is more efficient than this. Remember: If it's too good to be true, it may very well be!

The table shows the energy (KWH) per month that a "perfect" turbine designed to Betz' law could produce, and what a real-world model turbine could produce, taking inefficiencies and design into account. The table assumes a Rayleigh wind distribution at sea level.

Let's try an example. If you have a turbine with a swept area of 10 square feet in a 10 mph wind, you'll find that the "model" turbine value per square foot of rotor is 2.08. Multiply it by 10 because you have 10 square feet of rotor. If the manufacturer is claiming that the turbine can put out *more* than 20.8 KWH per month, the turbine is probably too good to be true. Next, multiply the Betz limit value of 3.5 by 10. If the manufacturer claims you can generate more than 35 KWH per month, then they are claiming to have broken the laws of physics.

—Mike Klemen

### Monthly Energy Output Per Sq. Ft. of Swept Area

| **Average Wind Speed** | | **KWH Per Month** | |
|---|---|---|---|
| **MPH** | **Meters Per Sec.** | **Betz Limit** | **"Model" Turbine*** |
| 5 | 2.2 | 0.42 | 0.25 |
| 6 | 2.7 | 0.74 | 0.44 |
| 7 | 3.1 | 1.21 | 0.72 |
| 8 | 3.6 | 1.83 | 1.08 |
| 9 | 4.0 | 2.60 | 1.55 |
| 10 | 4.5 | 3.50 | 2.08 |
| 11 | 4.9 | 4.46 | 2.64 |
| 12 | 5.4 | 5.38 | 3.19 |
| 13 | 5.8 | 6.23 | 3.69 |
| 14 | 6.3 | 6.94 | 4.12 |

*Based on 35% turbine efficiency

80 x 80). You'll want to keep your turbine out of that kind of wind's way (perhaps while still generating a bit of energy) so it can stay intact for the next reasonable wind.

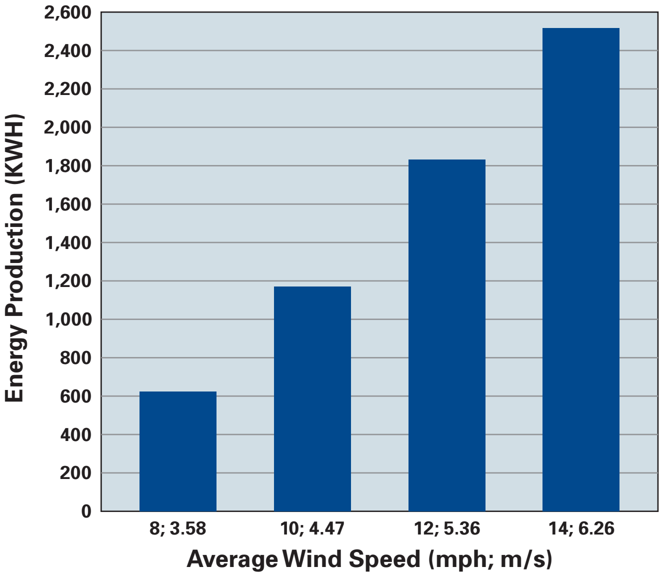
By looking at a power curve, you can see what a turbine does (or supposedly does) in high winds. If the curve keeps increasing above about 30 to 35 mph, don't buy it! Few turbines can withstand the forces of storms if their rotor has to take the full brunt of storm winds. Long-time wind-turbine tester Mike Klemen of Harwood, North Dakota, says, "Any turbine that doesn't protect itself well dies here. I will never buy a turbine without seeing a power curve that proves that the turbine protects itself." Perhaps we should rename power curves "governing curves," so wind turbine shoppers understand the main value of the curve.

The other value in power curves is to electrical designers who create the other components needed in wind-electric systems. Knowing the cut-in point, peak voltage and current, and what's in between is necessary to specify appropriate components, and design robust controllers and inverters to match the generating characteristics of a wind turbine.

## Energy is the Goal

The bottom line is that power curves are primarily an esoteric measure for wind geeks, with the unfortunate consequence of creating much confusion about wind generator performance. When we buy a car, most of us don't look at the horsepower of the engine or the cold cranking amps of the battery. We turn to more important overall measures like fuel economy. So we should leave power curves to the number nerds, and stop distracting ourselves from the prize—energy output. But what's an average wind system shopper to do?

## Monthly Production Estimates for ARE 442



*Based on a Rayleigh distribution

Veteran wind-energy expert Hugh Piggott says, "The power curve on its own doesn't tell you anything about energy, nor is there any simple way to determine that from a given power curve." We don't buy watts from the utility, and we don't put watts into our battery bank or into the grid. We buy, produce, and sell *watt-hours*—energy. So we should evaluate wind machines based on their energy performance, not peak power, or any other single point on the power curve.

Instead of using power curves, look on the manufacturers' Web sites or in their literature for *energy* curves or graphs (see the ARE 442 example). With an estimate or measurement of the average wind speed at your site, these curves can help you project the energy yield from a particular turbine. Then you can determine how that projection matches up with your energy needs, and get on with the job of designing and installing your wind-electric system.

Understanding power curves and energy curves can help you sort fact from hype, and real products from scams. See the "Perfect Turbine or Pipe Dream?" sidebar for how to do a reality check on the manufacturers' or promoters' claims. In addition, search the Internet for real-world users of the turbine you're considering, and compare the manufacturers' claims to reports of actual system performance.

Whether you are sizing a system or evaluating a product, you'll be working with an *estimated* average wind speed and an *estimated* energy production curve. That means that your numbers will be rough guesses at best. Get used to it—with small-scale wind systems, it is rarely practical or affordable to do much better than this. So be conservative when you design, and with luck, you'll be pleasantly surprised at your turbine's actual energy performance.

## Access

**Ian Woofenden** (ian.woofenden@homepower.com) devotes time to debunking wind myths at his wind- and solar-powered home in Washington's San Juan Islands.

Thanks to Mike Klemen (www.ndsu.nodak.edu/ndsu/klemen) and Hugh Piggot (www.scoraigwind.com).