

# Powering Your Home or Business with a Small Wind Energy System in Vermont



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Created by Ben Luce, Ph.D., with support from the

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Comments and suggestions on this guide are welcome: Please send email to [ben.luce@lyndonstate.edu](mailto:ben.luce@lyndonstate.edu).

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**About the NVDA:** Formed in 1950, at the same meeting where U.S. Senator George D. Aiken coined the term "Northeast Kingdom" to describe Caledonia, Essex and Orleans counties, the Northeastern Vermont Development Association has served the people, municipalities and businesses of this region as both the Regional Planning Commission and Regional Development Corporation.



As the Regional Planning Commission, NVDA assists municipalities, organizations, committees and individuals with a wide variety of planning and technical services. From assisting [municipalities](#) with regulatory options, to administering [grants](#), creating [maps](#), and implementing [transportation](#) and natural resource plans, NVDA is actively working with [land use](#) issues in the region.

As the Regional Development Corporation, NVDA works on [infrastructure improvements](#), assists [companies relocating](#) to the area, helps existing businesses to grow, and administers [revolving loan funds](#). NVDA also fosters key partnerships with the [Small Business Development Center](#), the [Northeast Kingdom Collaborative](#), the [Northeast Kingdom Travel and Tourism Association](#), and the various [Chambers of Commerce](#) in the region.

Please visit [www.nvda.net](http://www.nvda.net) for more information.

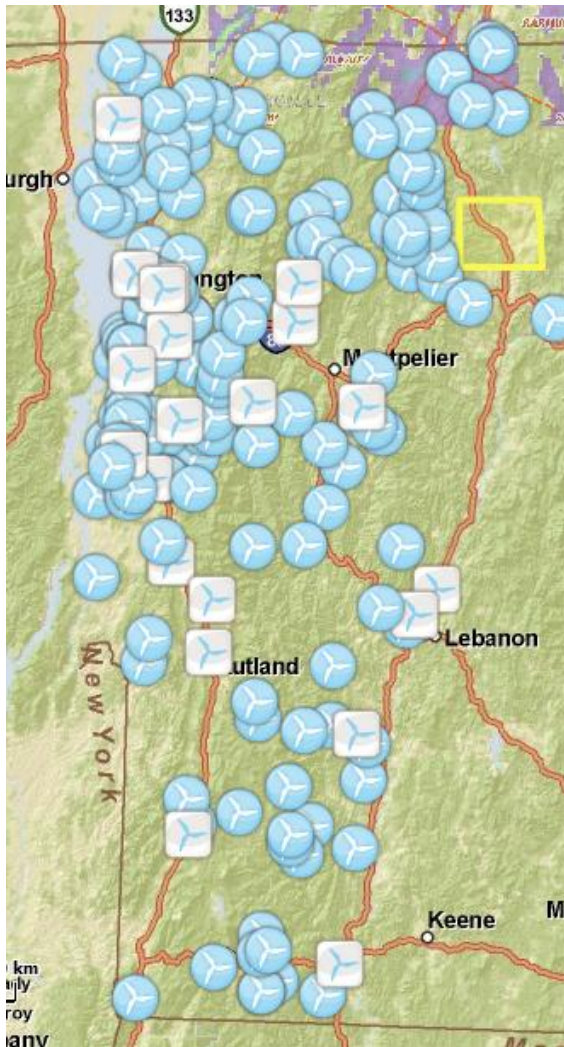
### Short List of Do's and Don'ts

- Consider your site carefully: Few sites have really strong wind resources: Many small turbine installations produce marginally at best. That might be ok, depending on your goals, but make sure your expectations are realistic. Expect a relatively long "payback time" unless you have a great site.
- Talk to your neighbors first, and make sure there won't be a major problem with siting, either due to local opposition or regulations prohibiting wind towers or towers over a certain height.
- Place the turbine as high as reasonably possible, and definitely more than enough to avoid turbulence created by obstacles (30 feet, or 9 meters higher than any obstacle within 90 meters or 300 feet is the tried and tested rule of thumb).
- In general, choose a smaller turbine installed at a greater height over a larger one at a lesser height.
- Purchase a more heavily built, well tested turbine model. Avoid new, well-hyped, flashy, models that don't have a good track record.
- Purchase a turbine with a good warranty – preferably at least 5 years if available.
- Work with an installer with a good track record, if possible.
- Expect the turbine to generate some noise.
- Expect that occasional maintenance will be required.
- Don't mount a turbine on your roof.
- Don't purchase an aluminum tower.
- Expect your power to be cleaner and greener.

## Overview of Small Wind in Vermont

Small wind energy systems are making inroads in Vermont. This guide provides essential information in a step-by-step format for evaluating the feasibility of and for obtaining small wind energy systems in Vermont. There are also separate guides in this series for obtaining power from photovoltaic systems, hot water from solar hot water systems, and heat from wood stoves, pellet stoves, and geothermal heating systems. Please visit [www.nvda.net](http://www.nvda.net) to obtain these.

The following image shows the locations of small wind systems in Vermont that are listed as of January 2011 on the Vermont Renewable Energy Atlas (<http://www.vtenergyatlas.com>). While these systems still do not yet add up to a significant amount of power generation compared with the utility generation, small wind is clearly beyond the experimental stage and developing steadily.



To obtain more information on these systems, one can visit the Atlas (how to do this is described below in detail). Detailed production information for some of these systems can be obtained from the Vermont Small-Wind Energy Demonstration Program at <http://www.vtwindprogram.org/>.

## Introduction to Small Wind Energy Systems

Small wind energy systems can have rated peak power capacities ranging anywhere from about 100 watts to 100,000 watts (100 kilowatts), a range of a thousand fold! The turbines used in small wind turbines can be roughly classified into four categories: **micro, mini, household, and small-commercial**:

Small Turbine Category	Application	Power Range
Micro Turbines	Boats, hobbyists, etc	100-500 watts
Mini Turbines	Small Cabins	1-3 kilowatts
Household Turbines	Homes	10-20 kilowatts
Small Commercial Turbines	Farms, commercial buildings	50 - 100 kilowatts

Small wind energy systems consist of:

- The **turbine**, which generates the electricity. The turbine itself consists of:
  - Fiberglass or wood “**rotors**” (the blades),
  - A **generator** usually a permanent magnet alternator.
  - Turbines 20 kilowatts and over usually have a **gearbox**.
  - Some kind of “**slip-ring**” mechanism to couple the power out while letting the turbine rotate.
  - Some kind of **over-speed mechanism**.
- The **tower**, to hold the turbine aloft.
- A “**regulator**” for controlling battery charging (if batteries are used)
- An “**inverter**”, which converts the DC power to AC.

Note that the inverters today are sometimes located inside the generator housing.

Also note that here are really two kinds of turbines: **Horizontal axis turbines**, such as that shown in the following diagram and the photos that follow, and **vertical axis turbines**. The former are much more common and better developed, and these are the only type discussed in this guide. Although some advertisements for vertical axis turbines may look attractive, they are not well developed as commercial products yet and not recommended in general.

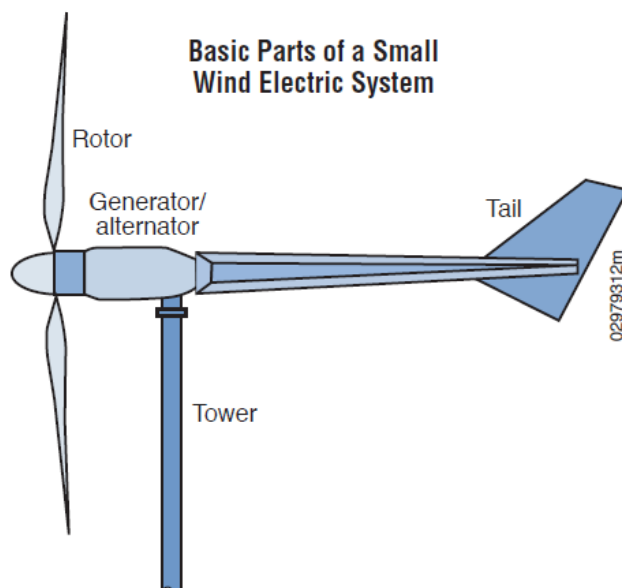


Diagram of a horizontal axis turbine (US Dept. of Energy)

**Examples of well known, highly reliable, small wind turbine products:**

**Micro-Turbine: The Ampair 300;** 300 watts at 28 mph wind speed. Diameter: 3.9 feet



**Mini Turbine: The Bergey XL.1;** 1000 watts at 24.6 mph. Diameter: 8.2 feet



**Household Turbine: The Bergey Excel;** 10 kilowatts at 27 mph. Diameter: 23 feet (7 meters)



**Small-Commercial Turbine: The Entegry EW50;** ~50 kilowatts, Diameter: ~50 feet



### Wind Towers

The tower can be a **lattice tower** (as shown just above) or a **tubular tower** (as shown just below, during the erection process), and both types can be either **guyed** or **free-standing**. Towers can also be of “**tilt-up**” type for smaller turbines (for household turbines and smaller), which enables installation maintenance to be performed on the ground.



## Connection to the Grid

Small wind systems can either be “**grid-tied**”, that is, connected with the grid, or used in an **off-grid system** to charge batteries. Grid-tied systems are usually “**net-metered**”, which means that any excess power not used by the system owner is fed back into the grid by the inverter, which literally runs the owner’s electric battery backwards, so that the owner pays only for the net amount of electrical energy used.

## Cost

A typical 10 kilowatt system, the most common size for homes that produce a significant fraction of their power from wind, will typically cost between \$30,000 - \$50,000 today, depending on turbine brand, tower height and type, and other site specific factors, or \$3-\$5 per watt. (Some websites and guides have slightly more optimistic costs).

The “**simple payback time**”, that is, the time it takes the system to produce enough electricity savings to fully offset its cost, will range, before incentives, from as low as 10-15 years at very good sites, to 30 years or more for more marginal sites.

We next discuss how to go about considering and then acquiring a small wind energy system.



## Step 1: Determine the Suitability of Your Site, and How High Your Wind Tower Can and Will Need to Be

Does your site have a location where a wind system can be located such that the turbine will be able to catch the **prevailing winds** without being (wind) shadowed by obstacles with several hundred feet?

If so, then you *may* have a good wind site, if the average wind speed is adequate at the height the turbine would be located.

Adequate turbine height is crucial! There are three things to keep in mind here: The effect of obstacles, the dependence of wind speed on height, and any regulations pertaining to your site that might limit tower height. The first two things, effect of obstacles and dependence of wind speed on height, are related, but are different things. For example, higher towers are still much better even where there are few obstacles around, due to the wind shearing effect of the ground.

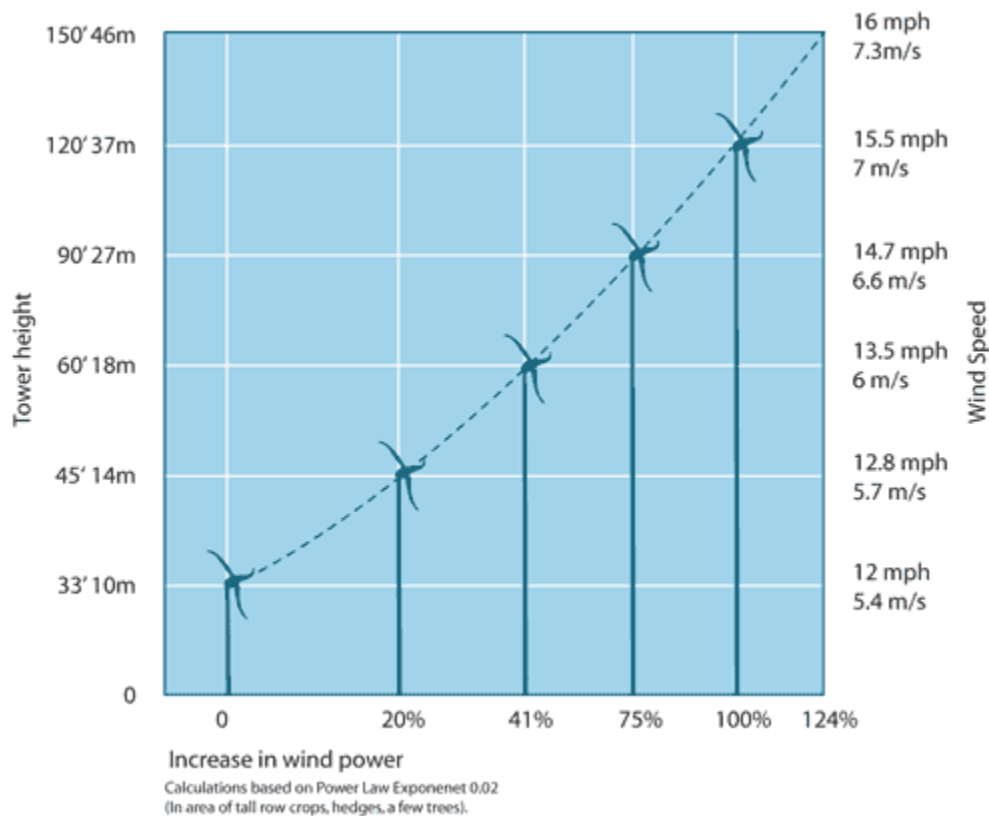
Turbulence, the swirling, chaotic motion of air, in particular, can reduce the production of wind turbines via wind shear, but also puts stresses on turbine parts. Turbulence tends to be greatest near the ground, and decreases with height. Obstacles such as trees and buildings will create turbulence in their wake, so turbines need to be placed well above such obstacles. In particular, the turbulence produced by an obstacle often exists at elevations up to **several times** the height of the obstacles.

**A tried and true rule of thumb is that the bottom of the rotor blades of the turbine should be at least 30 feet (9 meters) above any obstacle that is within 300 feet (90 meters) of the tower<sup>1</sup>.**

Wind speed also tends to increase with height, even above heights clear of nearby obstacles. In general, average wind speeds tend to increase as a certain power law of the height, as the following graph demonstrates.

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<sup>1</sup> Small Wind Electric Systems, A Vermont Consumer's Guide, by the US Dept. of Energy: [http://www.windpoweringamerica.gov/pdfs/small\\_wind/small\\_wind\\_vt.pdf](http://www.windpoweringamerica.gov/pdfs/small_wind/small_wind_vt.pdf)



**So in general, turbines should be as high as reasonably possible. If cost is an issue, it is better to place a smaller turbine at a good height, than a larger turbine at an inadequate height.**

**Placing a wind turbine in a very low wind site, or placing it too low, is like placing a solar panel in the shade.**

Once you have an idea of how high your turbine should be, you should next determine whether it is allowed be that high. Find out first about your communities restrictions, if any, on siting towers and turbines. Many communities will not allow a 100 foot tower, for example, without a variance.

Then discuss your interest in erecting a wind system with your neighbors. Take all precautions to avoid a bitter and protracted fight with your neighbors over a variance application. Turbines do have significant visual and sometimes auditory impacts. The best possible outcome is to obtain your neighbors full support ahead of time before even filing an application. If they strongly object, perhaps a photovoltaic system might be a better choice.

## Step 2: Estimate the Average Wind Speed at Your Site

Once you have an idea of how the turbine can and will be, you should next attempt to estimate the average wind speed. There are places where the average wind speed is very low even though this is not readily apparent. For a small grid-tied wind system to be even remotely economical, the average wind speed at hub height (the height of the generator) should be at least approximately 10 mph (which is “Class I” wind). Off-grid systems may still be useful at even lower speeds, because the cost of bringing in grid power may be extremely expensive.

There are several levels of rigor at which an assessment can be undertaken, ranging from quick and free estimates up to making precise measurements with an anemometer.

- **Free guesstimate:** Obtain a rough estimate based on a wind maps, local wind speed data from airports, vegetation characteristics, local lore, snow-drifting, etc.
- **Professional consultant:** Consult with an installation company or other contractor to obtain an estimate generated with computer software.
- **Rigorous measurement:** Install an **anemometer** (or have one installed) with memory to obtain full statistics on the wind at your site. This data can then be used with the table given below, or input to a more sophisticated production estimate tailored to the “**power curve**” of a particular turbine.
- **Just do it:** Simply install a turbine, or perhaps a relatively inexpensive micro-turbine, and see how it performs. Then sell it if it does not perform adequately. Turbine ads can be effectively placed in “Home Power Magazine” for example. Keep in mind that the production of a micro-turbine will yield only a rough estimate, and likely an underestimate, of what a larger and more efficient turbine will actually produce at your site. Differences in turbine height must also be considered here if the micro-turbine is placed at a lower height.

Highly accurate anemometer measurements at turbine height can be expensive (around \$8000), unless you already have an appropriate tower for some reason (about \$500 in this case).

Fortunately, if you are honest with your observations, the free guesstimate approaches can be a fairly reliable means to evaluate a site. If it’s a good site, it hard to imagine that strong winds at a site won’t create at least some noticeable effects!

On the other hand, it is important to utilize these methods objectively, and not fool oneself into thinking a site has adequate wind when it really doesn’t.

We now discuss these approaches in more detail.

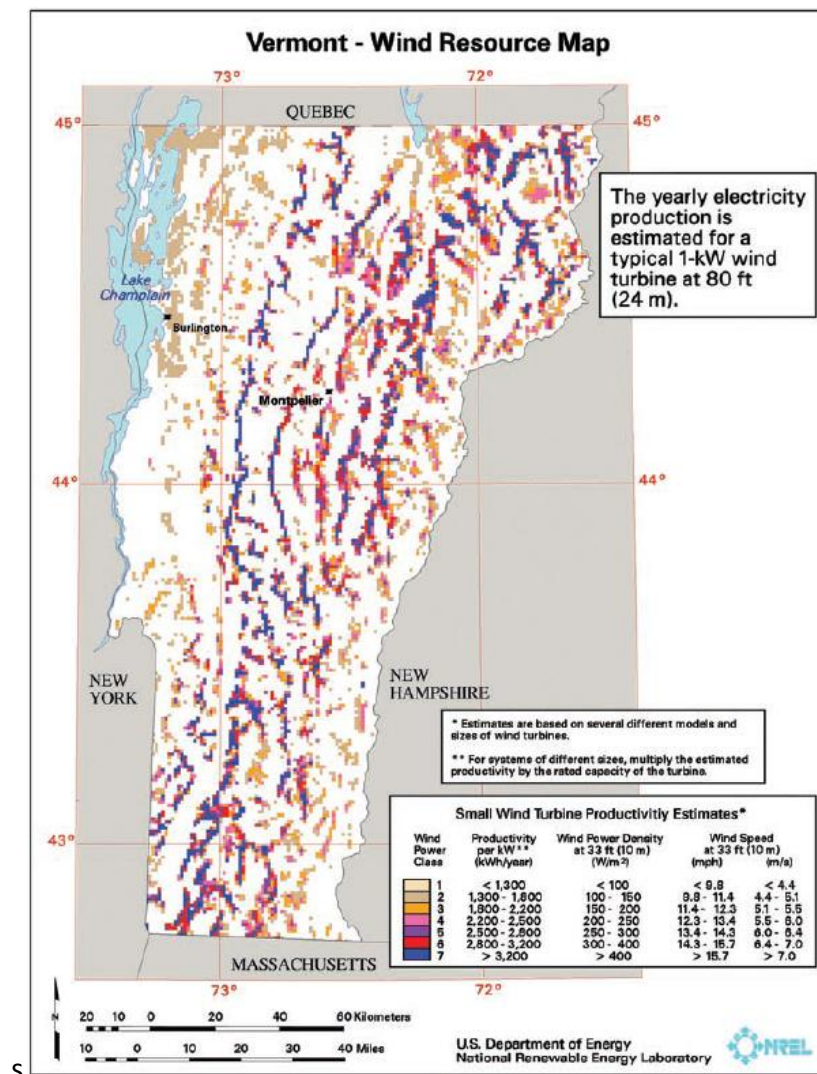
## Free Guesstimate Approaches

1. Consult a wind map.
2. Consult with a local airport or other nearby source of wind speed data.
3. Evaluate clues from the vegetation.
4. Evaluate clues from snow drifts and other visible effects.
5. Check the local lore.

**Consulting a wind map:** There are various wind maps available. When using these maps, pay special attention to both the resolution and the particular definitions used for “classes” of wind speeds used.

First, the following state-wide map of small wind resources is available at:

[http://publicservice.vermont.gov/energy/ee\\_files/wind/windclassap2-2.gif](http://publicservice.vermont.gov/energy/ee_files/wind/windclassap2-2.gif).



This map, which presents wind class estimates at 33 ft (10 meters), indicates the location of significant wind resources (Class 2 and higher) quite clearly, but not with great resolution. Also, the Class 1

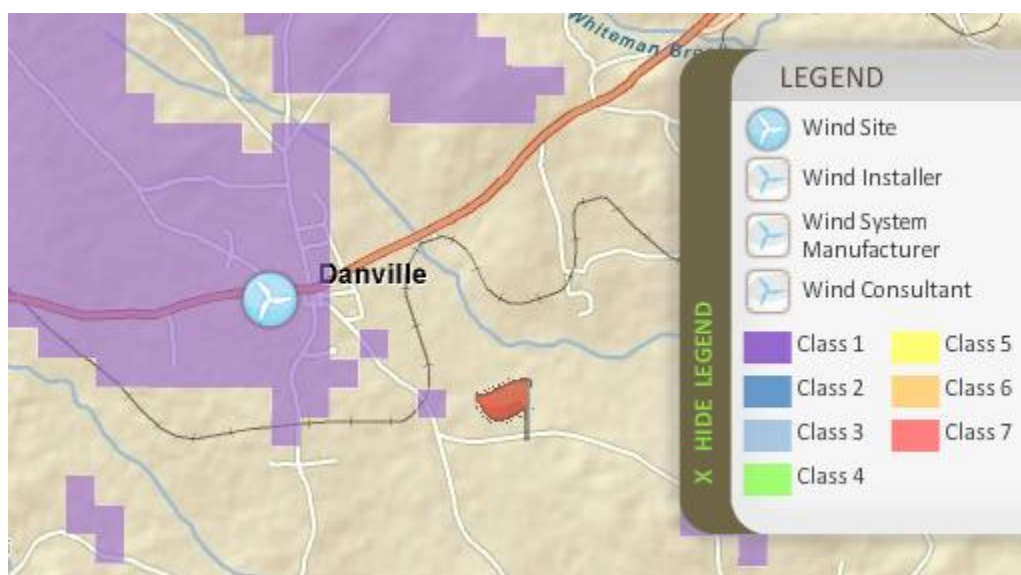
resources on this map, which are defined as having average speeds from 0-9.8 mph, include both sites with little or no wind (say, 0-5 mph) and sites with **marginal wind** (5-9.8 mph), which might still be acceptable for some people, depending on their needs. So this map is somewhat useful for identifying Class 2 and better sites with some confidence, but should not be used at all for completely ruling in or out a potentially marginal site. We stress this, because as we will see, small wind turbines are most likely to be sited in marginal regions, because, not surprisingly, this is where most people live (most of the Class 2 and higher areas are located on large hills or mountains).

Higher Resolution County level maps of wind resources in Vermont can be obtained at <http://www.vtwindprogram.org/windmaps/>. The same issue with Class I resources exists here as well: Class I is defined here to be 0-11.4 mph. But these maps can be quite useful, given their high resolution, for identifying Class 2 or better sites.

Another high resolution source are the maps provided by the **Vermont Renewable Energy Atlas**, available at <http://www.vtenergyatlas.com>. Here is how to utilize this site:

1. Click to enter the site. You will then be in the “**Select an Area**” section.
2. Navigate to the geographical location of your site using the options in this section: You can use either the “**user-defined**” option to draw a closed boundary with which to zoom into, or you can select your town or county. Note the zoom tools in the right hand corner.
3. Then select no. 2, the “**Select an Energy Option**”, from the menu, then select “**Wind**”, then click on “**Wind potential**”, and then click on the “**Residential – 30 Meters**” option. This will color code the map according to different “**wind classes**”. The location of wind systems known to the Atlas will also be indicated with small icons, which may be clicked for more information on those installations. Clicking on the map (away from the icons) will bring up a “wind rose” that shows the distribution of the direction of the winds.

For example, if one zooms in on Danville, VT in this way, one obtains the following map (which is cropped down here):



The class designations here represent the following average wind speeds:

Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7
10-11 mph	12-13 mph	13-14 mph	15-16 mph	16-17 mph	17-18 mph	19-25 mph

Note that Class 1 here is defined as 10-11 mph. As we will see, this might be more accurately interpreted to mean 5-11 mph.

Note also that the screenshot indicates that there is a turbine along the main road through Danville. Clicking on the icon reveals that this is a 10 kw Bergey turbine at Danville School, which happens to be a turbine that can be seen easily from the road. It also has a tilt-up tower, and it is possible to get close to the turbine should you want to see this one up close.

The Map also indicates that this turbine is located in a Class 1 location, implying a wind speed of 10-11 mph at a height of 30 meters above the ground.

How accurate is this estimate? As stated above, it turns out that Class 1 here should probably be interpreted to mean 5-11 mph. To see why, consider the data given in the following table, which provides wind speed data and also production data for five different wind turbines in Vermont, from the website of the Vermont Small-Scale Wind Energy Demonstration Program. ALL of this data was for 10 kilowatt Bergey XL-S turbines operating throughout 2007. All of these sites are listed in the Atlas as Class 1 sites.

<b>2007 Data for Some Small Wind Systems in Vermont, as reported by the Vermont Small-Scale Wind Energy Demonstration Program. All systems were Bergey XL-S (10kW) turbines.</b>				
<b>Location</b>	<b>Tower Height (ft)</b>	<b>Average Wind speed (mph)</b>	<b>kWh/year</b>	<b>Capacity Factor</b>
Danville School	100	6.4	2118	2.5%
Grand View Dairy	120	13.7	13,732	16.7%
Vermont Technical College	100	8.0	3478	5.3%
Middlebury College	100	7.7	4535	5.2%
University of Vermont	100	7.9	4538	5.3%

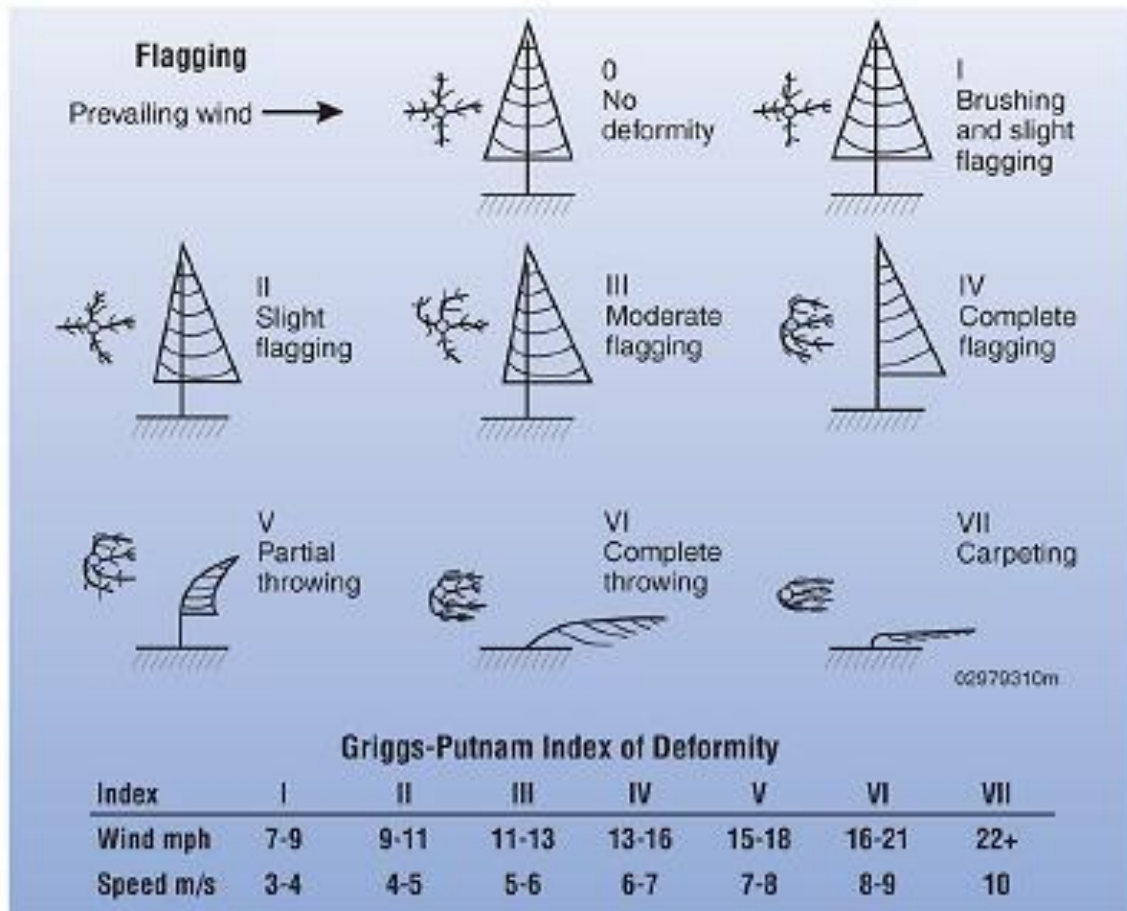
We see that four out of five of these systems did have measured wind speeds above 5 mph, but that only one actually exceeded 10 mph.

It is also instructive to note that the differences in energy production reported here are dramatic, and reveal the strong **nonlinear dependence** of wind production on average wind speed. This nonlinearity derives from the fact that the power output of a wind turbine depends on the **cube** of the wind speed, all other factors being constant. See the **Appendix II** for more information about the power output can be calculated from the average wind speed.

This nonlinear effect makes wind production estimation intrinsically difficult: It makes the estimates very sensitive to small changes in average wind speed. For example, a ten percent increase in wind speed causes a 33% increase in power output, while a fifty percent increase produces a 338% increase!

Finally, note that the “**capacity factors**” given in the table appear to be quite small. This factor gives the ratio of the total annual energy actually produced divided by what the turbine would produce if it produced steadily at its peak rated output 24 hours a day all year long. This is related to, but NOT the same as the percentage of time the turbine is actually turning. Utility-scale wind turbines, which are generally located only in Class 4 and sometimes Class 3 sites, typically have capacity factors ranging from about 25-35%. But small wind energy systems typically have much lower capacity factors.

**Estimate the average wind speed from vegetation characteristics:** Look for signs of “**flagging**”, which is asymmetrical arrangements of the branches of vegetation toward the downwind direction, and “**throwing**”, which is bending of vegetation towards the downwind direction. **Coniferous trees (evergreens)** are best used, as deciduous trees drop their leaves in the winter and thus change their effective cross-section to the wind. The following chart (calibrated more or less for conifers) can be used to determine the “**Griggs-Putnam index**” of these features, and hence the average wind speed.



**Estimate average wind speed from local airport data:** Average wind speed data from a local airport or similar source can also be utilized to develop an estimate for your site, if your site is reasonably similar to the airport in terms of the type terrain nearby, exposure to prevailing winds, etc. This should be

approached with some caution: Average wind speeds can vary significant even over short distances if due to the local topography. Also, airport anemometers are also generally positioned at much lower heights (typically at 10 meters) than wind turbines are best placed at (30+ meters). Airports are also often somewhat sheltered, so as to provide better landing conditions. For these reasons, airport anemometers will typically underestimate average wind speeds in the area.

But if your site is reasonably similar, and fairly close to an airport (how close is a matter of judgment), then you can use this approach.

To adjust for the relative difference in height between an airport anemometer and a good turbine height, you need to take into account the particular **wind shear** or **wind gradient** caused by the drag on the wind created by the ground. Wind shearing means that the wind will have lower speeds nearer to the ground. The amount of “roughness” of the terrain will determine how strong the wind shear is.

Fortunately, the wind shear can usually be characterized well with a “**surface friction coefficient**”  $\alpha$  (also known as the Hellman coefficient), which ranges from about .1 for smooth, hard, ground, up to about .4 for urban areas with tall buildings.

**A reasonable surface friction coefficient for many sites in Vermont that have trees within a few hundred feet is about .24, and about .16 for very open hilltops. See the table below for a range of values.**

Suppose that the average wind speed at a height  $h_0$  is known to have a value  $v_0$  at a site with some known value of  $\alpha$ . Then the formula giving the average wind speed  $v$  at a height  $h$  at the same site will be:

$$v = v_0 (h/h_0)^\alpha$$

**Example:** Suppose that an airport anemometer at a height of 10 meters indicates an average wind speed of 10 mph. Also suppose that the correct value of  $\alpha$  at the same site is  $\alpha=.14$ . Then the average wind speed at 100 feet (30.5 meters) would be:

$$v = 10 (30.5/10)^{.14} = 11.7 \text{ m/s.}$$

In this case, the increase is not so large, because the value of  $\alpha$  relatively small, which we might expect for an airport. Note that to perform this calculation with a standard scientific calculator, one first calculates the ratio 30.5/10, which is 3.05 in this case, and then one presses the exponentiation, or “y<sup>x</sup>” button followed by “.14” and followed by “Enter”. One then multiplies this result by 10.

Suppose instead that the value of  $\alpha$  had been much larger, say  $\alpha =.4$ . In this case we find:

$$v = 10 (30.5/10)^{.4} = 15.6 \text{ m/s.}$$

Given that the output of a wind turbine depends on the cube of the wind speed, then this is a big difference – a 237% difference! (Note that  $(15.6/11.7)^3 = 2.37$ )



If using the formula above seems too difficult, you can use the table below instead by following these steps:

1. Find out the height of the anemometer at the airport, and the average wind speed associated with it.
2. Divide the turbine height you are considering by the height of the airport anemometer. Find the nearest ratio to the ratio you calculated in the left hand column of the table.
3. Estimate the value of  $\alpha$  for your site (assuming it's similar to the airport).
4. Now trace across the table horizontally from the height ratio to the column underneath the correct value of  $\alpha$ . The value thus obtained is your "correction factor".
5. Multiply the airport wind speed by this correction factor. This is your estimated turbine wind speed.
6. To get fancy, you might interpolate between correction factors, if your height ratio falls more nearly in the middle of two values in the left hand column.

<b>Surface Correction Factors</b>									
Turbine Height Divided by Anemometer	Surface Friction Coefficient $\alpha$								
	Smooth, hard ground; lake or ocean	Short grass on untilled ground	Level country with foot-high grass, occasional tree	Tall row crops, hedges, a few trees	Many trees and occasional buildings		Wooded country; small towns and suburbs		Urban areas, with tall buildings
	<b>0.100</b>	<b>0.140</b>	<b>0.160</b>	<b>0.200</b>	<b>0.220</b>	<b>0.240</b>	<b>0.280</b>	<b>0.300</b>	<b>0.400</b>
1.7	1.052	1.074	1.085	1.107	1.118	1.130	1.153	1.165	1.226
2.5	1.096	1.137	1.158	1.201	1.223	1.245	1.292	1.316	1.442
3.3	1.128	1.184	1.212	1.272	1.303	1.335	1.400	1.435	1.618
4.2	1.154	1.221	1.257	1.330	1.368	1.408	1.491	1.534	1.769

**Example:** If an airport nearby has an anemometer at a height of 30 feet reports an average wind speed of about 10 mph, if the value of  $\alpha$  at this airport is about .24, and you are considering placing a turbine at a 100 ft height in the same general area with similar terrain, then: First, we find that the ratio of 100 ft to 30 feet is 3.3. Next, starting at 3.3 in the left hand column, we trace across to the  $\alpha=2.4$  column, and obtain a correction factor of 1.335 from the table. Therefore, the estimated average wind speed is:

**Estimated Avg Wind Speed = Correction Factor x Airport Wind Speed = 1.335 x 10 mph = 13.35 mph.**

Although an increase of a little more than 3 mph may not seem like a big change, this creates a very large change in the estimated annual production, also in this case by about the same percentage as in the previous example, about 238%, due to the cubic dependence of wind energy on wind speed.

**Estimate average wind speed by installing an anemometer:** Various products are available from a variety of companies:

Some of companies are:

- [www.nrg.com](http://www.nrg.com)
- <http://www.winddatalogger.com>

The “NRG-NOW System 34m” is a complete system (tower, multiple anemometers, data logger) that retails for about \$8000 and does not require heavy equipment for installation.

If you already have a tower, an anemometer with a data logger can be purchased for around \$500.

The Vermont Wind Assessment Program, run by Vermont Technical College, also provides site assessment services for small-scale and community-scale wind power systems. In the past, the program has loaned anemometers to farms, businesses, and residents who were considering the installation of wind systems. In 2009 the mission shifted to focus the equipment loan service on community-scale wind power sites where the potential for installing a wind system with a rated capacity of greater than 50 kW is being considered, but the program still encourages inquiries from farms and residents considering smaller wind systems (10 kW or less). The program is also developing an assessment protocol using wind map data and ground conditions to estimate potential wind system performance at these sites. Applicants are encouraged to submit an inquiry form as the initial step. See: <http://web.vtc.edu/users/jnk06190/VTALP/>

## Step 3: Estimate the “Average Annual Specific Yield” from the Wind Speed

Once you have an estimate of the average wind speed at your site then you can use this with Table 1 below to obtain and estimate of the “Average Annual Specific Yield”, that is, the number of kilowatt-hours (kWh) that the system will product per year *per unit area* of the turbine. This number can then be multiplied by the area of any prospective turbine you are considering to obtain the total estimate annual average yield, or you can work backwards from your annual electricity usage to determine the size turbine needed (see Step 3 below). Table 1 is taken from page 55 of one of wind expert Paul Gipe’s excellent book<sup>2</sup>, and factors in good general estimates of small wind turbine efficiencies and a typical “Energy Pattern Factor” (see Appendix II for discussion of pattern factors).

Keep in mind that average wind speed you utilize will need to match the average wind speed at the turbine hub height, that is, the height of the generator. If you place the turbine at a lower height than your wind speed was estimated at, the production will likely be substantially less.

Average Annual Wind Speed		Power Density	Turbine Efficiency	Average Annual Specific Yield
m/s	Mph	W/m <sup>2</sup>	%	kWh/m <sup>2</sup> /yr
4.0	9.0	75	0.190	120
4.5	10.1	107	0.195	180
5.0	11.2	146	0.200	260
5.5	12.3	195	0.190	320
6.0	13.4	253	0.180	400
6.5	14.6	321	0.175	490
7.0	15.7	401	0.170	600
7.5	16.8	494	0.160	690
8	17.9	599	0.150	790
8.5	19.0	718	0.145	910
9	20.2	853	0.140	1050

**Example:** Suppose that the average wind speed at your site at your proposed turbine height is about 10 mph, then from the table you can expect about 180 kWh/m<sup>2</sup>/yr (that is, 180 kWh per square meter of swept area per year). How does this number bear on the “**simple payback time**”? Suppose you purchased a 10 kilowatt **Bergey Excel** turbine for a total installation cost of \$30,000. To apply the number from the table, we also need to calculate the “swept area” of this turbine first in square meters. The diameter of the Bergey Excel is 23 feet. We first calculate the area in square feet (dividing the diameter by 2 in the process to obtain the radius):

$$A = \pi r^2 = 3.14 (23 \text{ ft}/2)^2 = 415 \text{ ft}^2$$

<sup>2</sup> “Wind Energy Basics, A Guide to Home and Community-Scale Wind Energy Systems”, 2<sup>nd</sup> Edition, Paul Gipe, Chelsea Green, 2009. ISBN: 978-1-60358-030-4.

Next, we note that  $1 \text{ m}^2 = 10.75 \text{ ft}^2$ , so that:

$$A = 415 \text{ ft}^2 \times (1 \text{ m}^2 / 10.75 \text{ ft}^2) = 38.6 \text{ m}^2.$$

We therefore estimate the annual energy production of the turbine to be:

$$E_{\text{annual}} = (38.6 \text{ m}^2) \times (180 \text{ kWh/m}^2/\text{yr}) = 6949 \text{ kWh/yr}.$$

Note that this is equivalent to 19 kWh/day on average, which is about right for a moderately efficient typical home.

If the retail cost of electricity is \$.13/kWh, then if this system is a grid-tied, net-metered system, then the annual amount of electrical savings (due to power not purchased from the utility on net) will be:

$$\text{Savings}_{\text{annual}} = \$.13/\text{kWh} \times 6949 \text{ kWh/yr} = \$903/\text{yr}.$$

The simple payback time will therefore be:

Simple Payback Time, before incentive, is therefore:

$$\$30,000/(\$903/\text{yr}) = 33 \text{ years}.$$

If a 50% incentive is available, then the simple payback time would be about 16 years.

From this example it can be seen that a 10 mph wind speed, along with an incentive, leads to a payback time that can be considered just barely “break even” over two decades or so (with the precise number depending on the precise cost of the system and the incentive).

Without an incentive, only a very long lasting system with virtually no maintenance costs (unlikely) would break even.

In contrast to this, the same system at a site with a strong average wind speed, say 16 mph, will produce four times as much, and have a payback time as short as 8 years.

It turns out that relatively few people own sites at which small wind systems will produce very significantly, at least from the perspective of having the wind system effectively pay for itself quickly.

Also, one’s intuition about a site may be misleading, because average wind speeds are quite hard to judge well without some kind of objective data. The existence of a significant number of small wind systems at very bad sites suggests that people generally tend to overestimate wind resources.

So don’t install a wind turbine just because you’re in love with the idea. Make sure that it’s because you’re in love with the idea AND because you have some real objective criteria for believing your site is up to the task.

## Step 4: Determine the Generation Capacity You Will Need

Suppose you do not already have a particular turbine model or capacity in mind already, but want to determine the turbine capacity from your needs and the average wind speed at your site (at the turbine height).

First, consult your electric bills to determine your average annual electrical consumption.

Once you have this, you can now determine the appropriate turbine capacity. Divide your annual consumption by the “Average Annual Specific Yield” for your particular site, as determined in step 3 above, to determine how many square meters of swept area the turbine needs to be.

For example, if you consume roughly 10,000 kWh/year, and your Average Annual Specific Yield (from Table 1) is 260 kWh/m<sup>2</sup>/yr for a site with an average wind speed of about 11 mph, then you will need a turbine with a swept area of 10,000/260 = 38 square meters.

You can then determine the rotor diameter needed, plug the swept area into the following formula:

\_\_\_\_\_

For our example we have:

\_\_\_\_\_

This happens to match a 10 kilowatt Bergey XL turbine, for example.

It should be kept in mind that different turbines have ratings which depend on their diameters, efficiencies, and also the particular wind speed that they are rated at. Because the average wind speed at your site is not likely equal to the speed at which a turbine is rated, it’s difficult to utilize a turbine rating directly to determine the capacity of the turbine you need, unless you use a chart that shows estimated annual turbine production as a function of average wind speed, which is often not available.

The swept area, however, is a highly reliable measure of actual turbine capacity relative to the average wind speed, assuming that the turbine is reasonably efficient. So this is the basis of the approach used here.

In Appendix II, a formula for the estimated annual production of a wind turbine is given, which we can use to double check our example. The formula is:

$$\text{Annual Turbine Energy Production} = (8760/1000) \times 1.9 e \frac{1}{2} \rho A v^3$$

Here, e is the efficiency of the turbine,  $\rho$  is the density of air (which we can take as 1.23 kg/m<sup>3</sup>), A is the swept area, and v is the average wind speed.

Using the fact that 1 m/s = 2.24 mph, then the 11 mph average wind speed in our example translates to 4.91 m/s. Assuming a turbine efficiency of about .2 (see Table 1), and using a swept area of 38 square meters, we have:

$$\text{Annual Turbine Energy Production} = (8760/1000) (1.9) (.2)(1/2) (1.23)(38) (4.91)^3$$

$$= 9208 \text{ kWh/year.}$$

This is reasonably close to our target of 10,000 kWh/year, and provides a good cross-check on our previous calculation.

This also suggests that another way to estimate the swept area in the first place: We can “invert” this formula for A. The resulting equation is:

$$A = \text{Annual Turbine Energy Production} / ((8760/1000) \times 1.9 \times \frac{1}{2} \rho v^3)$$

If we insert our desired production of 10,000 kWh/year into this formula, and assuming an efficiency of .2, an air density of 1.23 kg/m<sup>3</sup>, and an average wind speed of 4.91 m/s, we obtain a swept area estimate of:

$$A = 10,000 / ((8760/1000) (1.9) (.2) \frac{1}{2} (1.23) (4.91)^3) = 41.2 \text{ square meters.}$$

This is slightly larger but close to the estimate of 38 square meters originally determined above. Inserting this into the rotor length formula, we obtain:

\_\_\_\_\_

This is very close to the 7 meters obtained earlier.

## Step 5: Determine the Brand and Model of the Wind Turbine You Will Use

Now that you know the turbine's swept area, you can proceed to determining a turbine brand and model.

You need to identify a turbine that is reliable, has the right power rating, and is generally suitable for your site.

**Avoid “fantasy turbines”.** That is, avoid those that may look very interesting on the internet, but have little or no track record. The internet abounds with new small wind turbine products, but stick with the well tested machines.

Some of the newer turbines with not very much track record in the US so far include the ARE, Eoltec, Kestrel, and Skystream turbines. In general, contact a prospective turbine manufacturer and ask how many units have been installed, and see if you can learn if customers have been satisfied.

**Buy a heavier-built turbine, relative to the swept area.** Experience has shown that turbines which are more heavily built tend to last longer. Specifically, turbines that have a mass-to-swept-area ratio of about  $10 \text{ kg/m}^2$  or higher tend to have better longevity than those closer to  $5 \text{ kg/m}^2$ . A heavier-built turbine might cost more, but the investment is likely well worth it.

Lower rpm turbines tend to be quieter, more efficient, and last longer.

## Step 6: Determine the Brand and Model of Inverter You Will Use

For this step you should look closely at the documentation for your turbine, and consult with both the installer and the manufacturer. There are many inverters on the market today. Find one that has a strong track record, is well suited to your turbine, and has a good warranty (at least 5 years).

There are also different options for how inverters are integrated with batteries and/or the power grid and/or a “dump load”. For a good summary of these options, see <http://homepower.com/basics/wind/>.

## Step 7: Determine the Type of the Wind Tower You Will Use

Guyed-lattice towers, like the type that HAM radio operators use, are the least expensive. Tubular towers can also be guyed. Self-supporting towers are also available, but are generally more expensive.

Guyed towers have a guy radius between 50% to 75% of the tower height. Make sure your site can accommodate this.

Tilt-down towers are available for household turbines and smaller (roughly 10 kilowatts and down).

Avoid aluminum towers (due to cracking).

Avoid rooftop mounts, due to noise issues. Most roof mounts are not high enough any ways.

## **Step 8: Get Your Wind Turbine Installed**

Don't rush it. Take your time to do things right, step by step. Mistakes with wind installations are costly, and potential dangerous.

The installation details are dependent on the site, the turbine, and the tower. The installation itself is best left to a professional. In any case, follow all directions carefully. Especially be sure not to skip on weight and dimensions of guy wire anchors and the tower base.

In addition to evaluating your site's wind resource, the whole sequence of installing a system is basically:

1. Find out if there are local ordinances that would limit the height of your turbine, and what would be required to seek a variance if necessary. Seek a variance if necessary, and work closely and proactively with adjacent land owners to avoid misunderstandings.
2. If you can indeed install a wind turbine at an adequate height, find an installer and agree on a system size and design. See the website of Renewable Energy Vermont ([www.revermont.org](http://www.revermont.org)) for a list of Vermont installers. It is strongly recommend that you spend some time checking into a prospective installer. Ask to visit some of an installer's projects, and speak with the owners.
3. Work with the installer to develop a detailed design for your system, down to the specific components and their brands (this information will be needed for the next step).
4. Work with the installer to fill out the application forms for the Certificate of Public Good (needed for grid-tied PV systems) and then the state and federal rebates. Be sure to follow all of the associated rules for these applications, especially notification of adjacent property owners.
5. Place a down payment on your system. If a CPG is necessary for your project, you should be able to arrange terms such that your down payment will be refunded in the CPG is denied for some reason.



6. When and **only when** the permit and rebate reservation are issued, commence with the installation.
7. Complete the requirements for the rebate: The check will arrive in a month or so (hopefully).
8. Claim any applicable federal tax credits on your federal tax form.

## Resource List

- “Small Wind Electric Systems, A US Consumers Guide”, US Dept. of Energy. Available at: [http://publicservice.vermont.gov/energy/ee\\_files/wind/smallwindelectricsystems.pdf](http://publicservice.vermont.gov/energy/ee_files/wind/smallwindelectricsystems.pdf)
- “A Siting Handbook for Small Wind Energy Conversion Systems”, H. Wegley, J. Ramsdell, M. Orgill and R. Drake, Report No. PNL-2521 Rev.1, 1980; available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22151. (800) 553-6847. <http://www.ntis.gov/ordering.htm>
- “Siting a Wind Turbine on Your Property”, Jean Vissering, [http://www.state.vt.us/psb/application\\_forms/PSB\\_Wind.PDF](http://www.state.vt.us/psb/application_forms/PSB_Wind.PDF)
- Vermont Wind Assessment Program: <http://web.vtc.edu/users/jnk06190/VTALP/>
- Vermont Renewable Energy Atlas, available at <http://www.vtenergyatlas.com>.
- Vermont Small-Wind Energy Demonstration Program: <http://www.vtwindprogram.org/>
- County level maps of wind resources in Vermont: <http://www.vtwindprogram.org/windmaps/>.
- Wind Turbine Buyer’s Guide: From Home Power Magazine: [http://homepower.com/article/?file=HP119\\_pg34\\_Sagrillo](http://homepower.com/article/?file=HP119_pg34_Sagrillo)
- Public Service Board List of Small Wind Providers: [http://publicservice.vermont.gov/energy/ee\\_files/wind/wind.htm](http://publicservice.vermont.gov/energy/ee_files/wind/wind.htm)

## Appendix I: Power and Energy (Watts and Kilowatt-hours)

It is important to know the difference between **power**, which is the rate of energy delivery, and **energy** itself. Energy is a quantifiable thing. The thing that is quantified is somewhat abstract: It's the "**ability to do work**", where work means to exert a force on something through a displacement, or in other words to push something around. While this seems somewhat abstract, it has been shown that **energy cannot be created or destroyed**, or in other words, **energy is conserved**. For this reason it can be quantified, bought, sold, transported.

Energy is quantified with various units, some of which are:

- The **Joule**: A unit of energy defined in physics.
- The **kilowatt-hour (kWh)**: The amount of energy that electrical utilities bill their customers for.
- The **calorie**: The amount of energy needed to raise 1 gram of water by 1 degree centigrade. A calorie is equal to about 4.186 Joules. (A dietary calorie, or Calorie with a capital C, is equal to 1000 of these calories).
- The **British Thermal Unit (BTU)**: The amount of energy needed to raise 1 lb of water by 1 degree Fahrenheit. A BTU is equal to about 1055 Joules.

Energy can also be **transformed** from one form into another. Some forms of energy are kinetic energy and potential energy (both of which together are called "mechanical energy"), chemical energy, electrical energy, and thermal energy. We can therefore also speak of generating electrical energy, which is really just transforming some form of energy, such as the kinetic energy of the wind, into electrical energy. Similarly we can talk about using energy, which usually involves transforming electrical or chemical energy into mechanical energy or thermal energy, and we can also talk about wasting energy, which involves either using too much energy to do something, or allowing too much energy to be lost to thermal energy instead of a more useful end.

In all of these processes we need a way to speed of the *rate* at which energy is being used, or transformed, or lost, etc. This is where **power** comes in:

$$\text{Power} = \text{The rate of energy use} = \text{Energy/Time}$$

The best known unit of power is the watts (W):

$$1 \text{ Watt} = 1 \text{ Joule/second}$$

When it is said that a wind turbine has rated power output of 10 kilowatts, for example, this means that the turbine can produce 10,000 watts, because 1 kilowatt equals 1000 watts, and therefore 10,000 Joules per second.

The unit "kilowatt-hour" includes watts, so why is this a unit of energy, and not power? From the equation above for power, we also have, with a little bit of algebraic rearranging:

$$\text{Energy} = \text{Power} \times \text{Time}.$$

So, if a unit of power is multiplied by a unit of time, we obtain a unit of energy again. This is the case:

$$1 \text{ kilowatt-hour} = 1000 \text{ watts} \times 1 \text{ hour}$$

So this is the amount of energy delivered by a 1000 watt source over 1 hour. But it can also be interpreted as the same amount of energy consumed by a 100 watt light bulb over 10 hours, because:

$$100 \text{ watts} \times 10 \text{ hours} = 1000 \text{ watts} \times 1 \text{ hour} = 1 \text{ kilowatt-hour}$$

In fact, the unit “kilowatt-hour” is kind of hybrid unit, as it implicit involves units of both seconds (because seconds are involved in the definition of a watt) and hours. But it is a legitimate unit of energy, and not a unit of power.

It is useful to know that typical home utilizes about 24 kilowatt-hours of electrical energy per day (the precise US average is a bit higher than this at present). We can also say that a typical home draws about 1kilowatt of power on average.

## Appendix II: Calculating Power Output from Wind Speed

The total instantaneous power in the wind with a velocity  $v$  passing through an area  $A$  is:

$$\text{Instantaneous Power in the Wind} = \frac{1}{2} \rho A v^3$$

Where the power  $P$  is given in watts, and  $\rho$  is the density of the air ( $\text{kg}/\text{m}^3$ ), and  $v$  is the wind speed ( $\text{m}/\text{s}$ ). This formula can be recognized simply the kinetic energy of the wind per unit volume ( $\frac{1}{2} \rho v^2$ ) times the speed  $v$  of the wind.

The density can be estimated as about  $1.23 \text{ kg}/\text{m}^3$  at sea level (note the units here carefully), and  $v$  should be given in meters per second. Some helpful conversion factors here are:

$$1 \text{ m}/\text{s} = 2.24 \text{ mph} \quad 10.75 \text{ ft}^2 = 1 \text{ m}^2$$

**Example:** Calculate the power of the wind blowing at 20 mph through an area of 10 square feet, we first convert to metric units:

$$A = 10 \text{ ft}^2 \times (\text{m}^2/10.75 \text{ ft}^2) = .93 \text{ m}^2 \quad v = 20 \text{ mph} \times (1 \text{ m}/\text{s})/(2.24 \text{ mph}) = 8.92 \text{ m}/\text{s}.$$

Then the power in the wind in this example is:

$$\text{Power in the wind} = \frac{1}{2} \rho A v^3 = \frac{1}{2} (1.23) (.93) (8.92)^3 = 406 \text{ watts}$$

A small wind turbine will convert just a fraction of the power available in the wind into electrical power, generally around 20% or less. Utility-scale wind turbines have higher efficiencies, approaching 40%. The theoretical limit is 59% theoretically, which is known as the “Betz Limit”. If we represent the efficiency of the turbine with the letter  $e$ , then the instantaneous power output of the turbine will be:

$$\text{Instantaneous Turbine Power Output} = \frac{1}{2} \rho A v^3$$

From this formula we can understand why the production of wind turbine is so sensitive to the wind speed. For example:

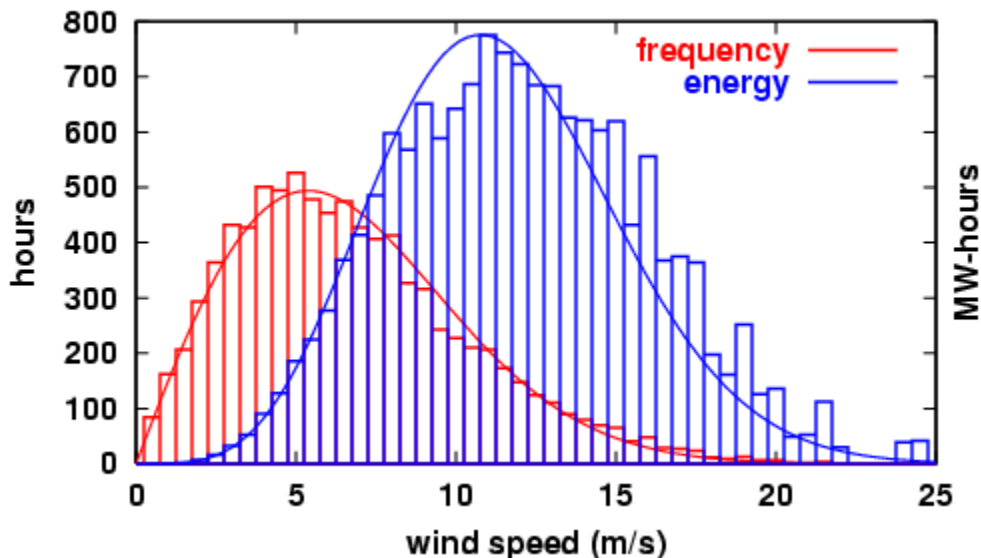
**Increasing the wind speed by just 25% increases the power in the wind by 95%!**

This follows from the fact that  $1.25^3=1.95$ , where the cubic power comes from the formula above (all the other factors divide out when we calculate the ratio to obtain the percentage increase).

By the same token, a site with very low average wind speeds will have very little wind energy.

**Pattern Factor:** While the formula above is adequate for the instantaneous power, we cannot just plug the average wind speed into this to obtain the average power output. It turns out that periods of high wind speeds will contribute disproportionately to the power production, and more than one might expect from just plugging the average wind speed into the formula above, because *the average of the cube is larger than the cube of the average*. This is another interesting consequence of the nonlinearity of the power on wind speed, but this time one that works in our favor.

The following graph (from Wikipedia) illustrates the situation well. It shows the statistic profile of wind speeds (in red), and of the wind turbine energy production (in blue) for a turbine at a ranch in Colorado:



Note that the majority of the energy production occurred at wind speeds of 10 m/s and above, which occurred only rarely. Specifically, half of the energy was delivered in only 15% of the time!

A precise calculation of the average power in the wind requires a full knowledge of the distribution of wind speeds, like that pictured in the graph above. Moreover, a complete calculation of the production of a wind turbine will also require knowledge of the so-called “power curve” of the turbine, which implicitly includes the turbine’s efficiencies at each wind speed. Performing such skills is the bread and butter of those in the “windustry”.

Fortunately, for our purposes here, it turns out that the statistics of the wind at most sites follows some well known characteristic distributions, and that we can estimate the overall efficiency fairly well.

To take the fact that *the average of the cube is larger than the cube of the average*, we can take advantage of the fact that wind in most places on Earth tend to follow the so-called weibull distribution, and in North America a slightly simpler special case of this called the Rayleigh distribution. The “pattern factor” for the Rayleigh distribution is about 1.9, so we can estimate the average power in the wind by:

$$\text{Average Power in the Wind} = 1.9 \times \frac{1}{2} \rho A v^3$$

Here,  $v$  is now the *average* wind speed. Note that this is substantially higher than what would predict by naively plugging the average wind speed into the formula for the instantaneous power in the wind.

So, the average power output of the turbine will be:

$$\text{Average Turbine Power Output} = 1.9 \times \frac{1}{2} \rho A v^3$$

Finally, to estimate the number of kilowatt-hours the turbine will produce over 1 year, we divide this by 1000 (to obtain kilowatts instead of watts), and multiply by the number of hours in a year (8760), to produce an answer in kilowatt-hours:

$$\text{Annual Turbine Energy Production} = (8760/1000) \times 1.9 \times \frac{1}{2} \rho A v^3$$