

## Wind Power Systems

Compiled by Tracy Dahl

### OVERVIEW

Wind is a force of nature familiar to every polar researcher. Although often perceived as something with which to contend, it also offers tremendous opportunities in the support of scientific research. Many polar locales such as ice caps, coastal regions, and areas experiencing katabatic winds are ideally suited for the use of wind turbines. In areas such as these, wind turbines can often provide the primary or even sole source of electrical power generation. Even locations typically regarded as having relatively poor wind resources, such as interior Alaska, often experience adequate wind speeds to provide at least a supplemental charging source for a battery-based system.

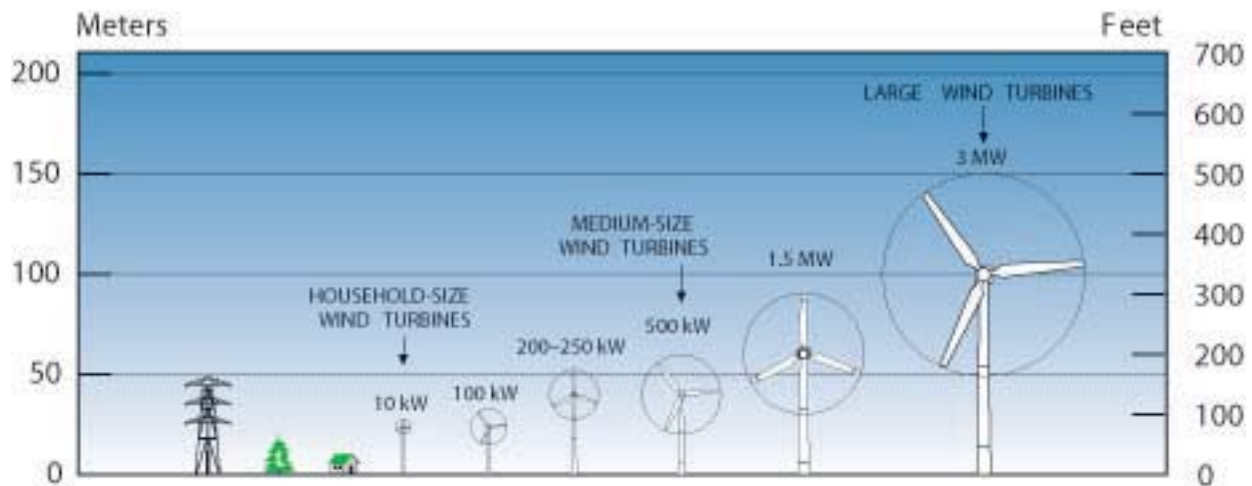
However, in almost all locations, the wind is an extremely variable source of power. A turbine must be able to take advantage of fairly low wind speeds to maximize energy production yet must also be able to survive the hurricane-force winds that sweep through the Polar Regions with varying frequency. Researchers have tried for many years to take advantage of this renewable energy power source—sometimes with disappointing results. Many researchers have returned to remote instrument sites in Antarctica and the Arctic to find their turbines non-functional due to broken blades, burned-up electronics, or, in some instances, an empty tower with no turbine remaining at all. Advancements in wind turbine technology and manufacture in the last 10 years have resulted in units much more capable of harnessing this force and surviving the rigors of the polar environment. Numerous mechanical furling systems designed to angle the blades out of the direct force of the wind, sophisticated electronic controls, and new and more robust blade and bearing materials have all contributed to the generally higher quality wind turbines found on the market today. For many research projects, wind turbines represent a viable and cost-effective solution for providing all or part of an experiment's electrical power requirements.



*Le Drift Hotel, from Raven 2001. Note the Bergey BW1500 in background.*



*Whisper H40*



*Diagram of relative turbine size, courtesy of Paul Gipe and Chelsea Green Publishing.*



Turbines are available in a wide range of outputs, from 50 watts up to several megawatts. Indeed, several mid-sized units (50-500 kilowatts) offer tremendous potential for powering larger polar research facilities. The Australian Mawson Station in Antarctica now has two Enercon 300-kilowatt turbines online (see <http://www.aad.gov.au/?casid=763>). This installation, completed in 2004, has reduced diesel fuel consumption at this facility by approximately 50%. Although the challenges are many, several other polar research facilities are highly suitable for employing this technology. With the high cost of transporting, handling, and storing fuel, wind turbines represent an economically viable alternative. The environmental benefits are also quite significant and are typically more in keeping with the requirements of the research community.

Because the majority of researchers have relatively low power requirements for seasonal or year-round instrument platforms, small- to mid-sized wind turbines will be the principle focus of this paper.

## HISTORY

Human beings have been putting the wind to useful work for a very long time. Sailing vessels provided the primary means of intercontinental travel until only a few hundred years ago. Stationary machines that converted the wind's energy into mechanical force were first developed in the Near East. As early as 1700 BC, Hammurabi employed windmills to water the plains of Mesopotamia (1). Evidence of other early windmills exists in Iran, Afghanistan, and China. All of the earliest windmills utilized a vertical axis and were used for milling grains or pumping water. As such, this technology played a major role in the widespread cultural shift from nomadic, hunter-gatherer cultures to permanent, agricultural settlement.

The horizontal-axis windmill was developed significantly later, circa 1100 AD. "As the most important driving engine apart from the water wheel, it spread from England and France via Holland, Germany (1200s) and Poland to Russia (1300s)" (2). The basic design of the horizontal-axis windmill underwent numerous iterations, culminating in the Dutch "Smockmill" in the 1700s and 1800s, which saw very widespread use throughout much of Europe.

The American farm windmill was developed in the mid-1800s and is readily recognizable by the numerous metal blades creating a rosette-like swept area. Utilized primarily for providing drinking water for humans and livestock, this technological innovation was responsible for opening up much of America's arid West for ranching and agriculture. Capable of pumping water from much greater depths, these mills are a common sight even today, not only in the American West but also in Australia and Argentina where the needs are quite similar.

Wind was not commonly utilized to spin generators for the production of electricity until the 20<sup>th</sup> century. "During the 1930s, when only 10 percent of the nation's farms were served by electricity, literally thousands of small wind turbines were in use, primarily on the Great Plains. These home light plants provided the only source of electricity to homesteaders in the days before the Rural Electrification Administration (REA) brought electricity to all." (3). The old Jacobs turbines and other wind generators from this era were often salvaged by the first advocates of renewable energy during the oil crisis of the 1970s. Indeed, many are still flying and reliably producing power today—a testament to the simple and rugged construction of these units. However, the choices available to researchers are now far greater, with power-to-weight ratios more favorable for remote installations.

Due to the ever-increasing economic viability of the technology and the relatively ubiquitous nature of the resource, wind turbines are also finding an increasingly broader application in the global energy production market. Denmark has long been a leader in large wind turbine manufacture and currently provides more than 20% of the nation's electrical power requirement using this clean, renewable energy source. Germany is now the world's leading producer of large wind turbines, and an ever-increasing percentage of that nation's electrical demand is being produced from grid-interconnected wind farms. Spain is also rapidly becoming a global leader in wind turbine technology, boasting many large, grid-connected wind farms and a healthy export business of Spanish-built turbines. While the United States currently meets less than 2% of the national electrical energy requirement with wind power, there are nevertheless some very large installations. Several states have now enacted regulation, mandated by popular demand, requiring utilities to generate certain percentages of the total power via renewable energy sources. Since wind power is currently far and away the most cost effective method to generate utility scale

power from an environmental resource, large wind farm installations are likely to become a familiar feature of the landscape.

For economic reasons, the trend in infrastructure-based, grid-connected applications has moved toward larger turbines. The NEG-Micon “NM110” is a turbine rated at 4.2 megawatts and boasts a rotor diameter of 110 meters (361 feet). This prototype model (2004) is designed for offshore wind applications.

These enormous wind turbines are fascinating and herald a major movement away from conventional, centralized fossil-fuel-fired generating facilities. There is no doubt that wind-generated electricity will continue to become an increasing part of the global energy production mix in the 21<sup>st</sup> century.



California wind farm.

## THE RESOURCE

In essence, wind is actually another form of solar energy. On a global scale, uneven heating of the Earth’s surface combined with the rotation of the planet causes convective currents that run generally from the lower latitudes toward the higher latitudes. More localized surface features affect and are affected by global circulation, thereby creating a complex and intricate pattern that includes the hydrologic cycle. This system as experienced on the face of the Earth is described as “weather”—a diverse and difficult-to-predict expression of a dynamic planet.

The primary determining factor influencing the electrical power production from any given wind turbine is wind speed. “Wind energy potential increases very rapidly with increasing wind speed. In fact, if wind speed doubles, the energy content goes up by a factor of eight” (4). Additionally, air temperature and density play a role in how much power one can hope to obtain from the resource.

Wind speed can be expressed as meters per second (m/sec), miles per hour (mph), or knots (kts). Here is the relationship between them:

$$1 \text{ mph} = 0.447 \text{ m/sec} = 0.868 \text{ kts}$$

$$1 \text{ kt} = 0.514 \text{ m/sec} = 1.152 \text{ mph}$$

$$1 \text{ m/sec} = 2,237 \text{ mph} = 1.943 \text{ kts}$$

In general, Polar Regions are pretty windy places. Antarctica boasts the highest average wind speed of any continent. At Black Island, a communications hub near McMurdo Station, wind speeds in excess of 140 mph have been recorded. There is a wind installation at this site, and it has provided a lot of valuable lessons on how to deal with polar extremes. The Arctic, as a region, experiences a somewhat similar wind regime to that of Antarctica. In both Polar Regions, the highest average wind speeds occur along the coasts and in mountainous areas, whereas the interiors can often experience fairly low average wind speeds. Moreover, the windiest times of the year tend to be when solar insolation is lowest—that is, during the boreal or austral winter. It is for this reason that photovoltaic (PV) panels and wind turbines are such complementary technologies. Both power sources can be utilized to feed a common battery bank and balance-of-system components in a *hybrid* system. For year-round system deployments, this is a sound strategy to pursue. Properly sized and designed, this also confers a measure of redundancy to a power system that directly relates to overall reliability. For a detailed discussion on hybrid power systems, please go to <http://www.polarpower.org> > Technologies > Hybrid Systems.

Although the wind resources in many parts of the world are now quite well researched, wind resources throughout many of the Polar Regions remain relatively poorly documented. However, it has become increasingly clear that the Polar Regions play a key role in influencing, moderating, and forecasting global weather patterns. Indeed, in some instances, meteorological observations represent the primary data researchers are seeking when installing remote instrument platforms. It is hoped that informational sources such as this web site will provide a forum for the exchange and dissemination of information relating to the topic of renewable energy resources in these least



documented areas of the world. The lack of wind information for many Polar Regions can make it rather difficult to develop precise calculations on the amount of electricity one can expect to generate from a given site. Nevertheless, data from neighboring or geographically similar regions, coupled with on-the-ground observations, can reveal a great deal about wind speeds at a given site. The National Renewable Energy Laboratory and the National Weather Service both maintain wind data records, although the emphasis is clearly on the contiguous United States. For more information on wind resource links, including some global wind resource links, see <http://www.polarpower.org> > Links > Wind Resources.

“The amount of energy embodied in the wind is a function of speed and mass. The relationship between mass, speed, and energy is given by the equation for kinetic energy where *m* represents the air’s mass and *S* its speed:

$$\text{kinetic energy} = mS^2$$

The air’s mass can be derived from the product of its density *d* and its volume. Because the air is constantly in motion, the volume must be found by multiplying the wind’s speed *S* by the area *A* through which it passes during a given period of time *t*.

$$\text{wind energy} = (dAst)S^2 = dAtS^3$$

Power is the rate at which energy is available, or the rate at which energy passes through an area per unit of time.

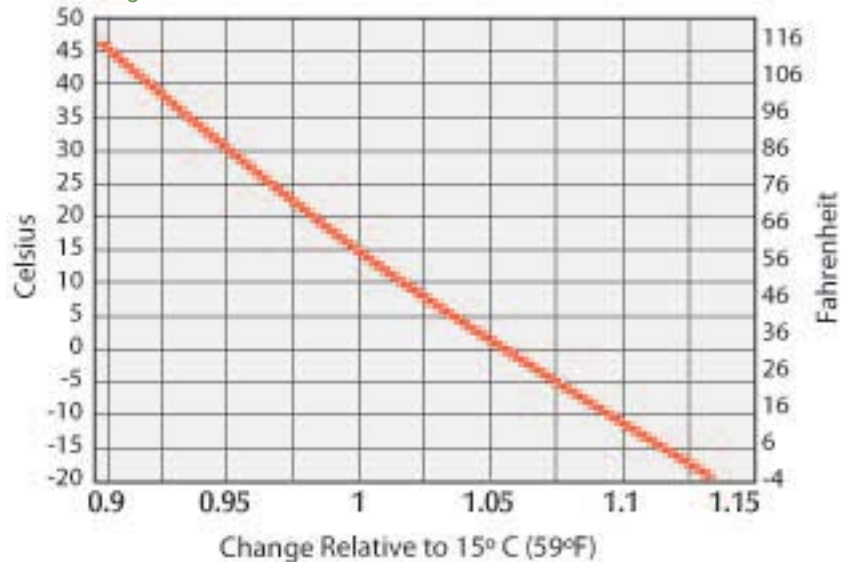
$$P = dAS^3$$

Power is dependent upon air density, the area intercepting the wind (swept area), and wind speed. Increase any one of these factors and you increase the power available from the wind” (5).

Air density increases with lower temperatures but decreases with altitude. At an elevation of 10,000 feet (e.g., South Pole Station, Antarctica, and Summit Station, Greenland), the air density is 70% what it would be (given the same temperature) at sea level. However, the dramatically colder temperatures at these locations cause a greater air density that somewhat offsets the altitude penalty. Low altitude/high latitude locations experience low temperatures and therefore greater air density. This can significantly boost wind turbine output, as there is more force exerted per any given wind speed. However, it takes a well-built turbine to withstand these forces. Wind turbines have burned out in polar locations because the windings could not pass the amount of current that the rotor delivered. In coastal polar areas, turbines may frequently produce in excess of their maximum power rating. Breakers, conductors, and balance-of-system components must be sized accordingly. Power production from high-altitude wind turbines, on the other hand, can sometimes be less than anticipated if air density has not been taken into consideration. For a far more comprehensive analysis of how to estimate the power available to a wind turbine at a given location, see *Wind Power for Home and Business* by Paul Gipe, listed in the “Further Reading” section at the end of this document.

One final point to bear in mind when analyzing wind resources is that no turbine is 100% efficient at capturing the power of the wind and converting it into electricity. In fact, most small wind turbines will deliver

*Air Density vs. Temperature, courtesy of Paul Gipe and Chelsea Green Publishing.*

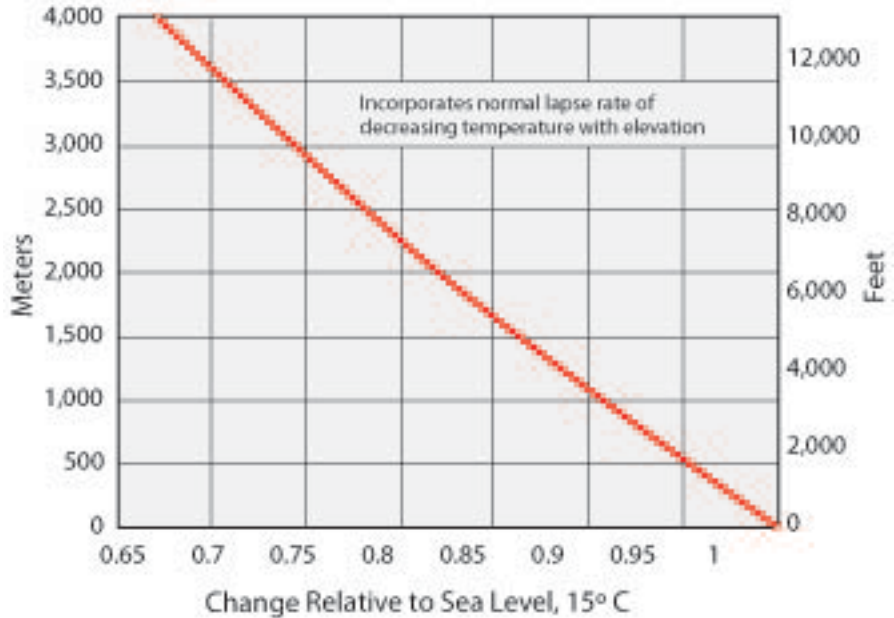


less than 23% of the wind's power to the batteries in a stand-alone power system (6).

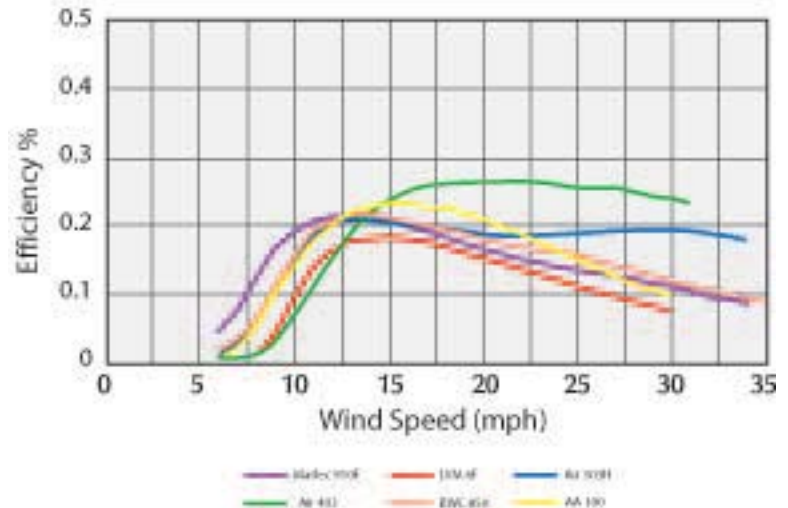
Here are a few general guidelines when considering utilizing wind power for a research location:

- Polar ice caps are typically good locations for locating wind turbines, although the average wind speeds experienced are considerably variable. Presence of sastrugi and/or a heavily scoured surface are good indications of at least periodically high wind speeds. It is fairly easy to erect and maintain towers (more on this later) in areas of permanent snow cover, and the absence of vegetation and other surface obstructions means that relatively low tower heights will still provide reasonable turbine performance. Of course, a taller tower will invariably lead to greater power production, but the penalty for using an easily erected tower of 10 meters or less is not as pronounced as in environments with more obstructions and therefore greater turbulence. Heavy icing problems are not typically encountered in interior ice cap locations.
- The transitional zones between costal and ice cap environmental regimes (such as Greenland's "equilibrium zone") almost invariably experience strong winds and can be excellent locations for wind power production. However, due to the ablation and large-scale melting frequently experienced during the summer months, properly erecting and maintaining the tower can be a tricky business. Both the tower and guy anchors tend to melt out due to the negative mass balance of the summer months. Masts and guys should be set very deeply in the ice, and timely maintenance visits are essential.
- Mountaintops can be excellent locations for wind turbines, although they are typically quite turbulent and seemingly minor variations in position can dramatically effect power production. Placing a turbine lower on the flanks of a mountain can be problematic and power production may be erratic, although a carefully selected site on the predominantly windward side may still provide excellent performance. Icing conditions can sometimes lead to problems. A wind turbine for a mountaintop site must feature very robust construction.
- Coastal areas typically experience significantly higher wind speeds than locations in the interior. As one might infer, islands tend to be very good wind sites, although the "coastal bonus" tends to drop off within 1 to 2 miles inland. High wind speeds and potentially heavy icing conditions are distinct possibilities.

*Air Density vs. Altitude, courtesy of Paul Gipe and Chelsea Green Publishing.*



*Small Turbine Efficiency, courtesy Paul Gipe and Chelsea Green Publishing*





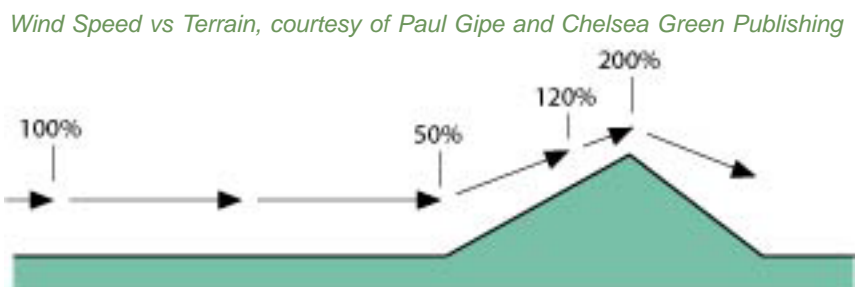
Additionally, ocean coastal environments tend to be quite corrosive, so a marine-rated turbine and components are essential to system longevity.

- Interior tundra or taiga areas generally have fairly low average wind speeds. In areas with enough vegetation to make a determination, growth patterns can often be quite telling. Homogeneous growth patterns imply low to moderate wind speeds, whereas uneven growth patterns, deformities, flagging of branches, leaning, or carpeting indicates that the wind sometimes howls. It is important to note that even areas with relatively low wind speeds (3 m/sec or less) can still contribute substantially to an overall power budget. In these lower latitude arctic locations, towers must be tall enough to avoid the turbulence and wind buffering caused by vegetative cover.
- Bases of mountains vary widely in the amount of wind they experience. Protected lee areas are common and are typically poor locations for wind turbines. On the other hand, katabatic winds can sometimes be quite strong and reasonably predictable in certain mountain base locations. These can be excellent areas for wind power production.

In some cases, it might be appropriate for a researcher to collect data on a site prior to investing the time, money, and effort in a wind system. For instance, if a PV system is currently powering an instrument site but power requirements have increased due to an extension of the field season or the addition of more equipment, it is entirely feasible to set up a tower and anemometer to record wind conditions. This can provide fairly accurate records; bear in mind, however, that the anemometer

tower height must correspond to the wind turbine tower height for the results to be precise. Of course, this takes time, significant investment, and effort. In many instances, when specific data for a site are unavailable, it can be acceptable for a researcher to make a best guess at whether a site will be suitable for a wind power system based on experience. It can

sometimes be more cost-effective to simply put up the turbine and see how much power is produced. Of course, if this strategy is pursued, it is best not to count exclusively on wind power production for the success of the experiment. Remember that if you are planning on using wind as a sole source of power, you will need more detailed wind information to properly plan the system. This includes not only how much wind there is but how much there is not—in other words, how long calm periods typically last—as battery autonomy (i.e., the size of the battery bank) will need to be based largely on this factor.



## WIND SYSTEM CONSIDERATIONS

There are four elements that will determine whether the wind can be successfully harnessed in support of a scientific research project:

1. *Is it a good wind site?*
  - For remote applications, a good site will have average wind speeds of greater than 4 m/sec (9 mph), although sites with significantly lower average wind speeds are acceptable if power requirements are modest or wind is not the exclusive energy source.
  - A good wind site will not have major surface obstructions to cause turbulence or lees.
2. *Are the project's power requirements suitable for utilizing wind energy?*
  - High, continuous power demand may necessitate the utilization of an on-demand power supply as part of a hybrid system.
  - Low or intermittent power demands combined with a good site and balanced system design may allow for the use of wind as the sole energy source.



3. *Do you have the appropriate wind turbine for the job?*
  - Wind turbines vary widely in size, quality, and the type of site for which they are designed. Some turbines are designed to take advantage of low wind speeds but may not hold up well to sustained high wind speeds or turbulence. Others are designed to survive high-speed, turbulent winds but will fail to produce much useable power at lower wind speeds.
  - Some turbines produce a higher voltage alternating current (AC) thereby allowing the tower to be located some distance from the controller and battery bank. Others rectify the power to direct current (DC) right at the point of generation and must therefore be located close to the point of use (or at least close to the point of energy storage).
  - Some turbines are designed to hold up well to icing conditions, whereas the design of other turbines may not account for this potential environmental issue.
  
4. *Have you taken a comprehensive, “system design” approach?*
  - A power system is really a chain of elements or components integrated into a whole. The chain is only as strong as its weakest link. Errors at any stage of the design or implementation can lead to failure of the system. An excellent turbine mounted on an insufficiently tall tower will likely yield poor performance. If the tower collapses because an anchor pulls out, the performance will be dismal indeed.

## **COST AND OTHER CONSIDERATIONS**

In some instances, wind power can provide the most economical means for supplying power to remote research projects or larger infrastructure-based research stations. To illustrate this point, the following quote is from Mike Bergey, a noted expert in the field. The dollar amounts mentioned are a bit dated and in some cases are actually significantly lower now, but the comparative cost relationship between PV systems and wind power systems remains true:

“Unlike PV, which stays basically at the same cost per watt independent of array size, wind turbines get less expensive (per watt) with increasing system size. At the 50 watt size level, for example, a small wind turbine would cost about \$8.00/watt, compared to approximately \$6.00/watt for a PV module. This is why, all things being equal, PV is less expensive for very small loads. As the system size increases however, this “rule of thumb” reverses itself. At 300 watts the wind turbine costs are down to \$2.50/watt, while PV is still at \$6.00/watt. For a 1,500 watt wind system the cost is down to \$2.00 a watt, and at 10,000 watts the cost of a wind generator (excluding electronics) is down to \$1.50/watt. The cost of regulators and controllers is essentially the same for PV and wind.” (7)

This statement should be taken very generally. Unlike PV, where there is not a tremendous variation in the price of similar modules, wind turbine prices are highly variable. Some small wind turbines, such as the Finish-built, vertical-axis “Windside” models, are quite expensive. When the additional costs of the tower, controls, and balance-of-system components are figured in, the cost of a small wind power system might actually be as high as \$65 per watt. This is just the component cost and does not include any transportation and labor costs. Small, high-end, horizontal-axis turbines, such as the Scottish-built Proven, can have system prices as high as \$15 per watt, again, excluding transportation and labor costs. As with most things, with wind turbines, you tend to get what you pay for. Both turbines mentioned above are very rugged and well built and are likely to survive the environmental extremes of a polar application.

Generally speaking, wind power systems require more maintenance and will not last as long as comparable PV systems. In deep field applications, it is probably reasonable to expect a service life of between 4 to 10 years out of a top-quality, well-designed, and well-maintained wind turbine, although longer (or shorter) service lives are certainly possible. Crystalline PV panels are typically guaranteed for 20 years or more, whereas wind turbine warranties typically run from 1 to 5 years. In terms of powering remote research, taken on a life-cycle cost basis, small wind power systems can often actually be much more expensive than PV systems.

As Mike Bergey stated in the quote above, when moving into larger infrastructure-based systems, wind power begins to look very economically attractive. For polar research stations requiring 100 kilowatts or more on a continuous basis, wind/diesel hybrid systems offer an economically viable and reasonably flexible alternative. Wind turbines can stand alone and do not greatly affect operations. A PV array capable of producing 100 kilowatts would require more than 1,000 square meters of surface area and, of course, would only be productive so long as it was in direct sunlight.

The bottom line is that the application, environmental conditions, and research requirements must dictate the system design approach. In determining how to power a research experiment through a polar winter, the cost per watt should not be the defining criterion. Reliability of the power source should be valued above all else, and given the right circumstances, wind power is often the best way to meet that requirement. Most typically, the equation is not reduced to an either/or scenario. PV-wind hybrid systems offer year-round power production and enhanced reliability. In many remote science applications, the addition of a wind turbine to an existing PV system may supplement power input enough to enable year-round research. For systems with greater power demands, the addition of an engine generator component allows for on-demand power supply and heat recovery options. However, these tend to be more complex and expensive systems. The researcher is usually best served by beginning with a careful evaluation of how much power will be needed and for how long. For modest power requirements or summer-only projects, simple and reliable PV systems are hard to beat. When power requirements are greater, the research project needs to operate year-round, or the data indicate a good wind resource, consider utilizing a wind turbine as a single power source or a PV-wind hybrid system. If power requirements are greater still, an on-demand power source will need to be considered.

## SYSTEM COMPONENTS

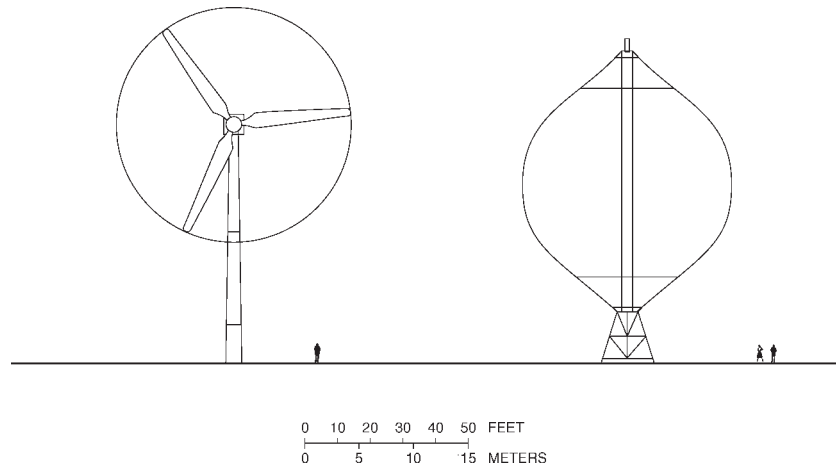
### Wind Turbine

There are two basic wind turbine configurations: the horizontal axis and the vertical axis. Vertical-axis wind turbines can be further subdivided into two basic designs. The Savonius design was invented in 1924 by Finnish inventor Sigurd Savonius. Only a few years later, the Darrieus wind turbine was patented in France.

#### Vertical Axis

There are advantages and disadvantages to vertical-axis wind turbines. The most desirable attributes include nearly silent operation and an avian-friendly design. However, most vertical-axis wind turbines are difficult to mount high on a tower to capture the higher speed and less turbulent winds found at greater elevations above grade. As such, they must utilize the generally lower speed winds found near ground level with a consequent reduction in power output. The silver lining is that having the generator mounted at or near ground level makes maintenance significantly less challenging. Also, vertical-axis wind turbines are omni-directional and accept wind from any direction. This somewhat reduces the penalty of utilizing more turbulent air. Vertical-axis wind turbines tend to be significantly more expensive to produce, and this above all else is likely responsible for the small number of models available for purchase. In terms of polar applications, there are really only two vertical-axis wind turbine manufacturers to consider: the Finish Windsides and the Italian Ropatec design. They are extremely robust, heavy machines capable of withstanding the most extreme environmental conditions. They are also quite expensive with a very poor power-to-weight ratio. See <http://www.polarpower.org> > Links > Wind Turbine Manufacturers, for access to Windside turbines.

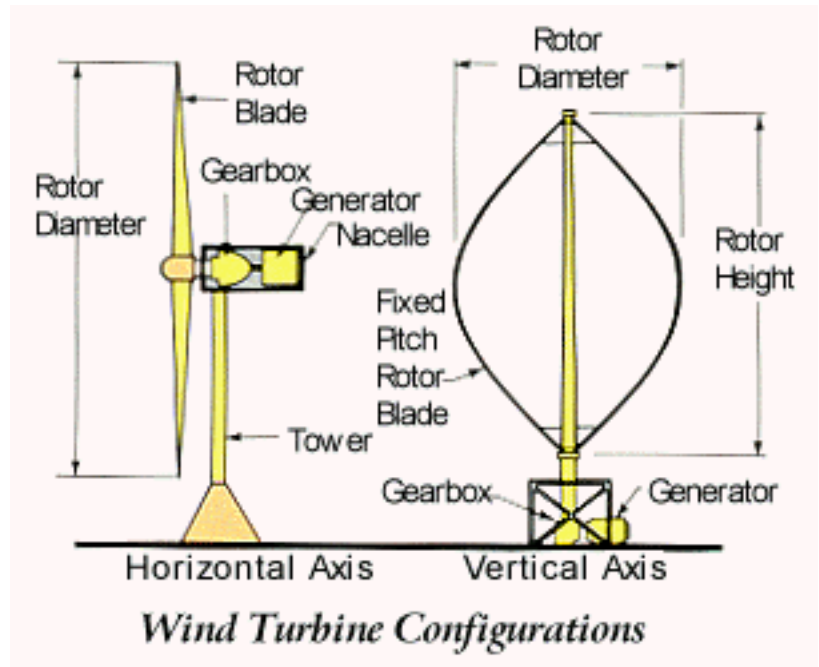
*Two Turbines – Vertical and Horizontal Axis Configurations*



## Horizontal Axis

Given the reasons listed above, with cost perhaps representing the most significant factor, the horizontal-axis wind turbine has come to dominate the industry. Whereas the researcher has few choices when it comes to vertical-axis wind turbine manufacturers, there are many horizontal-axis wind turbines suitable for use in polar environments. The basic elements of a horizontal-axis wind turbine are described below.

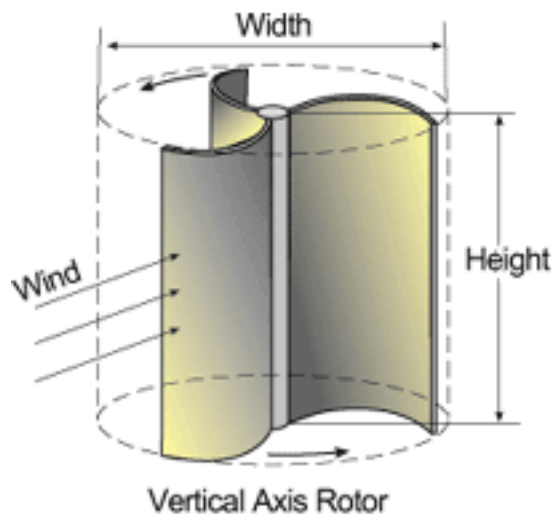
The *rotor* constitutes the spinning part of the wind turbine—basically, the blades and hub. The *swept area*, or amount of area captured by the rotor, is a definitive measure of a wind turbine, as much as the rated power output. The longer the blade is, the greater the amount of torque that can be exerted on the generator. Doubling the length of each blade, thereby doubling the rotor diameter, increases the swept area of a wind turbine by 4 times.



Most modern blades are composed of layered fiberglass, carbon fiber, special plastics, or combinations thereof. Most are designed to flex with the forces of wind and centrifugal motion, and this flexion helps to control rotational speed. An added benefit of utilizing flexible materials is that ice buildup tends to be minimized and is typically quickly shed as rotational speeds increase. Some manufacturers offer optional blades for their machines (e.g., carbon fiber vs. fiberglass) to cope with more extreme environmental conditions.

Many manufacturers utilize mechanical systems to control blade speed in high wind conditions. *Furling* changes the angle of the rotor in relation to the wind direction thus reducing the frontal area intercepting the wind. Some upwind models furl on a horizontal axis and others on a vertical axis. Either of these strategies helps to protect the turbine from damage but can sometimes result in dramatically reduced output in high winds. Downwind Proven turbines allow the blades to furl back, hinging on the hub. This reduces the swept area and changes the blade pitch to control the blade speed but allows for continued full-power output in very high winds.

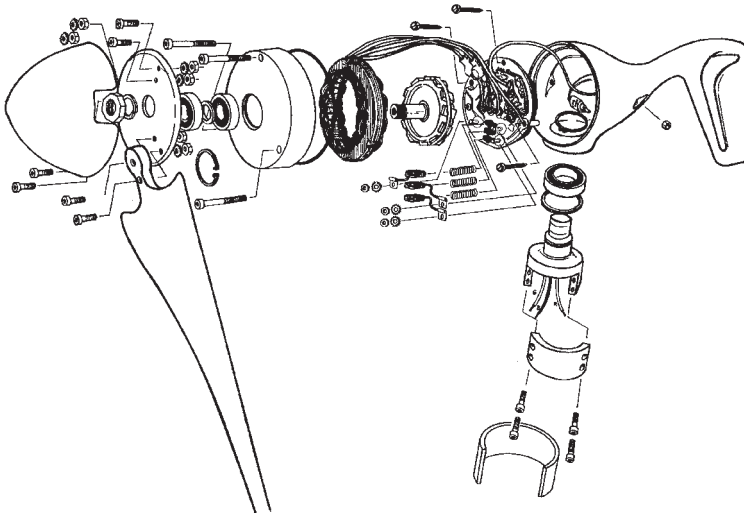
## Swept Area - Vertical



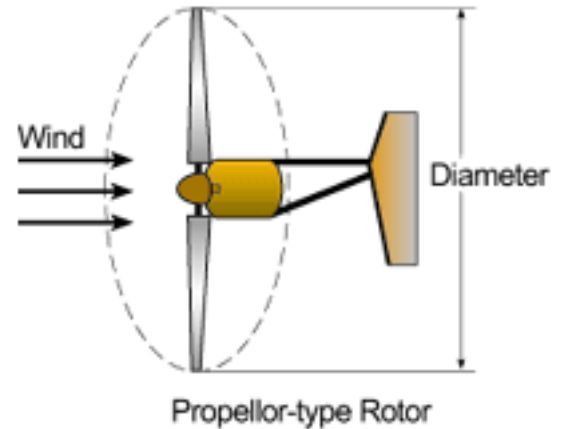
Windside turbines in Antarctica.



Air 403 exploded view.



Swept Area - Horizontal



Large wind turbines typically change the pitch of the blade to control rotational speed, often in conjunction with other controls. One small wind turbine manufacturer (Kestrel) has adopted this approach. The mechanical governor actuated pitch control, in combination with a many-poled alternator, allows for high power output at comparatively low rotational speeds. This should equate to low noise levels and a long service life, however, at the time of this writing, the machines have not been tested in polar environments.

Other manufacturers utilize electronic controls to essentially load the generator internally thereby reducing blade speed. In this strategy, a lot of internal heat can build up, which if not dissipated can lead to failure. Many early-model Southwest Windpower "Air 403s" met untimely ends in Antarctic applications due to this design. Even with very low ambient temperatures, they simply could not dissipate enough heat. Subsequent redesigns have resulted in more robust and reliable products.

Some smaller wind turbines utilize the blade design exclusively as the rotor speed control. Between blade flexion and the cavitation created by the blades themselves, severe overspeeding is avoided. Interestingly, several British manufacturers of small wind turbines have utilized rotors with many blades. LVM, Ampair, and Marlec all offer models with six-blade rotors. Like the old American farm windmill, this design offers a high starting torque and good low wind-speed performance. Of course, with low wind speeds, one can never expect too much power production. However, the above-mentioned turbines do better than most in low wind applications, and because of inherent design qualities and rugged construction, they (usually) do not blow apart in high winds.

Large wind turbines employ many diverse strategies to control rotor speed. Some early models exclusively used mechanical *brake systems* to control rotor speed in high winds. However, the duration of the wind events often exceeded the durability of the braking system, sometimes producing disastrous results. The history of wind power is a history of lessons learned. Now, most large wind turbines also incorporate some form of aerodynamic overspeed control as a type of fail safe. Many large wind turbines utilize some type of actuator motor to turn the blades out of the wind. In large-scale utility applications, the power grid itself can play a role in regulating rotational speeds. These more sophisticated control schemes are not typically applicable to polar installations.

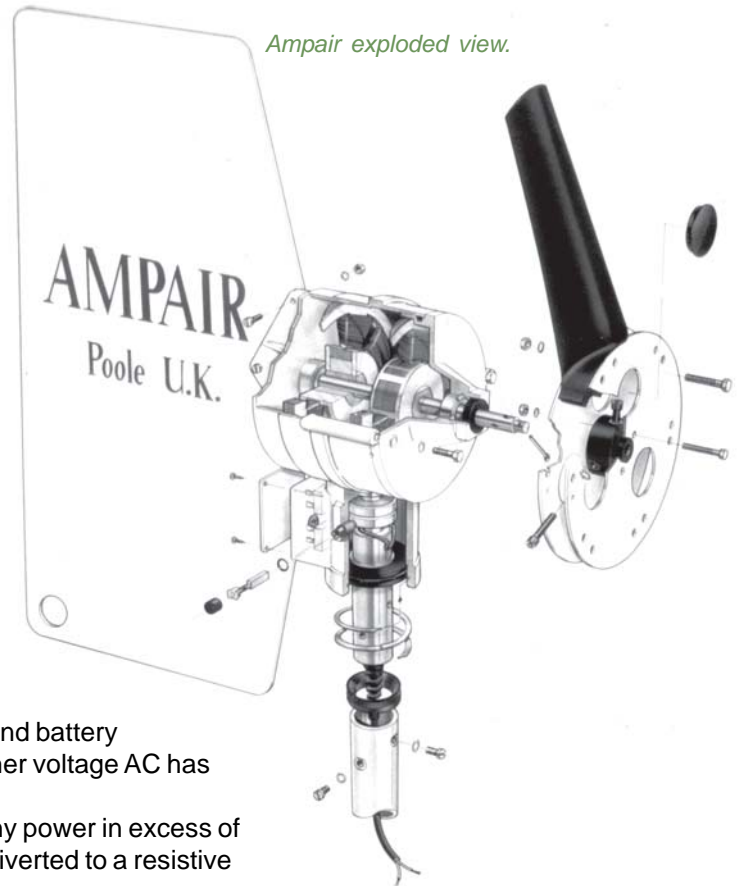
Some manufactures of small wind turbines offer mechanical brake systems, but these are typically used for locking the rotor for maintenance rather than as a means to control rotor speed. There will be more on this subject later.

The *nacelle* is the body of the wind turbine. It houses the drive train, generator, and balance-of-system components that allow the unit to follow the wind direction and transfer electricity. Remember that what the generator is really doing is *converting* one form of power (the wind) into another form (electricity). This is why, regardless of the size of the generator, the swept area of the rotor is the best indicator of potential power production.



Most small wind turbines are direct drive—that is, they do not utilize a gearbox to change the rotational speed of the generator rotor. The rotor attached to the blades is directly connected to the electrical rotor within the generator. Most small wind turbines utilize 3-phase alternators with permanent magnets. Permanent magnet alternators eliminate the need for field windings. Because the majority of wind turbine manufacturers choose to rectify the 3-phase AC to DC for battery charging via a charge controller placed near the battery bank, the comparatively poor voltage regulation inherent with permanent magnet designs is not an issue. In fact, most run a completely wild AC signal (both voltage and frequency are relatively uncontrolled) to the controller. There are three main advantages to using this strategy:

- The wind turbine can be made lighter since most of the electronics are located remotely.
- The wiring from the nacelle to the controller and battery bank can be much smaller given that the higher voltage AC has lower line loss.
- Many controllers allow for diversion loads. Any power in excess of what is required for battery charging can be diverted to a resistive heat load. More on this later.

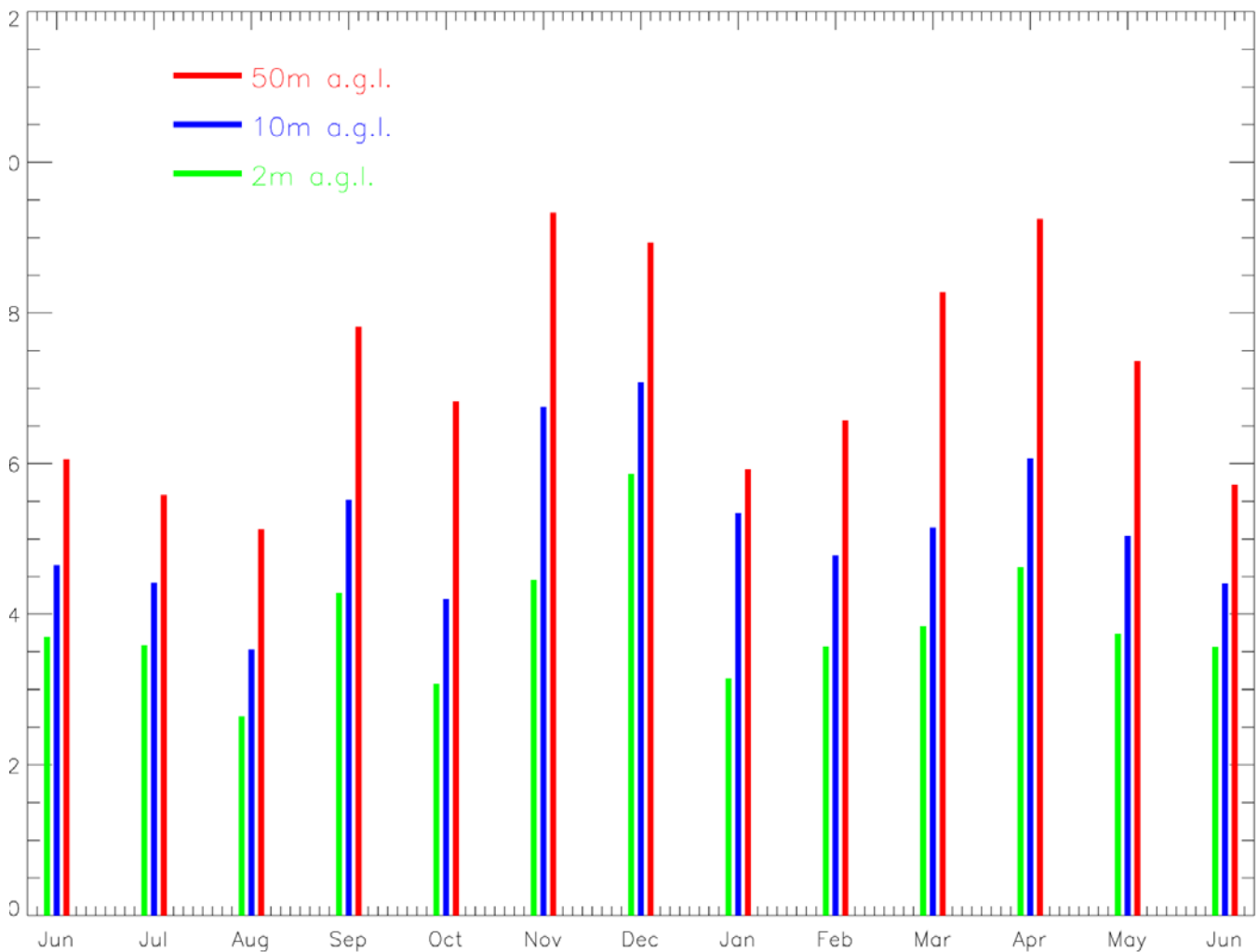


For more on how electrical generators work, please see <http://www.polarpower.org> > Technologies > Engine Generators, as well as the section on “Electrical Fundamentals.”

The primary function of the *tower* is to raise the machine above grade where it can better utilize the wind resource available. Simple in concept but varied in form, the importance of the tower is often underestimated in designing a wind power system.

Wind speed and therefore power production correlate directly with the height of the rotor above the ground. The uneven surface of the ground produces friction and turbulence that reduce wind speed and disrupt the even flow of the air mass. Not only does this reduce power output, it can dramatically increase the stress on the blades and other components. Even in most polar areas that lack significant foliage, low-level turbulence exists. Increasing the tower height by 5 times can double the power production of the wind turbine. Generally speaking, it is prudent to design for the maximum tower height that remains practicable to install and maintain, as wind speeds will be stronger, more constant, and less turbulent at greater heights. Additionally, the greater the distance from grade, the less blowing snow to which a turbine will be subjected. Most blowing snow events involve only the first 20 to 30 feet above the surface level.

Although taller tower heights provide definite benefits in power output, they can dramatically increase the difficulty of installation and service. For most small systems in remote Polar Regions, erecting towers greater than 50 feet (15 meters) will be problematic. Most installations are done by hand without the advantage of cranes or any heavy equipment. Sometimes even providing an adequate anchor for erecting a tall tower can be difficult. Generally speaking, 30-foot (10-meter) towers will provide good results for wind turbines of 2 kilowatts or less. Smaller wind turbines (< 500 watts) have been erected on towers as low as 15 feet (4.5 meters), and although the results may be less than optimal, system performance is still typically adequate to contribute significantly to the overall power budget.



Scale on left edge of graphic is m/s. Note the higher wind speeds with increasing height above the surface. Note also the stronger winds in the winter months. One year of wind speed data from Summit Station, Greenland. Courtesy of ETH Group.

Due to poor substrates (snow, bog, tundra, permafrost, etc.), tower types employed in the installation of small wind systems in the Polar Regions are generally limited to guyed designs. These can be mono-pole, tilt-up towers or sectional lattice towers, such as the Rohn. For wind turbines of 1 kilowatt or less, the tilt-up tower design is almost always preferable. Being able to install and maintain the turbine while standing on the ground has tremendous advantages over clinging to a steel tower 30 or more feet above the surface in the bitter cold. However, for turbines larger than 1-kilowatt output, the greater strength of the guyed lattice tower may be required. More on tower set-up and installation follows later in this document.

## SELECTING A WIND TURBINE

If you have determined that a wind turbine will meet (in part or in whole) the power requirements of your research project, the next step is selecting the appropriate size and type that suits your environmental conditions. Wind turbines intended for powering remote scientific research projects must be designed for unattended operation in very harsh environmental conditions. Features to look for include simplicity, ruggedness, and low maintenance.

### **Power Output**

As with many products targeted for emerging markets, there is tremendous variation in how closely wind turbines produce the claimed rated output. Some wind turbines will never equal the performance advertised, regardless of wind conditions. In other cases, wind turbines have been known to significantly exceed the maximum output stated. Either condition can be bad, as it makes the balance-of-system design rather difficult to account for. One fairly telling method for determining if a manufacturer's claims are based on science or fantasy is to compare the rated outputs between various models with the same swept area size of the rotor. It will become apparent that in some instances, performance claims simply cannot be true.

"The rated power for a wind turbine is not a good basis for comparing one product to the next. This is because manufacturers are free to pick the wind speed at which they rate their turbine. If the rated wind speeds are not the same then comparing the two products is very misleading. Fortunately the American Wind Energy Association (AWEA) has adopted a standard method for rating energy production performance. Manufacturers who follow the AWEA standard will give information on the Annual Energy Output (AEO) at various annual average wind speeds" (8).

Redundancy can sometimes equate to greater reliability. In very critical applications, a better strategy may be to employ multiple smaller wind turbines than one large turbine. In the event of a single turbine failure, there will still be power input, although reduced, to the battery bank. Smaller wind turbines can also be easier to set up. However, much of the cost and installation time involved with wind power systems is really associated with the tower. It will invariably be more expensive and time consuming to erect multiple smaller turbines. Also, wind turbine placement must be considered so as to avoid one turbine resting in the turbulence wake of another. In some cases, the wind direction is predictable enough to plan for this, as the elegant lines of offshore wind farms in Europe illustrate. Finally, very small wind turbines (< 500 watts) are often simply not as robust as their larger brethren. This is because weight is often a key design criterion for these applications. Although it is not true that there are no quality lightweight turbines, there is a lot to be said for the "heavy metal" school of design. Consider all the options carefully, for in some instances, a design employing one ruggedly constructed wind turbine may actually be superior to a system using multiple turbines of lower quality.

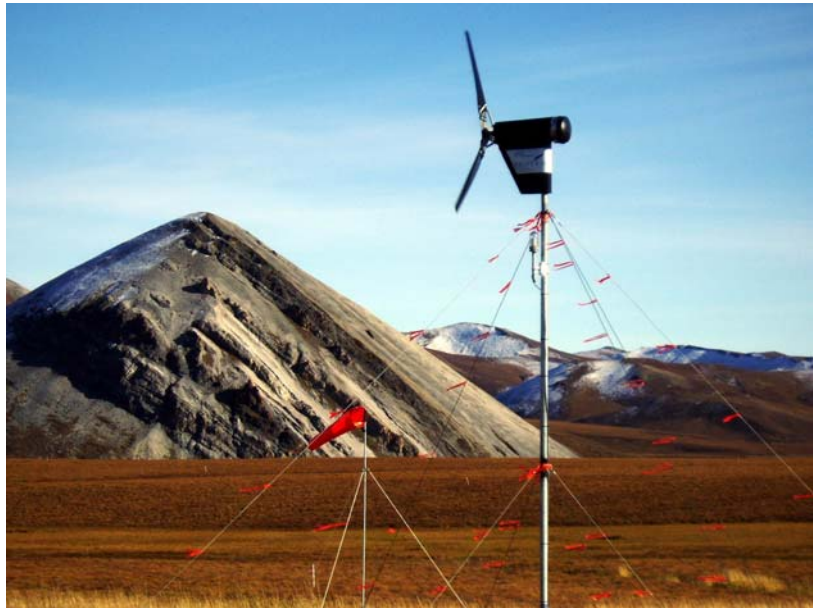


*Guyed, tilt-up tower.*

## Design

Although wind turbines typically bear a superficial resemblance, numerous design features vary from one model to another. Here are some features to look for:

- *Rugged design.* Does the turbine look like it can handle the rigors of the environment in which it will be placed? What materials have been used in the construction?
- *Minimum wind speed.* This is the speed at which the turbine must spin before it can generate power. If you are putting the machine in an area with an average wind speed of 3 m/sec and it does not start producing significant power until 5 m/sec, it is not well suited to the application.
- *Rated wind speed.* Again, this value should match up fairly closely with the average wind speeds of the location in which the turbine will be placed.
- *Survival wind speed.* Most manufacturers selling a quality product will post this number. Remember that cold air is dense, and cold air filled with blowing snow is denser still. Also, extreme cold usually has a deleterious effect on the strength of materials. For polar applications, de-rate the claimed survival speed by 25%.
- *Power curve.* Does the machine continue to consistently put out power even when it goes into overspeed control? This can make a big difference in the total amount of power produced by a turbine. The production of some units drops off dramatically when wind or rotor speeds cross a certain threshold.
- *Noise level.* In most cases, this may not be an issue. However, if the turbine is to be placed in a manned site or if wildlife observation is an element of the research project, then the acceptable level of noise could come into play. Wind turbines can be very loud in some instances. For example, Southwest Windpower's "Air Industrial" model, although a fine turbine in many respects, is exceedingly loud in high wind conditions. Not all manufacturers post sound-level information, but those companies that have put some effort into reducing noise levels generally do.
- *Marine rated.* If you are placing the machine in a maritime environment, it is essential to make sure that it is marine rated. Salt is exceedingly hard on electronics, and corrosion can sometimes occur in as little as a few months. Sealed or encapsulated electronics, stainless steel fasteners, and specially coated metal are typical attributes of a marine-rated unit.



*Proven WT600 at Ivotuk, AK.*

## BALANCE-OF-SYSTEM COMPONENTS

Although we have described the basic elements of the wind turbine, there are numerous other components that must be considered in the overall power system.

### Batteries

The wind does not blow with equal intensity in all places at all times. Gale-force winds on one day may be followed by a week of calm weather. This is the primary reason why wind remains a tricky resource to harness. The load requirements of a power system, on the other hand, seldom correspond with times of peak power production. For the purposes of polar scientific research, an energy storage system must be employed. This will most typically comprise a set of batteries, which allows for the storage of power to help regulate the variability of the wind.



A battery stores electrical energy in the form of chemical energy. When sized appropriately, it can absorb the full output capability of the wind turbine via the charge controller. It also allows for the use of DC-powered instruments and equipment, which typically provides a more efficient power supply for small scientific loads. To operate effectively in conjunction with a wind power system, the electrochemical processes must work in both directions—in other words, the system must be rechargeable. To this end, batteries perform three main functions in a wind power application:

1. *Autonomy*—by meeting the load requirements at all times, even when wind turbine input is low or absent.
2. *Surge-current capability*—by supplying, when necessary, currents higher than the wind turbine can deliver, especially to start motors or other inductive equipment.
3. *Voltage control*—thereby preventing large voltage fluctuations that may damage the load.

Any battery suitable for remote power applications will be a *deep-cycle* type of battery as opposed to a starting (*SLI*) type. Although these two fundamental classes of batteries may appear similar on the outside, the internal structure is quite different. SLI batteries are intended to deliver a high-amperage output for a short period of time, but repeated deep discharges cause rapid deterioration of battery performance. These batteries are typically rated in cranking amps, or cold cranking amps (CCA). Deep-cycle batteries are designed to deliver a typically lower current for the size of the battery, but they are capable of withstanding numerous deep discharges without damage.



*Deka AGM type battery*

The amount of energy a deep-cycle battery can store is referred to as its *capacity*. The unit that describes capacity is the *amp hour (Ah)*. Battery capacity is determined by the manufacturer based on a constant discharge over a period of time. Often, batteries will appear to have multiple ratings due to this rating process. The 20-hour rate (C/20) and the 100-hour rate (C/100) are referred to most frequently. When determining which battery to choose, be sure to compare all batteries at the same discharge rate.

Deep-cycle batteries vary widely in type, price, and quality. Low-cost trolling batteries represent the low end of the scale and are generally not suitable for use in remote power applications. The most expensive battery per amp hour is generally the gel-cell battery. Battery failure has often been the cause of sub-optimal power system performance. Without a doubt, this is not the area to cut expenses. The battery bank for any power system must be of the highest quality available, of the correct type for the application, and of sufficient capacity to ensure that the depth of discharge does not exceed design parameters. In the absence of an on-demand power source, such as an engine generator, the size of a battery bank for even relatively low-power applications can be surprisingly large, particularly if year-round autonomy is a design requirement. Cold temperatures reduce capacity but tend to extend battery life. System sizing worksheets (see the end of this document) are essential for ensuring adequate battery capacity for a given project.

The most common type of battery found in remote power systems is the lead acid battery. Although the discussion will focus on this blanket technology, other rechargeable battery types do exist, including nickel-cadmium (NiCad), nickel metal hydride (NiMH), nickel-iron (NiFe), lithium ion, and lithium polymer batteries. Of these, the NiMH and lithium polymer batteries show significant promise for broader application in autonomous power systems. These battery types demonstrate up to a 4-fold greater energy density and enhanced performance across a wider temperature range, which might ultimately favor this emerging technology. NiCad batteries have been used in a few polar applications, as they have superior performance in extreme cold. However, the high price, low efficiency (about 65% vs. 85%-95% for lead acid), and restrictive charging parameters make them unsuitable for most applications. At the moment, the comparatively low prices and well-documented performance of lead acid batteries favor their continued use for remote power systems.

In the lead acid class of batteries, two specific types stand out for their applicability to polar power applications: the *gel cell* and the *absorbed glass mat (AGM)*. These two types of batteries represent good choices not only due to performance characteristics but also because they are both suitable for air transportation. Because the electrolyte solution in both of these battery types is immobilized, they represent a lower hazard class than standard *flooded* batteries and do not require a great deal of specialized packing before being shipped via aircraft into the field. Although the performance characteristics of flooded deep-cycle batteries may meet or exceed those of the gel-cell and AGM types, the transportation and maintenance issues can prove to be quite problematic for remote scientific research projects.

Both of these types of batteries are classed together as *valve-regulated lead acid (VRLA)* batteries. A battery charging at a high amp rating or an excessively high voltage can release gases (hydrogen and oxygen) due to an overcharge condition. In a VRLA-type battery, gases are not released during a normal, controlled charge cycle. There is a closed loop that keeps the chemical levels balanced and internal pressures below the release threshold of the valve.

One very important difference to note between gel-cell and AGM batteries is that the gel-cell battery is a plate-limited design, whereas AGM batteries are an electrolyte-limited design. This can be very important in polar applications where extremely cold temperatures are often the norm. Freezing the electrolyte solution in a battery must be avoided. It causes irreversible damage to the battery, which could lead to catastrophic failure. Also, a frozen battery cannot recharge until it has been thawed out again—not always a simple proposition in the field. Electrolytes freeze at higher temperatures as they discharge and the specific gravity decreases. AGM and flooded-cell batteries can continue to discharge until the electrolytes become severely depleted thereby resulting in a low specific gravity and a relatively high freezing point. A quality load controller somewhat obviates this concern, as it will typically incorporate a low-battery disconnect capable of opening the circuit between the battery and the load prior to the onset of problems. In a plate-limited battery, the chemical reaction that causes the flow of electrons ceases before the electrolyte specific gravity falls too low. This provides a certain measure of inherent protection by design. It is



*Industrial battery stacks offer the ability to reconfigure voltages based on 2-volt cells. They can also allow for a lot of energy storage in a compact space.*

### Liquid Electrolyte Freeze Points, Specific Gravity, and Voltage

<u>State of Charge</u>	<u>Freeze Point</u>	<u>Specific Gravity</u>	<u>Voltage</u>
100%	-71° F	1.260	12.70
75%	-35° F	1.237	12.50
50%	-10° F	1.200	12.30
25%	3° F	1.150	12.00
0%	17° F	1.100	11.70

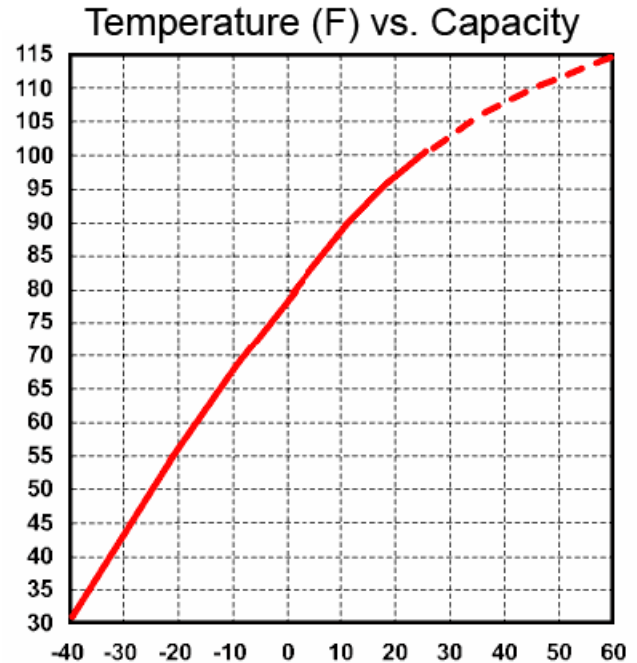
\* Adapted from *Photovoltaics Design and Installation Manual* (2004), SEI.



important to note, however, that gel-cell batteries are vulnerable to damage in other ways. Charging at excessively high rates can create voids in the gelled electrolyte that significantly reduces the capacity of the battery. Voltage and current must be carefully controlled and cannot exceed the C/20 rate (approximately 5% of the amp hour rating for the battery bank).

For wind power systems capable of delivering a lot of power in high wind-speed conditions, AGM batteries are typically preferable due to a superior high-current rate performance (9). It is worth noting that many battery manufacturers offer both gel-cell and AGM types. Gel-type batteries have fallen somewhat out of favor in the industry in recent years, but there are still applications where this is the most appropriate technology to use. The optimal battery choice for a given research project must be determined on a case-by-case basis, but generally speaking, AGM batteries are considered superior for use with wind turbines due to their ability to be charged at a high current rate.

Battery capacity is dramatically affected by the cold. Capacity is reduced by 50% at -10° F, and the risk of freezing becomes much greater. At the same time, battery life is increased by 60% due to a lower rate of self-discharge and generally depressed chemical processes. This applies to all types of lead acid batteries and explains the phenomenal service life of some batteries deployed to polar environments. The reduced capacity must be taken into account when determining the battery bank size required for a system.



The *depth of discharge* also has a direct bearing on how long a battery will last. A battery discharged to 50% on each cycle will last about twice as long as one discharged to 80% per cycle. Given the often-unpredictable nature of the wind, it can be very difficult to estimate how large a battery bank is required to avoid overdischarge. It is always better to err on the side of caution. The battery bank must also be large enough to accept the full charge current capability of the wind turbine without overheating or causing a pressure release on a VRLA battery. “For small wind turbines a general rule of thumb is that the Ah capacity of the battery bank should be at least six times the maximum renewable charging current, including any PV elements” (10). Bear in mind that the autonomy requirements of the system will often necessitate a battery bank much larger than this. Be aware that it is also possible to oversize a battery bank. To prevent premature sulfation of the plates, a battery must be periodically taken to a 100% full state of charge. With a large battery bank and a relatively modest charging source, this can sometimes be difficult to attain.

When diagnosing battery problems, be sure to differentiate between the *surface charge* and the actual *state of charge*. This is particularly important in a system incorporating an alternate charging source such as one using PV or wind power. A battery still connected to the charging source may appear to have adequate voltage, but this can be very misleading. When analyzing a battery, first ensure that it is fully charged. If possible, run a generator charge cycle to top off the batteries. Next, disconnect it from any charging source as well as the loads. Allow it to sit for an hour before taking a baseline voltage measurement. Next, hook it up to a dummy load, which should be a resistive load. Watch the battery over a period of time and observe the voltage decline. If it drops dramatically right away or maintains voltage for a short time before the bottom drops out, the battery is bad. Generally speaking, it is poor economy to replace only one battery or cell in a battery bank. As with any interconnected system, the performance tends to be reduced to the level of the poorest performing module.



## Charge Controller

Regardless of the battery type chosen for a particular system, a *charge controller* remains an essential component. The primary function of a charge controller is to prevent the battery bank from being overcharged when there is abundant wind energy available. Overcharging a battery can lead to electrolyte imbalances and depletion. In cases of severe overcharging, batteries can be completely destroyed along with any instrumentation in the vicinity.

Controlling the input current to the battery bank can be challenging when utilizing a variable power source like the wind. Most manufacturers of small wind turbines also offer charge controllers specific to their product, or they at least recommend a suitable charge controller from another manufacturer. Unlike PV systems, where the charge controller can often be quite simple, wind system charge controllers tend to be a bit more sophisticated. To ensure reliable operation and ease of installation, researchers are advised to utilize the manufacturer's specified charge control system whenever possible.

Most controllers utilize a diversion load to accept the full current capacity of the wind turbine after the battery has been topped off. This is typically a resistive load for heating air or water. This feature can be used to excellent effect in most polar applications where heat can be a tremendous asset for keeping batteries and electrical components in a temperature-moderated environment. Although there are few implemented examples, it is easy to envision how a resistive heater in a tank containing a water/glycol mix could store heat energy for later use. Of course, it is also possible to see how a prolonged wind event could lead to overheating of the storage medium, enclosure, and batteries. A thermostatically controlled relay could activate a relay that activates a contactor to divert the power to a resistive air heater located outside the enclosure. It is not a difficult problem, but it is trickier to work out than it appears on first glance. Many systems simply dump any waste heat to the environment to avoid this complication. More work is required in this area to create reliable and relatively standardized thermal control systems. More on thermal strategies follows below.

## Inverters

An inverter is a device that converts DC power from the battery bank to AC power for various loads. In small wind power systems, it may be possible to eliminate this component altogether. In larger systems incorporating components that demand AC power, an inverter must be utilized. Also, if the instrument site is located some distance from the battery bank, an inverter allows for an efficient means of getting electricity to the point of use. AC is easier to transport over long distances and has become the conventional modern electrical standard.

There are two fundamental categories of inverters: *synchronous* and *static* or *stand-alone*. Synchronous inverters are capable of being tied into the electrical *grid*, or utility power. Except in the largest of infrastructure-based systems, this type of inverter finds little application in the field of polar research. Static inverters are designed for independent, utility-free power systems and are the type used for remote-power PV applications.

A second classification refers to the type of AC waveform they produce. Inverters are available in *square wave*, *modified square wave*, and *sine wave* outputs.

- Square wave inverters are inexpensive, but they typically provide poor output voltage control, limited surge capacity, and significant amounts of harmonic distortion. In general, this type of inverter is inappropriate for remote scientific research applications.
- Modified square wave inverters utilize more complex circuitry to create a wave form more closely approximating a true sine wave. They are capable of handling greater surge loads and have an output with less harmonic distortion. Although capable of powering a wider range of loads, there are still issues of concern for the polar researcher. Some electronic devices can pick up inverter noise, or buzz, and any device utilizing a digital timekeeper will run either fast or slow when powered by a modified square wave form.
- Sine wave inverters are best for powering sensitive electronics that require a high-quality wave form. They have little inherent harmonic distortion, and typically have surge capacities of double or greater the continuous output rating. This is an important consideration if motors or other inductive loads are part of the overall power budget. Because sine wave inverters are now available in sizes from a few hundred watts to



many kilowatts output, there is little reason to consider any other type for polar research applications.

**Note: If AC power is part of the project requirement, use an inverter with high-quality sine wave output.**

When selecting an inverter, many additional criteria must be considered:

- *DC voltage input* must match the battery voltage of the system.
- *AC power output* must be adequate to satisfy the maximum potential combined AC load, or all of the AC-powered equipment that might be on at one time. However, the system designer should also be cautious about over-sizing the inverter, as most operate at their maximum efficiency toward the middle to upper end of their output range.
- *Voltage and frequency regulation* should be very tight in a high-quality unit. Voltage and frequency should match the system requirements (60 Hz/120 volts for U.S. equipment and 50 Hz/240 volts for European equipment). Note that step-up or step-down autotransformers can be utilized to change output voltages if required but at the expense of a bit more power consumption.
- *Efficiency* should be high across a broad range of output levels. Some inverter manufacturers claim high efficiency levels, but they may be measured at or near maximum output where the inverter will rarely operate. Choose an inverter rated for high efficiency over a wide range of load conditions.
- *Construction* should be consistent with the application requirements. Some inverters offer a sealed design or special coatings on the electronics to enhance reliability in wet or corrosive environments. Other inverters utilize open construction with a cooling fan for increased load capacity. A limited range of marine-rated inverters is available for maritime environments.

## Conductors

Wind power/battery systems always incorporate DC circuits and often utilize an inverter for AC circuitry as well. AC and DC wiring systems have distinct requirements and should never be mixed in conduit, raceways, or junction boxes. DC systems are typically low voltage (< 48 VDC) and thus require much larger wire sizes than AC systems. Indeed, the wire size required to avoid unacceptable voltage drops across any distance or in high-current applications is often surprisingly large. Many systems have experienced poor performance due to inadequately sized conductors.

The polar environment introduces additional challenges in system wiring. Larger cables used for battery connections become incredibly stiff and difficult to work with due to the insulated sheathing. Coarse-stranded wire intended for residential AC-type use exacerbates the difficulty. Pre-assembling as much of the system as possible will reduce field installation woes. However, installing battery cables and runs from the wind power system are often difficult to avoid.

Although conventional wire will often work just fine for the majority of applications, there are a few wire types that are of special interest for remote, cold-weather installations:

- "Arctic Flex" is a product that utilizes a special rubber insulating sheath that stays flexible up to very low temperatures. It is also a fine-stranded wire thus making it quite malleable and easy to work with. It is UL rated and National Electric Code (NEC) compliant. A wide range of sizes and colors are available.
- Welding cable, while not code compliant, offers a perfectly safe and considerably less expensive alternative for high-ampacity cabling requirements.
- For smaller wire sizes, automotive "primary" wire tends to be more flexible and easier to work with in the cold.
- Another favorite wire type of the polar installer is "SO" cord. This type of cord contains three or four insulated conductors inside an outer sheath. This is essentially the same material that extension cords are made out of. It is available in bulk in sizes up to #6 gauge. The outer sheathing varies widely in how flexible it remains in cold environments and seems to be somewhat color coded, with yellow and blue remaining the most flexible. Be sure to check the ratings.




- Armored “liquidtight” cable is heavier and more difficult to work with but offers a higher level of protection for the internal conductors. This is the type of cable to use for long runs in rocky or abrasive terrain or where animals might be a problem.

Remember that if wires are to be left exposed to the environment, they must be rated for the exposure, including UV radiation. UV-resistant sheathing is generally marked as such on the outside. If it does not say “UV rated,” it probably is not.

Remember to include the correct adapters to bring your cables and conduit into junction boxes and enclosures. Every type of conduit, armored cable, or SO cord requires something a bit different. The devil is in the details, so make sure you have the correct adapters, and plenty of them. Again, pre-assembly back at your home institution is an effective way to ensure you have what you need when you arrive at the field site.

Combiner blocks, mechanical lugs, split bolts, and a variety of solderless connectors should have a place in your field tool kit. Rubber splicing tape and low-temperature electrical tape are essential as well. Red electrical tape serves as *code tape* to ensure that you know which of those black cables is the DC positive.

The convention for DC color-coding is as follows:

-  Red is for positive—the current-carrying conductor.
-  White is for negative. (I code tape mine black.)
-  Green or bare is the equipment ground.

The fine-stranded wire recommended above is much easier to work with in cold environments but poses some additional requirements for system installation and maintenance. Mechanical lugs can damage or break the fine strands resulting in a weak connection and reduced ampacity. Take care during installation, and regularly check the tightness on all connections during all maintenance visits.

The positive and negative conductors in a DC system should be kept close together and in parallel for any long runs to avoid inductive potential.

### **Grounding**

Grounding is a deceptively complicated issue. Although the NEC requires *equipment grounding* on all wind power systems regardless of operating voltage, obtaining a true *earth ground* in a polar environment can often be difficult or impossible to obtain. In areas of permafrost, rocky soil, or muskeg, grounding plates or grounding rings made of 4/0 bare copper will typically provide a satisfactory earth ground. This earth ground must be bonded to every metal electrical box or component enclosure, receptacle, and bare metal frame. In most of the world, it is common practice to ground the turbine tower separate from the actual generator ground wire if the balance of the system is located some distance from the tower. This is primarily for lightning protection, not a major concern in most polar environments but a possibility in some areas. If there is adequate grounding potential (tundra, muskeg, etc.), drive a grounding rod at the tower and at each guy anchor. Connect all the ground rods with #4 bare copper and special ground-rod clamps. Alternatively, bare 4/0 cable can be used to create a grounding ring around the perimeter of the tower, equidistant between the tower and the guy anchors. Tie the tower and each guy cable into this grounding ring with split bolt connectors.

In most remote systems powering scientific research, the wind turbine tower is often not too distant from the balance of the system. As a general rule of thumb, if the tower is within 100 feet of the balance-of-system components, all ground wires should be tied in common and referenced back to the primary earth ground. The grounding wire is never fused or switched.

In an ice cap environment, achieving an earth ground is typically not possible. As such, grounding is dealt with in the same way as within the automotive industry. In this method, the frame or chassis becomes the grounding point to which all of the negative conductors are referenced. Although not as good a system as a true earth ground, it does ensure that overcurrent devices will operate as designed. It will not, however, protect equipment from lightning strikes or static discharge.

For an extensive discussion of system grounding, see the Sandia National Laboratories report, *Photovoltaic Power Systems and the National Electric Code: Suggested Practices* (2001). The PDF version is available at: <http://www.re.sandia.gov/en/ti/tu/Copy%20of%20NEC2000.pdf>.

### **Overcurrent Protection**

Although remote scientific research projects are unlikely to receive a visit from the Electrical Inspector, it is wise to include adequate circuit protection. Breakers and fuses serve to protect the equipment, provide safety, and allow for easier maintenance of the system. Moreover, these devices protect conductors from currents exceeding the rated ampacity. The NEC specifies the maximum overcurrent protection for each conductor size.

When the current exceeds the rated amperage of a breaker or fuse, the circuit opens and the flow of current ceases. Breakers are typically considered preferable, as they can simply be reset, whereas a blown fuse must be replaced. This necessitates having spare fuses on site. It should be noted that not all breakers are rated to handle DC. The arcing inherent in DC-type power systems will quickly burn out the contact points of a non-DC-rated breaker or switch. Specialized, DC-rated breakers are available from most suppliers of renewable energy equipment and should be used for main battery disconnects and other high-amperage applications. For smaller DC load protection, Square D “QO” series breakers are rated for up to 48 VDC and are widely available at a significantly lower cost.

Breakers are triggered by unequal expansion of a bi-metal strip as current flows through it and heats it up. In cold climates, the rated ampacity of a breaker can end up significantly lower than the current level at which it actually trips. Fuses are somewhat less affected by temperature extremes. Remember that overcurrent protection is really providing protection for the conductors or wiring in a circuit rather than the electrical device itself. If multiple sizes of wires exist within a protected circuit, the breaker or fuse must be sized to protect the smallest wire.

Although your project may fall outside the auspices of the NEC, there is still good reason to comply with the provisions it contains to ensure a safe and reliable system. The NEC requires every ungrounded conductor to be protected by an overcurrent device. This is the positive wire in a DC system and the black and red conductors in an AC system.

At a minimum, DC-rated overcurrent protection should be supplied:

- between the wind turbine and the charge controller,
- between the charge controller and the battery bank,
- between the battery bank and the DC load center,
- between the battery bank and the inverter (if present), and
- for each DC circuit originating in the DC load center.

At a minimum, AC overcurrent protection should be supplied:

- for each AC circuit originating from the AC load center.

### **Shorting Switch**

All wind turbines will require annual maintenance, or at the least a thorough inspection. Completely calm winds will rarely coincide with the timing of this operation. Obviously, one should never attempt to lower a pivoting-type tower or climb a fixed tower while the turbine blades are spinning. To stop or at least slow down the rotor, a shorting device can be employed. This device will disconnect the turbine from the rest of the system and short the windings of the generator together. Many manufacturers offer specific devices for this purpose. If not, then a triple-pole/double-throw (3-phase) transfer switch can be employed. This device is most commonly used to control multiple



power sources (such as two-engine generators or utility power and an engine generator) to a single load. It is easily reconfigured for use with a wind turbine and ensures that the load is disconnected before the windings are shorted. The drag imposed on the rotor by shorting the windings is fairly dramatic and will usually slow the blades to the point where maintenance can proceed safely. Other strategies can be used for safely shorting the windings. The manufacturer-supplied equipment or the 3-phase transfer switch illustrated below are recommended.

*Note: Some manufacturers offer a mechanical brake option, typically on machines of 2 kilowatts or larger. This can positively lock down the rotor to ensure safe maintenance but does not obviate the need for the shorting switch.*

## POWER CONSUMPTION (LOAD)

In a well-designed wind power system, there should be a relative balance of power. In other words, there should be enough power input to equal (and slightly exceed) the amount of power going out to instrumentation and other loads. Because the wind is a somewhat unpredictable resource, the margin must often be fairly large. In some instances, this will need to be calculated on an annual, rather than a daily or weekly, basis. A wind turbine or battery bank will ultimately lead to failure if it is too small, whereas the penalty for too large of a system is excessive cost, weight, and difficulty of deployment. Essentially, a researcher should always plan on oversizing the system to ensure reliability. How much the system is oversized and where the emphasis will lie (turbine vs. battery) are determined by the relative “safety margin” required and the amount of information available on wind speeds for the site. A 25% margin is usually considered normal, although a site with well-documented wind speeds and familiar system components might require only a 15% margin. For a relatively undocumented location and/or equipment, one might choose to run a 35% margin. For the purposes of this paper, the average value of 25% will be used. A couple of simple formulas help to define the relationship between the variables in the power balance:

$$\text{Power consumption} = (\text{instrument loads} \times \text{time}) + (\text{system losses} \times \text{time})$$

$$\text{Power available} = (\text{power input} \times \text{time}) - (\text{system losses} \times \text{time})$$

Power consumption can best be expressed in *watt hours* per day. A watt is the product of amps times volts:  $A \times V = W$ . (Amps or *current* can also be expressed as *I*.) Watt hours is the product of watts multiplied by hours:  $W \times \text{time} = \text{watt hours}$ . For a more in-depth discussion on electrical concepts, see <http://www.polarpower.org> > Technologies > Power System Fundamentals > Basic Electricity.

The best way to determine the average watt hours per day that your system requires is to first determine the cumulative amount of power used in a week, then divide by seven. As expressed above, the sum of all instrumentation and other loads should be padded by 25% to compensate for system losses.

### **Efficiency**

Clearly, the greater the efficiency a system operates at, the lower the overall power requirements will be. In designing residential renewable energy power systems, it is generally accepted that every \$1 spent on energy efficiency measures results in \$3 that will not have to be spent on additional power-producing equipment (i.e., a larger wind turbine, battery bank, etc.). Equivalent documentation does not seem to exist for this relationship in wind-powered research projects, but it is probably safe to assume that the ratio is equal to or greater than that expressed above. Small systems are relatively easy and inexpensive to deploy, whereas large systems are costly to build and often expensive and challenging to deploy. **Note: It is in the researcher's best interest to create systems that approach the problem comprehensively and that emphasize efficiency as one of the prime design criteria.** Too often, instrumentation is selected on other criteria such as familiarity, but running an experiment in a laboratory setting and having it run reliably in a polar environment are two dramatically different things. Oftentimes, there is comparable equipment available that can perform the same function at a fraction of the power requirement. Time used in reducing the power requirement is invariably time well spent.



Here are a few things to consider:

### 1. DC-Only Systems

- Most electronic equipment actually operates on DC power, despite the fact that most of the commercially available equipment is designed to plug in to AC power sources. This is because our electrical infrastructure, or grid, is an AC system due to its better transmission qualities. In essence, AC travels long distances better than DC. In a typical research project, however, distances are typically rather small, and DC may provide a more efficient power supply.
- Another advantage to a DC-only type of system is that it eliminates the inverter (DC to AC converter), which is one of the more costly and complicated items in a stand-alone power system. Although they are typically very reliable, inverters have certainly been known to fail. Keep it simple. The fewer components there are, the fewer places there are for a failure to occur.
- Consider that the battery bank that stores the energy produced by the wind turbine is a DC power supply. It is best to try to match the system voltages across the board (e.g., a 12-volt battery bank feeds 12-volt equipment), but this might not always be practical. It is generally easier to convert voltages downward (e.g., 24 volts to 12 volts), although step-up DC/DC converters are also available. Step-down DC/DC converters are very efficient and reliable. Design the system so that the primary system voltage matches or exceeds the highest voltage requirement in the system. System voltages should typically not exceed 48 VDC nominal. Higher DC voltages are suitable for some larger systems but require special equipment and present a much greater shock hazard.
- The actual DC requirement for a device typically intended for AC service is often listed on the nameplate information. It is often not very difficult to cut a device over to DC operation for dramatically enhanced efficiency. Essentially, the AC circuitry (rectifier and transformer) is bypassed or removed. A DC/DC converter may be required to match the component requirement, but this is still typically much more efficient. **Note: Familiarity with electronic equipment is a necessity!**

### 2. Logic Circuits

- The use of a programmable logic circuit, or PLC, allows for much greater control of the system. For instance, does every instrument need to be on all the time for sampling, or could some be quiescent for the majority of the time, waking up to take a sample once an hour? The power reduction can be dramatic when this approach is taken.
- Many pieces of equipment have this functionality built right in.
- Ladder-logic circuitry can often be employed to control when instrumentation becomes active. As the name implies, ladder logic simply requires one step to be completed (parameter satisfied) before the next step is initiated. This can often be accomplished with relatively simple circuitry.

### 3. Thermal Strategies

- All electrical equipment performs best within a certain temperature regime, and typically this is not  $-40^{\circ}\text{C}$ . PV panels are the exception: The colder it gets, the more efficiently they work. However, we are referring here to the balance-of-system components. Efforts made to control the internal temperature environment can yield great rewards. Batteries have less available power, lower voltages, and accept a charge with greater difficulty at low temperatures. On the positive side, the self-discharge rates are much lower as temperatures decrease. Excessive heat will rapidly deteriorate the performance of a battery bank.

Most electrical components have temperature specifications as well. If they are operated outside of those parameters, reliability and accuracy cannot be assured. Obviously, a system that can maintain a more steady-state temperature—or at least reduce the dramatic swings—will perform better than a system with no thermal strategy employed. Except for medium to large systems of greater complexity, it is typically an acceptable strategy to moderate temperature extremes rather than attempt to hold a system within tight temperature parameters.

To this end, batteries and other equipment should be housed inside enclosures. These enclosures should be well insulated. The inefficiencies discussed elsewhere in this section refer to energy that was not directly utilized to perform a function. The wasted energy is expressed as heat. In most polar environments, heat is a resource we can use. As mentioned earlier, wind power systems frequently utilize a diversion-type regulator and resistive dump load.

It should be the objective of every system designer to find ways to harness that otherwise wasted heat to modify the environment of the battery and/or equipment enclosure.

Controlling the thermal environment of any type of enclosure, be it a battery box or a home, really relies on just three things:

1. A thermal energy source
2. Insulation to prevent the heat from escaping
3. Thermal mass to moderate temperature swings

Methods employed vary widely from simple, passive systems to active systems that control temperature within tight parameters. How this problem is approached will be determined by how closely the temperature needs to be controlled and by the extremes of the environment the experiment is placed in.

The simplest systems rely on waste heat as the thermal energy source, insulation, and the thermal mass of the batteries to moderate the swings. The next step up might incorporate water (or a water-glycol mix) as additional thermal mass by actively heating it whenever there is available electrical energy in excess of system requirements. Hybrid systems utilizing engine generators can tap into an enormous amount of heat energy that would otherwise be wasted to the environment. Finally, active systems can use stored energy (typically a fossil fuel source) to create on-demand heat as required.

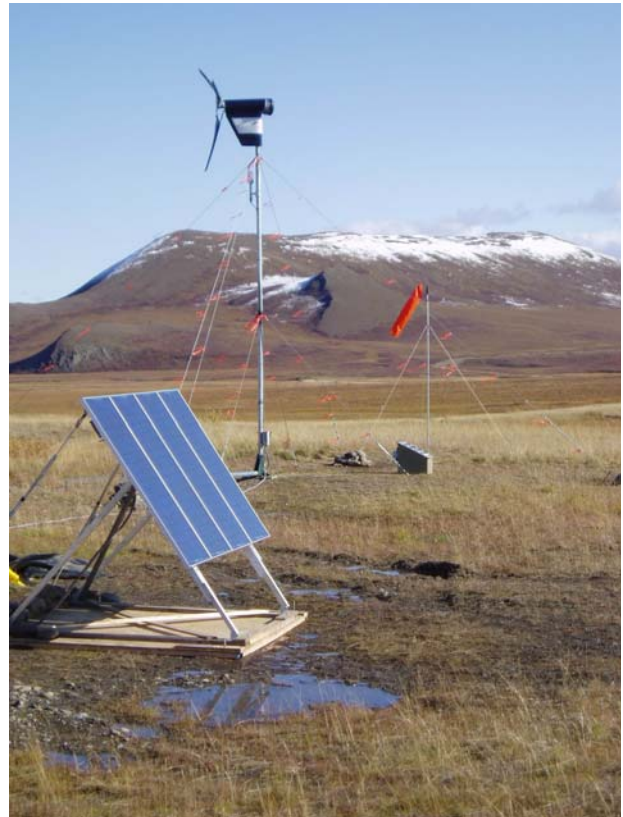
For more information on thermal strategies, see the general section on “Thermal Strategies” <http://www.polarpower.org> > Power System Fundamentals > Thermal Strategies.

## PUTTING IT ALL TOGETHER

### **Safety**

Working in remote, polar environments poses some inherent difficulties. Long hours in extreme cold, wind, and blowing snow can make an already difficult job nearly impossible. It is tempting in these conditions to relax one’s standards and take shortcuts to get the job done more quickly. However, this is exactly the time when one should slow down and move more cautiously. Good work habits are safe work habits and thereby reduce the risk of accident and injury and increase the likelihood of successfully completing a project.

In addition to the environmental hazards, installing and maintaining wind power systems bears many potential hazards. The potential for sustaining a mechanical injury is higher than with any other type of power system. The possibility of electrical shock, although low, does exist. Dealing with towers and rotors in high wind situations is difficult and potentially dangerous and should be avoided, even when braking systems are employed. Raising and lowering pivoting towers or climbing fixed towers pose distinct hazards, and appropriate measures should be taken. Fixed towers require the use of special climbing safety gear to facilitate installation and/or maintenance and to ensure protection in the event of a fall. Pivoting towers require special winches, or great familiarity with rope and pulley systems, to ensure that the tower can be raised and lowered safely in a controlled manner. Batteries pose numerous potential hazards. Although the shock hazard in a low-voltage system (< 50 volts) is relatively minor, batteries do have a very high short-circuit potential. Arcs can cause collateral damage by making a person jump



*A stellar day for RE.*

back in reaction. In severe short-circuit instances, batteries have been known to explode. The acid electrolyte can cause severe burns, and the installer must be prepared to treat immediately with baking soda and water. Charging batteries can release hydrogen gas, which is highly flammable.

A well-planned and organized work site will dramatically reduce the risks involved with wind turbine installation. Pre-wiring as much as possible and performing a “dry run” while still at the home institution ensures that everything works properly and increases familiarity with the system. All of this helps to ensure a safe and successful field deployment. For more on safety, see <http://www.polarpower.org> >Power System Fundamentals > Safety.

### **System Voltage**

Wind turbines are available in a range of voltages. For most smaller, autonomous systems, a 12- or 24-volt configuration will be optimal. These lower voltages pose a somewhat lesser electrical hazard and are closer to the operating voltages of equipment typically deployed for purposes of scientific research. Although 12-volt systems have fallen somewhat out of favor in the industry due to the larger gauge cabling required, for many science experiments, this is still the optimal voltage to utilize. When power requirements or longer distances require it, a 24-volt system will usually provide an adequate solution. For only very large systems with high power requirements or systems that need to run DC power for a substantial distance should one ever consider going above 48 volts. High-voltage DC poses significant safety hazards, and even most DC-rated devices are not rated for voltages above 50 VDC.

Batteries are modular and are typically available in 2-, 6-, or 12-volt ratings. The 2-volt cells are typically industrial-type batteries and are often already wired in series within an outer container. The 6- and 12-volt batteries are also composed of 2-volt cells, but they are molded into an integral unit. Most researchers will likely utilize 6- or 12-volt batteries. However, for higher power applications or instances where a very large battery bank is required to provide winter power for even low-power experiments, the 2-volt industrial cells can offer some significant advantages. Battery cabling can be expensive and time consuming, and often the footprint of a battery bank can end up being fairly large. Industrial cells are usually pre-configured in an outer container or a rack and utilize solid bars to interconnect a 12-volt string. Although the cells are typically rather heavy and must be handled individually, the finished bank can end up being much more compact and requires far fewer cable interconnections. Series/parallel connections are also possible and allow for increased amperage and voltage. **Note: It is very important to deliver and pull power from diagonal corners of the bank, thus ensuring equal loading of the system.**

## **INSTALLATION AND MAINTENANCE**

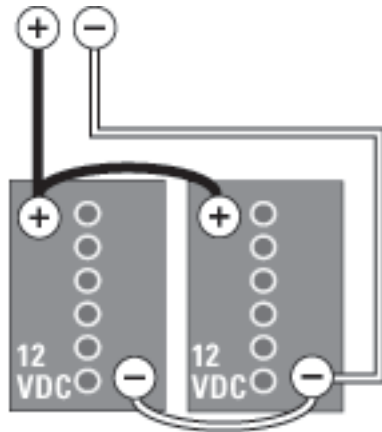
Installing a wind turbine in Polar Regions can be a tricky business. Unless the researcher has a lot of experience in this area, one should not attempt to install a wind turbine greater than 1-kilowatt output (a rotor 3 meters in diameter) without professional assistance. Most 50- to 400-watt turbines are fairly easy to install, largely because weights and tower heights are both lower. As the weight of the turbine and the height of the tower go up, so does the level of difficulty.

Wind turbine installation can be hazardous and risky in ideal conditions, and one is unlikely to find ideal conditions in the field. Here are a few cardinal rules:

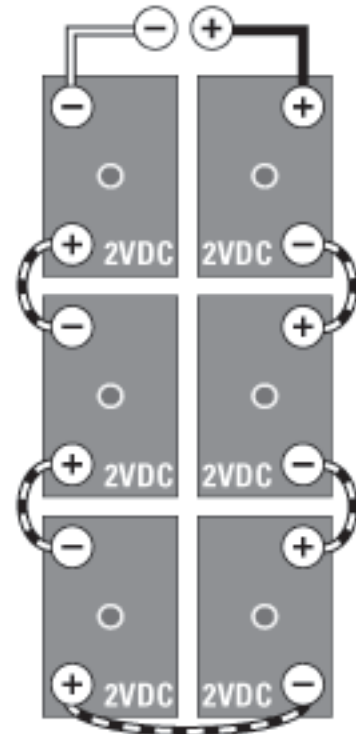
1. Plan out the installation thoroughly. These installations can be rather complicated, and one missing element can jeopardize the entire project.
2. Inventory all components, fasteners, conductors, electrical connectors, and tools. Have extras of certain items, such as thimbles, swedges, and/or cable clamps.
3. Record all of the model numbers and serial numbers of every component as you inventory. You may need to order components, and if the unit is on the top of a tower in the middle of Antarctica, matters are complicated slightly.
4. If possible, pre-assemble and erect the system at your home institution before heading out into the field. Problems almost invariably arise, and it is better to discover them when the hardware store is only a few miles down the road.



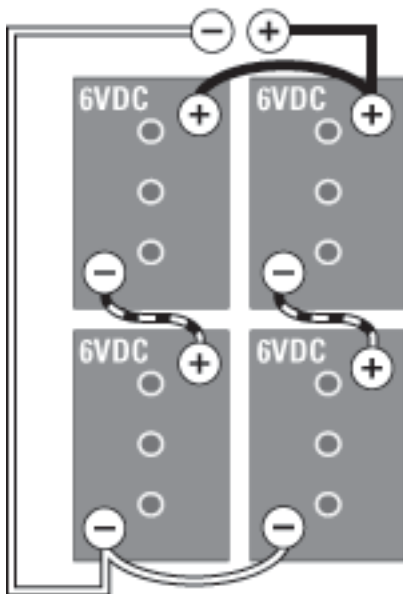
The drawings below illustrate some common series, parallel, and series-parallel configurations.



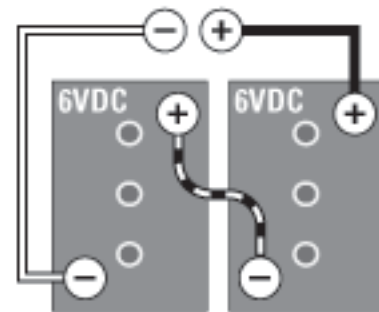
**12-VOLT CONFIGURATION**  
with 12-volt batteries in *parallel*



**12-VOLT CONFIGURATION**  
with 2-volt batteries in *series*



**12-VOLT CONFIGURATION**  
with 6-volt batteries in *series/parallel*



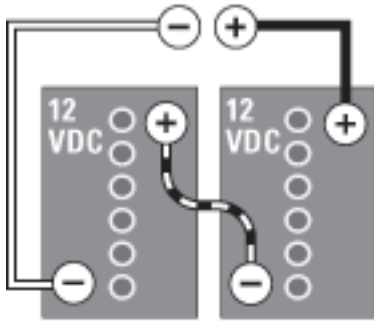
**12-VOLT CONFIGURATION**  
with 6-volt batteries in *series*

## 12 VOLT BATTERY CONFIGURATIONS

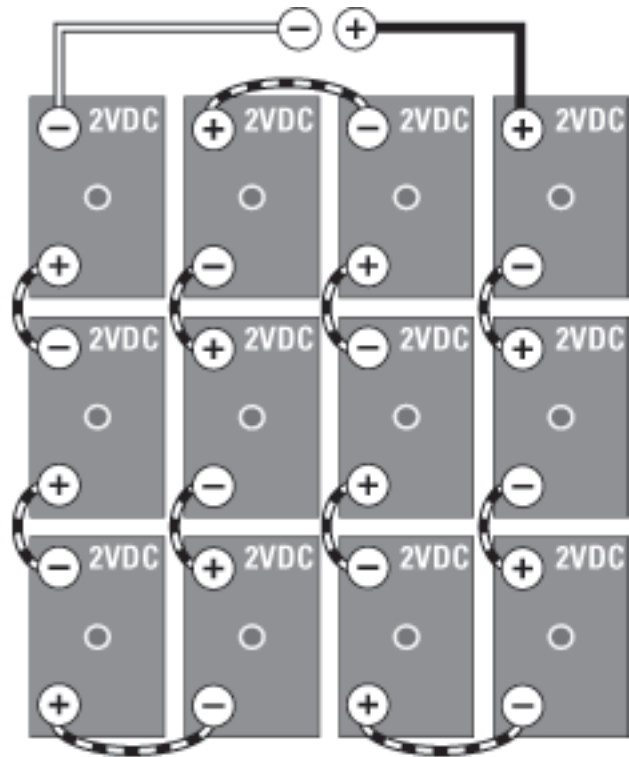
Image courtesy of Solar Energy International.



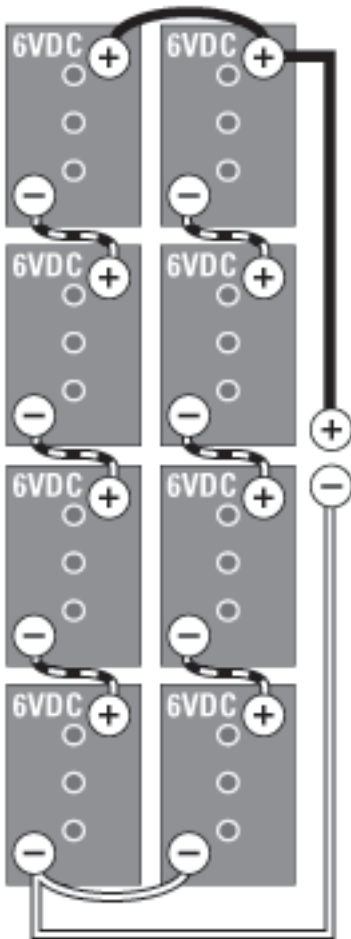
Image courtesy of Solar Energy International.



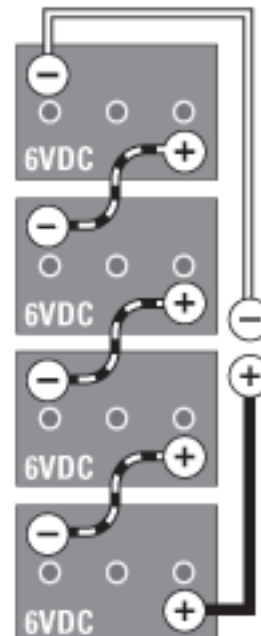
**24-VOLT CONFIGURATION**  
with 12-volt batteries in *series*



**24-VOLT CONFIGURATION**  
with 2-volt batteries in *series*



**24-VOLT CONFIGURATION**  
with 6-volt batteries in *series/parallel*



**24-VOLT CONFIGURATION**  
with 6-volt batteries in *series*

## 24 VOLT BATTERY CONFIGURATIONS



5. Erect the tower without the turbine before attempting the big event. It is lighter and easier to deal with. If something does go wrong, there is less to loose.
6. Keep your work area clean and organized.
7. Do not rush. Be methodical.
8. Never leave the job unfinished. If it becomes obvious that you will not complete the installation that day, then get to a solid stopping point and wrap it up. Assume that there will be a major wind event during the night and act accordingly.

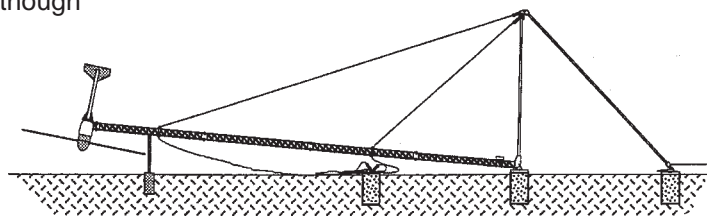
Erecting the tower is often the most demanding aspect of an installation. Each type of environment demands a different approach to setting anchors, establishing a base for the tower, and finally raising the tower. All environments bear one thing in common, however: They do not consist of the flat, loamy soil that all purveyors of tower kits seem to assume as a given. Boggy tundra soils do not hold earth anchors well. Permafrost requires specialized equipment, and snow and ice either accumulate or ablate away, neither of which is a good thing. Concrete is typically not an option, and conventional screw-type earth anchors often cannot be installed or, if they can be, will often fail to hold. Generally speaking, polar substrates are difficult to deal with, and what works fine elsewhere will fail here. The one exception is a nice solid rock outcrop upon which to place the tower and anchors.

Because of these difficulties, towers will almost invariably be of the guyed variety. In more temperate climates, three or four anchor points are used, and all the guy cables from various heights on the tower run to these anchor points. Four guys are preferable due to the reduced force on each individual anchor. However, if erecting a three-sided Rohn-type tower, then three guys will have to do. In the case of tilt-up pole towers, four guy cables are essential. When properly laid out, two slightly loosened cables can control the tower during the raising. These cables will control the tower on the x-axis, leaving the persons erecting it to worry only about the y-axis. When it reaches the vertical position, a third guy cable prevents it from continuing over center.

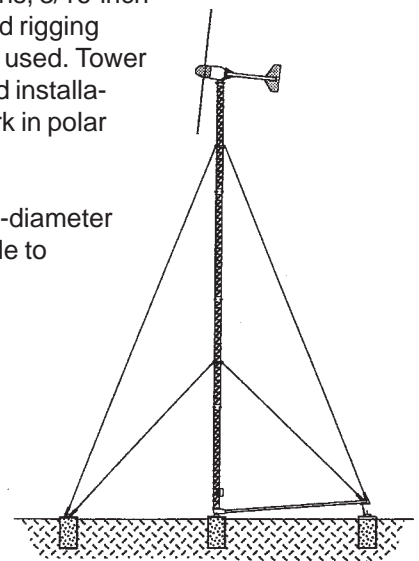
Another advantage of the four-guy system is that it reduces the amount of force on each anchor thereby making them less likely to pull out. Increasing the radius from the tower to where the anchors are placed also results in reduced force, as vector calculations demonstrate. In reasonably good substrates, the radius should be between one half to two thirds the height of the tower. In poor substrates, that radius should be increased to three quarters to the full height of the tower. In very poor substrates, such as bogs, each individual guy cable along the height of the tower should go to a corresponding anchor set the same distance in radius as the height, thus creating an equilateral triangle with the hypotenuse represented by the guy cable. For worst-case scenarios, extreme measures must sometimes be taken. Custom "deadmen" anchors and multiple anchors securing single guy cables are possibilities.

Steel cable or wire rope can be purchased by the foot or by the spool. For most small wind turbine applications, OD cable is more than adequate. For micro-turbine installations, 3/16-inch or even 1/8-inch cable may be adequate and will save a lot of weight. All associated rigging items (thimbles, swages, cable clamps, etc.) must correspond with the cable size used. Tower kits are available from a number of manufacturers, but these kits are geared toward installations in standard environments and will typically require a lot of modification to work in polar terrain. It is usually better to build your own rigging kit.

Take care in working with steel cable. It is possible to kink it, particularly the small-diameter cable, which lessens its working strength. If possible, roll the spool to remove cable to avoid putting twists in it. If swages are to be used in making connections, a special crimping tool will be required. Cable can be cut with bolt cutters, although special cable cutters tend to make more uniform ends, facilitating getting the swages over the cable.



Tilt-up tower Bergey



The length of the guy cables can be determined using the Pythagorean theorem:

$$\text{guy length} = (GR^2 + GH^2)^{1/2},$$

where GR is the guy radius and GH is the guy level or height above ground. Allow plenty of extra cable for sag and slight errors in the position of the anchors. Three lengths of cable will be needed for each guy level on a fixed tower; four lengths will be needed for a hinged, tilt-up tower (11).

Guy cables must always utilize thimbles where connected to the tower or anchor to avoid damaging the cable.

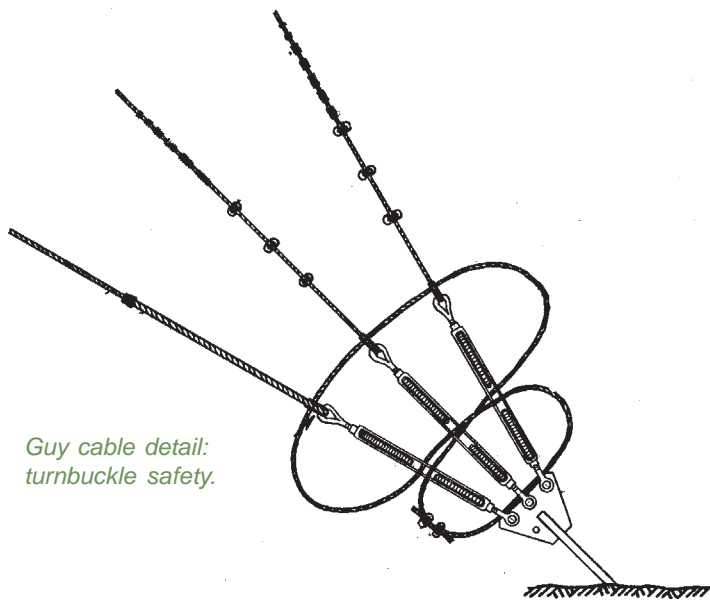
Thimbles are installed by twisting the ends past one another, inserting in the eye, and then back again. Shackles offer another alternative for attachment of guy cables. Wire rope clips (cable clamps) must be positioned properly for adequate holding strength. The saddle bears on the live end of the cable, whereas the u-bolt bears on the dead end or tail of the cable. For rough adjustment of cable tension, cable grips (pork chops) and a come-along can be used. Turnbuckles allow for fine adjustment of the tower and are recommended regardless of turbine size.



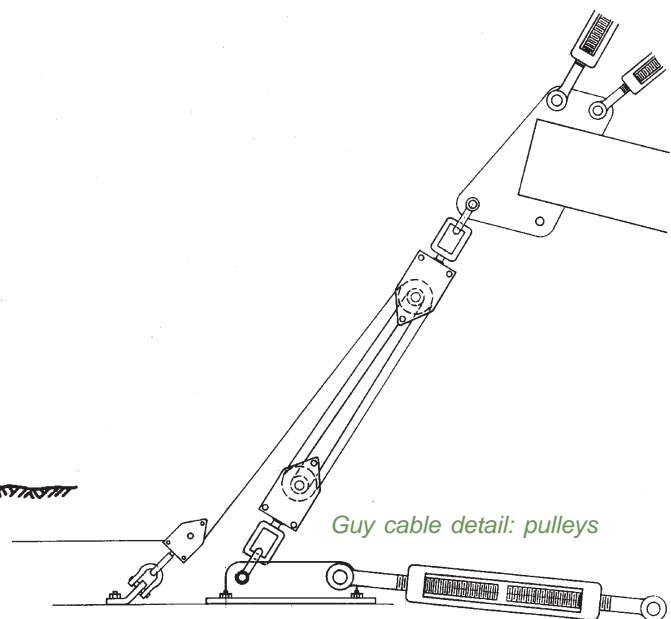
*Guy cable detail: thimbles*

For small wind turbine installation, tilt-up towers are recommended whenever possible. Hinged towers allow for the installation and service of the wind turbine on the ground. With the leverage advantage of a *gin pole*, these towers can be raised with a *griphoist* or a rope and pulley system—really the only viable options for deep field installations. This system is typically also the most cost-effective solution. Although this system is most widely used on pole-type towers, virtually any type of tower can be made to hinge at the base. For manual installations, consider utilizing a longer gin pole. The longer the gin pole, the greater the leverage advantage and therefore the less force required to raise and lower the tower. The weight of an extra section of thin wall tube is often more than compensated for by the advantage conferred in erecting the tower.

The main difference between installations in various environmental conditions is in what kind of anchor system is employed. Details on installations in some common polar substrates follow.



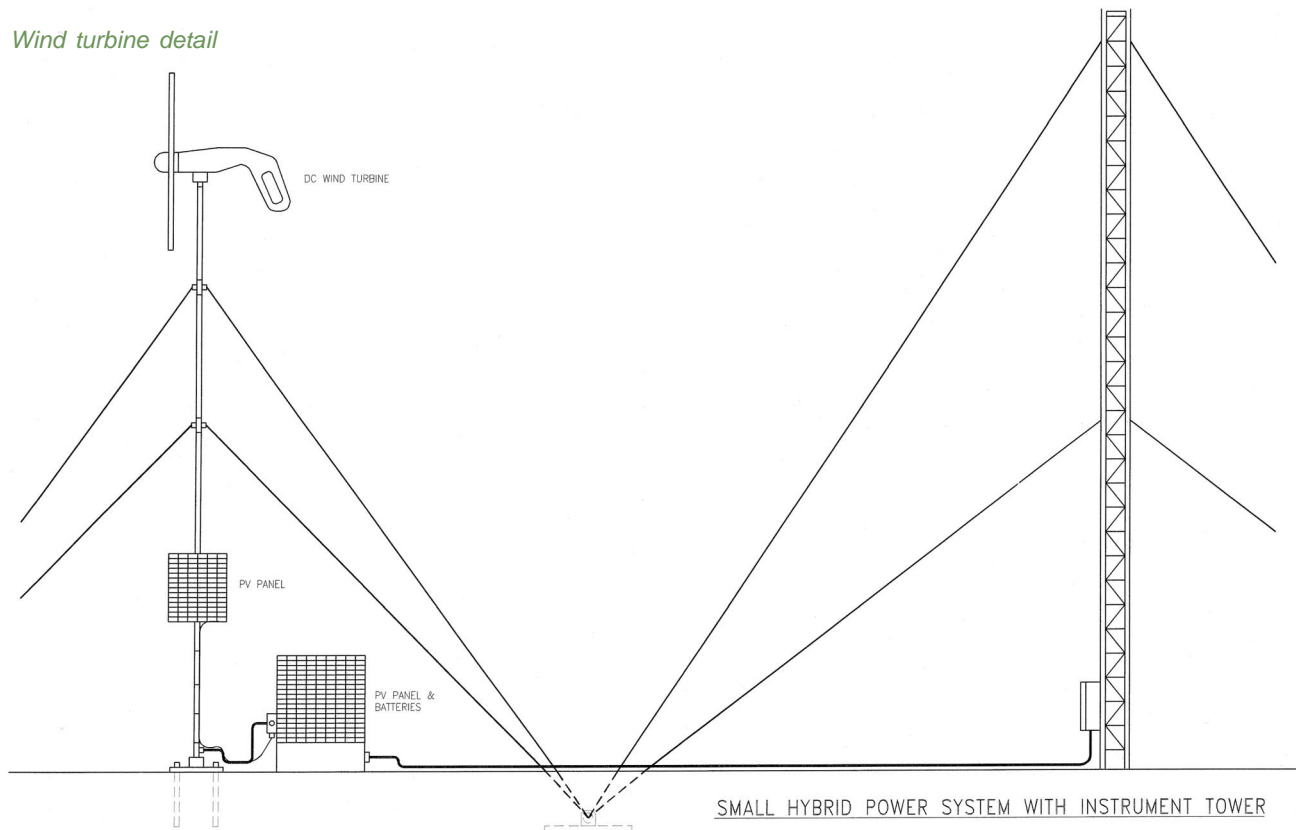
*Guy cable detail: turnbuckle safety.*



*Guy cable detail: pulleys*



Wind turbine detail



## Polar Substrates

### **Snow and Ice**

Snow and ice pose unique challenges but are actually among the easiest of substrates with which to work. Consolidated snow has good holding strength, and because it is permanently frozen, frost heave is not an issue. Due to snow accumulation or loss, tilt-up towers may not be the best choice in this environment. If a tilt-up tower is required, consider installing a base that extends above grade to the height necessary to still be above grade at the proposed end of the research project. This base could be a single section of guyed lattice tower with a solid steel plate bolted (not welded) onto the top. This plate then becomes the foundation for the base of a tilt-up tower. When the snow accumulation reaches the top of the lattice tower section and the research grant is extended another 5 years, the tilt-up tower can be removed and a second section of lattice tower can be bolted into position. Remember that the guy cables will need to be extended as well. There is no need to set new anchors, as the old ones are now so deeply buried as to be bomb proof. Guy cable extensions are acceptable as long as they are properly made using thimbles at the connection points.

In many cases, it may be simpler just to utilize a fixed tower in the first place. Guyed lattice towers should be placed on a solid foundation located several feet below grade. In most polar areas with permanent snow cover, 3 feet is adequate to ensure that heat transfer and resulting subsidence is minimized. This foundation can be as simple as a couple of pieces of plywood screwed together. The size of the base will vary depending on snow conditions and the weight bearing on the base. Larger turbines and taller towers require a larger (and more robust) base to bear the weight. Remember that as the wind attempts to push the tower over and the anchor holds it upright, that force is transmitted down to the base, attempting to push it further down into the snow. For turbines of 1 kilowatt or less, a 2-foot x 2-foot pad is typically adequate. If the tower is quite tall, consider a larger base and/or adding a steel plate on top to prevent the tower feet from pushing through the plywood. The base is secured from kicking out when the excavated hole is filled in.

Wood also works well for the anchors. It is light, strong, and does not transfer heat very well—all key considerations for deep field installations. Deadmen anchors can be made from 4-inch x 4-inch lumber or multiple-layer plywood plates similar to the tower base. A 4-inch x 4-inch x 4-foot deadman properly dug into well-consolidated snow creates a very strong anchor. A piece of 3-inch channel steel along the back can reinforce it even further. Again, be sure that the depth is adequate and that the “grave” rests under undisturbed snow.

If a larger turbine (> 3 meters in diameter), taller tower (> 50 feet), or a particularly high wind regime demand it, steel-reinforced plywood plates can be utilized. Properly constructed and installed, these make superb deadmen anchors. Something else will fail before these pull out.

Remember that if this is a snow accumulation zone, turnbuckles should be placed at the tower end of the guy cables. This makes adjustment a bit more difficult at first, but consider the difficulty of adjusting the turnbuckle if it were placed near grade. After several years of accumulation, one would have to dig down and find it before any adjustment could be made.

Common sense may lead one to assume that guy cables will loosen with time as the tower presses down into the snow. Strangely, the reverse is sometimes observed, with guy cables coming under increasing tension as the years pass. Also remember that tower installation will likely occur during the warmest time of the year; therefore, the guy cables are as expanded as they will likely become. In mid-winter, thermal contraction may render the guy cables too tight, placing undue stress on all components. Set the guys a bit loose. As a reference, a 30-foot cable span should have a slight but visible sag. Essentially, they should not be tight as a guitar string or so loose that they will suddenly come under tension as the tower is subjected to gusts.

A guyed lattice tower is assembled one section at a time using a tower-mounted gin pole. When one section is bolted into place, the gin pole is moved up the tower to raise up the next section and so on. The wind turbine is typically attached to the tower without the blades for ease of installation and safety. Top-mounted work platforms are available as an option and greatly facilitate tower-top installations. As always, all tower work should be performed only in reasonably good weather and with a full safety harness and fall protection system in place.

### **Rock**

Fortunately, setting anchors in rock in polar areas is no different from setting rock anchors elsewhere. Commercial anchors are available that will provide enormous holding power. Rotary hammer drills and special bits are required for boring the holes, which are also commercially available. It is wise to go to a specialty vendor for these items. See <http://www.polarpower.org> > Links > Vendors.

Be aware that uneven terrain poses some special challenges. On tilt-up towers, the x-axis (the non-tilting axis) must be reasonably level from side to side to allow the tower to tilt up and down properly. If a tower must be installed on uneven terrain, make sure the tower tilts down to the uphill side. This ensures that there is room for the gin pole to clear the earth on the downhill side. Of course, guy cable lengths will vary according to terrain.

### **Permafrost**

Setting a tower in permafrost can be challenging. In a tundra environment, a relatively small turbine and tower can utilize a floatation-type base that essentially rides on top of the super-saturated soil. This can be constructed similar to that described for a snow environment. However, add a hole in each corner to accept rebar “earth pins.” These are hammered through the holes in the base into the soft earth below and will adequately keep the base from kicking out.

Anchors are another story. Rebar driven into the ground like big tent poles will not last long. If permafrost is at a depth of 3 feet or less, some type of earth anchor will be required. Permafrost is both hard and resilient and therefore resists devices such as auger-type anchors, particularly since they will typically be driven by hand. Pre-drilling a hole to allow the auger to bite will sometimes work. One type of device that has proven to be reasonably effective is the product line from Foresight Products. “Duckbills” and “Manta Rays” are toggle-type earth anchors. They are

driven into the ground with a jackhammer or tractor-mounted device and then retracted via a hydraulic system that simultaneously sets the device and tests its pullout resistance. The polar researcher will typically not have access to any of these tools. What works reasonably well is to pre-drill a hole in the permafrost with an engine-powered earth auger to the maximum depth possible. This is often easier said than done, but it is possible. The anchor does not have to penetrate deep into the permafrost but should at least go in 10 to 12 inches. Gauge on the auger when you hit the frost (you will know), and then drill the hole 12 inches further. The earth anchor should then be driven into the hole and retracted as much as possible. A “Hi-Lift” jack can provide a lot of pressure to help toggle the anchor out fully. In some instances, the tower itself can be used to ensure that the anchors are fully set. If the anchor pulls out, it obviously did not toggle out properly. Try it again. Even without the hydraulic anchor-setting device, you can usually tell when you have it locked in. If in doubt, two earth anchors per guy can be utilized. These devices are available with either all thread or cable attachments. Cable seems preferable in most instances. **Note: It is essential that the system be put into place at the peak of the summer thaw. If placed too early in the summer, the melt layer may extend down to where the anchor is deployed thus dramatically reducing its holding strength.**

Properly set anchors in permafrost are actually quite resistant to pulling out. This may be as much due to them freezing in place as any inherent quality of the soil. On multi-year projects, be sure to annually gauge the depth of the thaw. Due to global climate change, the melt layer in many areas is growing deeper every year. Heat transfer down the steel cable could exacerbate the problem. Anchors that are solidly placed in permafrost now may not be 5 or 6 years into the future. Hence, it may be necessary to periodically set new anchors.

### **Bogs**

In boggy or otherwise super-saturated soils where the permafrost level is too deep to hit, other types of earth anchors with larger bearing surfaces will need to be employed. These environments are the most difficult in which to establish satisfactory anchoring systems.

“Anchor holding capacity also decreases as the moisture content increases. Creep can be troublesome in saturated soils because the soil particles become fluid and tend to flow around the anchor. Water also increases the buoyancy of the anchor. The holding capacity of anchors can be reduced 50 percent in wet soils” (12). Assuming an even lower anchor holding capacity of boggy arctic soils is recommended.

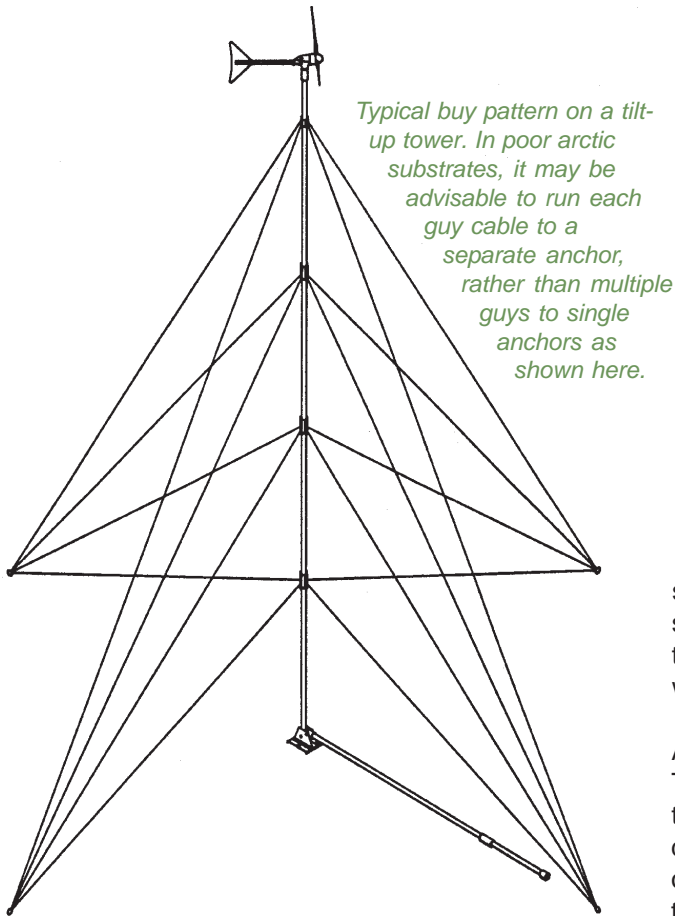
In some instances, deadmen anchors similar to the type described for snow installations will work. However, placing them can be difficult, and frost heave will likely be an issue in the future. Regardless of the anchor method selected, in marginal areas like this, it is typically best to run each guy to one or more separate anchors rather than running multiple guys to a single anchor. The reasoning is obvious: Spread the load. Similarly, in very poor substrates, one may wish to increase the guy radius even beyond the height of attachment on the tower.

The examples above are not an exhaustive analysis of all polar environments, nor are all the methodologies for coping with them. The above discussion is presented solely as a general approach. The polar researcher must often be inventive and resourceful in getting a wind power project up and running.

### **Raising a Tilt-Up Tower**

Two people can easily handle the operation of raising a 30-pound micro-turbine on a 20-foot tower. It is still necessary to first set anchors and attach guys for a dry run without the turbine attached to ensure that there are no snags. Following this, simply bolt the turbine on, run the conductors, and raise up the tower.

Raising a 200-pound turbine on a 40-foot or greater mast is a significantly more involved operation. Specialized equipment will be required, and proper layout, planning, and coordination are key. Once the tower is assembled on its base, anchors are securely installed, and three of the four guy cables are installed (with turnbuckles loose), the tower can be raised without the turbine. Given a gin pole half the length of the tower (e.g., a 20-foot gin pole on a 40-foot tower), it is possible to raise the tower and turbine with a simple rope and pulley system. A 3:1 reduction system will work with turbine weights up to 100 pounds. For heavier turbines, a 6:1 reduction system will be neces-



AWP installation at Beaufort.

sary. If you are familiar with using these rope and pulley systems, it minimizes the amount of equipment required, and the installation is quick and expedient. If you are not familiar with how to rig these systems, now is not the time to learn.

A better choice for most people would be to use a griphoist. These hand-operated devices do not utilize a spool to wind up the lifting cable but pull it directly through the body of the device. The griphoist is attached to the anchor point on the operating end, whereas the bitter end attaches to the top of the gin pole. It is then merely a matter of working the lever until the gin pole is down and the mast and turbine are up.

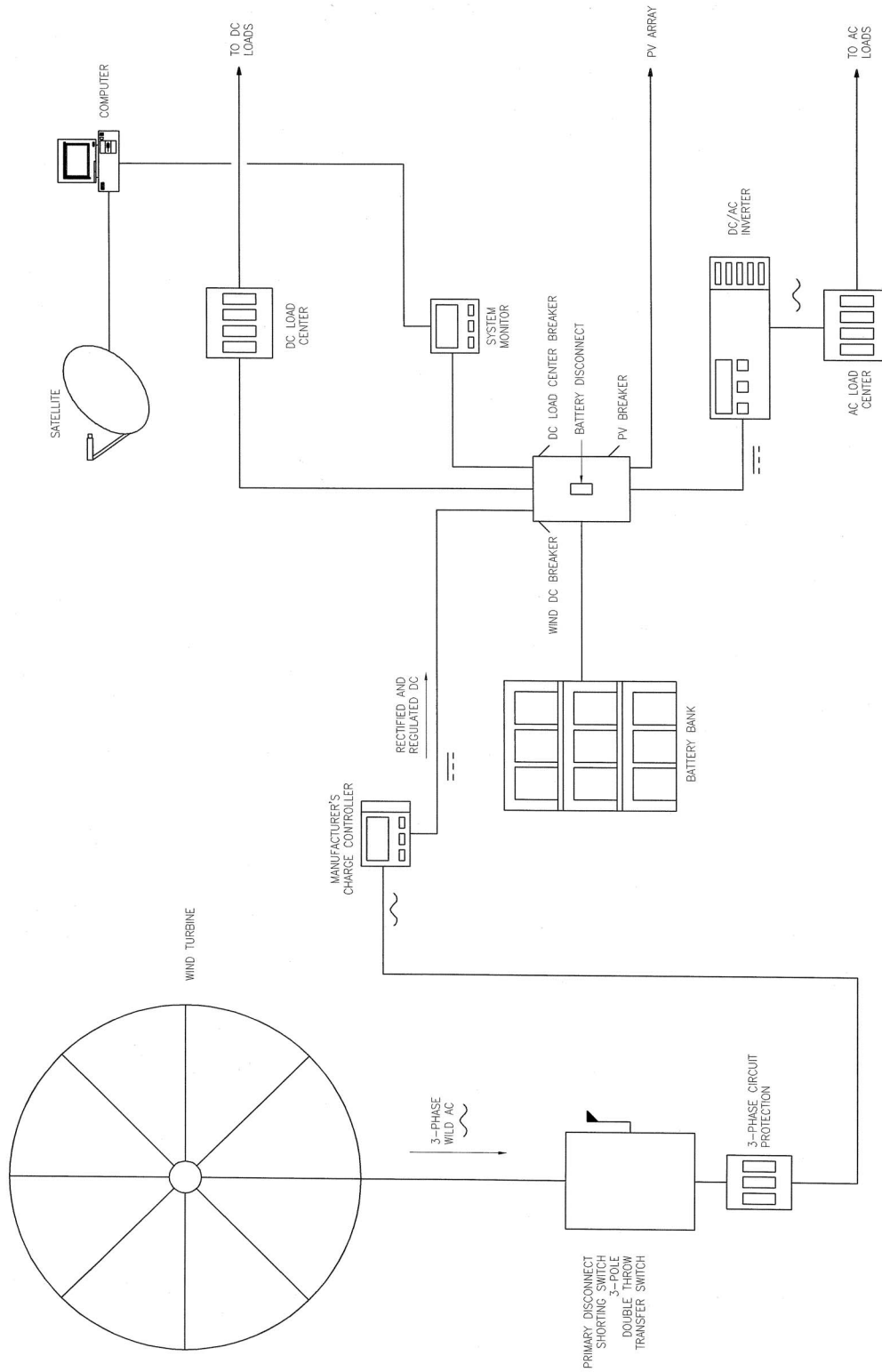
These tools are available from a 700-pound pulling capacity all the way up to 8,000 pounds—far more than the researcher should ever need. The cable must be ordered at the same time as the tool. Make sure to have more than enough cable to span the distance, and do not utilize guy cable.

The best strategy for raising a tower is to have four people on hand to help. One person will operate the griphoist. Two people will assist with the initial lift of the tower from the turbine end and then move away to the sides (well out of the way in case something goes wrong). They will also help with the guy cables once the tower is vertical. The last person is standing back, watching it all, and calling the shots. The tower-raising crew should be viewed as a team, and the person calling the shots is the team captain. Towers can be raised with as few as two people, but it is both more difficult and not as safe.

### Electrical Installation

The best turbine in the world does not serve much purpose if the electrical connections fail. It is imperative to ensure your electrical installation addresses the following areas:

1. Electrical connections must be clean, solid, and well insulated. Crimp or compression fittings are the best, followed by mechanical lugs and then split bolts. Wire nuts should be avoided for stranded wire connections. Regardless of the method used, be sure that the connections are very well insulated. Split bolts in particular have sharp edges and have been known to wear through insulation, particularly when subjected to vibration.



SCHEMATIC FOR WIND/PV HYBRID SYSTEM



2. Use conductors rated at or above the maximum amperage the turbine can produce. Undersized conductors between the generator and the load can lead to excessive line loss and subsequent poor performance. Most wind turbine manufacturers will specify a conductor of a given size for a given distance. For a discussion of Ohm's law and how it relates to voltage drop in conductors, see <http://www.polarpower.org> > Technologies > Basic Electricity. Also see the "Voltage Drop in Conductors" charts.
3. Circuit protection must be provided for all conductors. Breakers and/or fuses also allow various components of the system to be isolated thereby facilitating installation and maintenance.
4. Mechanical protection of conductors is essential. When hanging conductors inside the tower, use a strain relief appropriate for the type of wire utilized. Braided wire nets work well on most types of cable. Suspend this net at the top of the tower where the connections are made.

Provide protection for the conductors for the run from the tower (breakers or disconnect) to the charge controller at the battery bank. Most researchers opt not to trench in this line. Most will find that digging the anchors already provides sufficient opportunity to study soil composition. For low-output micro-turbines with relatively short runs, SO or SOW cord may be adequate. For all other installations, conduit or waterproof armored cable will be required.

Flexible "liquidtight" conduit is available in a wide range of sizes and provides a good level of protection against the weather and curious animals. However, for arctic researchers, no level of conductor protection is adequate for deterring a really determined bear. If you are in an area with a lot of bear activity, consider trenching in the line.

5. *Surge protection is important in areas at low enough latitudes to experience lightning. Grounding the tower and conductors (see section on grounding above) provides a partial solution;*

*surge arrestors are the other necessary component. Surge arrestors provide a path to the ground when a high voltage spike exists in the conductor. This can save not only the wind generator but also sensitive electronic instruments. However, it is not foolproof, particularly in most polar environments where adequate grounding is hard to come by.*



*Proven turbine lowered for maintenance.*

## Maintenance

Most small wind turbines require very little maintenance. An annual inspection is usually adequate to ensure that things are in proper working order. Although a cursory walk around the tower may be adequate, climbing the tower to carefully inspect the turbine (or lowering the tower in the case of a tilt-up design) will potentially reveal problems not evident from a distance. Disconnect the power and short the windings if equipped with a shorting switch prior to climbing or lowering the tower.

All fasteners should be checked for tightness and wear. If guy cables have become a bit loose, the anchors may have settled in. Tighten the turnbuckles accordingly. If guy cables are very loose, it is possible that frost heave or some other problem exists, and more dramatic corrective actions will be required.

Slip rings and brushes should be inspected for wear or poor conduction. A resistance check with a multimeter is a more definitive test than a visual inspection. Slip rings and brushes can be cleaned with fine emery paper or a pencil eraser if necessary. Check all the electrical connections to ensure nothing has loosened and insulation is intact.



Check the leading edge of the blades (particularly wood and fiberglass) for nicks or abrasion. Snow can be quite abrasive. Some blades have edge tape that can be replaced if there is wear evidenced. Take the rotor in hand and give it a good wiggle to check for excessive bearing play. Rotate the rotor and feel and listen for anything unusual. A slight notchy feel is normal in permanent magnet generators. It is the resistance of the magnets passing the windings. Most small turbines use sealed bearings that require no service, but a few have grease zerks in a few key locations. Use grease rated for low temperatures, and do not use too much.

A quality wind turbine properly installed and maintained should deliver years of reliable performance. Depending on the environment and the system design, wind power can provide all or a portion of a research project's power requirement with a high degree of reliability and relatively low maintenance. Combined with PV in a hybrid system, wind power can make year-round research possible in many of the polar Regions. It is an *environmental* power system, utilizing renewable energy from the environment, while doing no harm to the environment—a win/win scenario.



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\*There were many other Internet sites perused in the writing of this paper—too many to mention.



### Suggested Reading

The best all around reference on the subject of wind power is Paul Gipe's book, *Wind Power: Renewable Energy for Home, Farm, and Business*. I have quoted from Mr. Gipe's book liberally throughout this paper, but there is a lot more detail to be found in this nearly 500-page reference.

Special thanks to Paul Gipe and Chelsea Green Publishing Company for allowing me to use many graphics from the above publication.