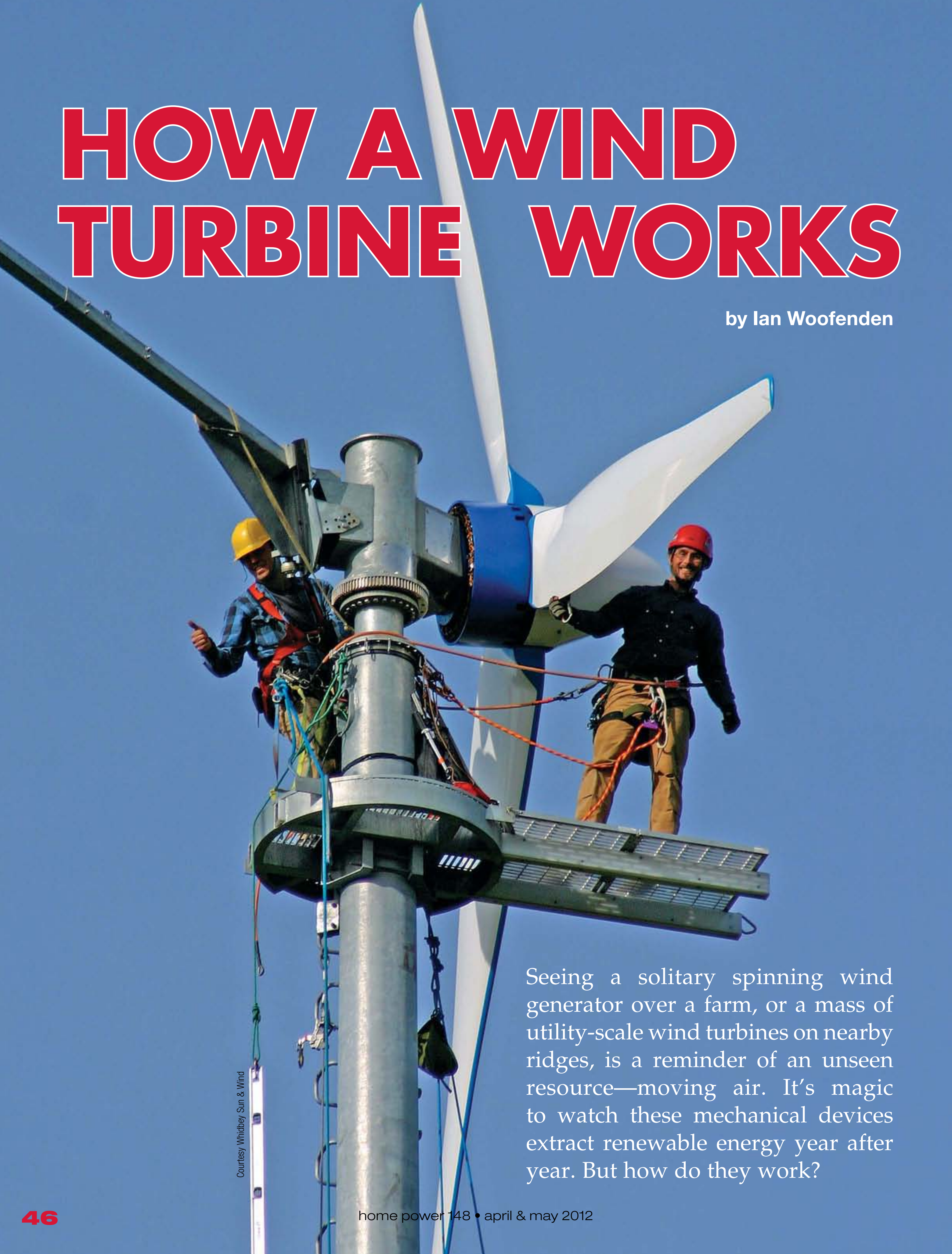


HOW A WIND TURBINE WORKS

by Ian Woofenden

Courtesy Whidbey Sun & Wind

Seeing a solitary spinning wind generator over a farm, or a mass of utility-scale wind turbines on nearby ridges, is a reminder of an unseen resource—moving air. It's magic to watch these mechanical devices extract renewable energy year after year. But how do they work?

Let's follow the energy flow, from the wind itself to electricity in your home, your batteries, or the grid. This article will help you understand the basic principles, components, and functions involved in a wind-electric generator.

What is the Wind?

Wind is created by differences in air pressure—globally, regionally, and locally. Uneven heating of the earth, water, and air create high and low pressure areas, and the air moves to equalize the pressure, moving from high- to low-pressure areas. The earth's rotation also affects the wind (the "Coriolis effect"), especially near the equator.

Local geographic features direct, intensify, diffuse, and otherwise influence the wind, with a variety of effects, such as the increase in wind speed over a ridge, or the up-/down-valley phenomenon we see in mountainous areas.

Remembering that wind is a *moving mass of air* can help you understand the physical demands of capturing it. Imagining this invisible resource as a colored mass can help you understand how hills, valleys, trees, buildings, and wind turbines interact with it.

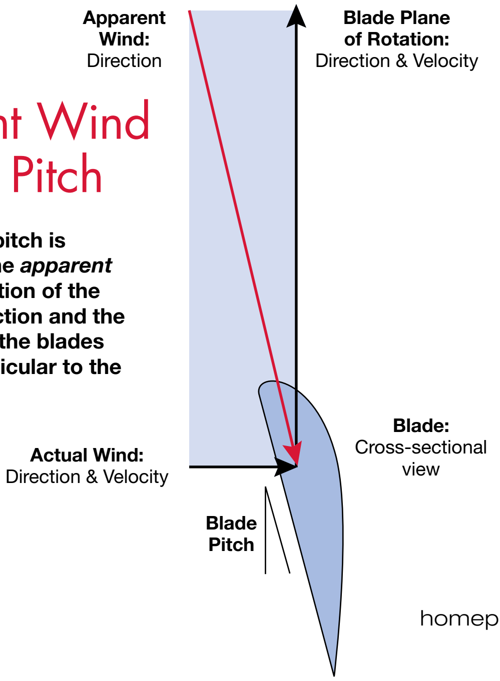
Aerodynamics—Capturing the Wind

To capture wind energy, we have to stick something up into the wind that will convert the horizontal flow of moving air into some sort of usable motion. To pump water, we might want a vertical, reciprocating motion, but to make electricity, we need rotary motion.

The simplest conversion might look something like your basic anemometer—a series of half-cups (imagine half of a ping-pong ball) sticking out from a vertical shaft, and being pushed around by the wind. This is an easy way to make a shaft spin, but not the most efficient way to capture the energy in moving air. This strategy uses what we call "drag"—the wind is dragging the collector with it, and the device cannot go faster than the wind itself. The back side of the rotor is moving against the wind, which slows it down—so the efficiency is inevitably very poor compared with other methods.

Apparent Wind & Blade Pitch

Optimum blade pitch is determined by the *apparent wind*: a combination of the actual wind direction and the wind created by the blades rotating perpendicular to the actual wind.



An anemometer is a drag device that can't spin any faster than the wind is moving. The upwind cup hinders it even further. Only through calibration does it register accurate wind speed. Drag devices are inefficient collectors of wind energy.


© iStockphoto.com/pcross

Most successful wind generator designs rely primarily on another physical phenomenon—"lift." We see this property in airplane wings, kites, sailboats, and other devices that use moving air to direct mechanical parts in a direction other than the wind direction.

The most common (read "most established, successful, and engineered") wind generator designs use two or more blades (usually three) on a shaft that turns on a horizontal axis (parallel to the ground). We call these "horizontal-axis wind turbines"—HAWTs. It may seem counterintuitive that these work, because the blades are spinning at roughly right angles to the wind. This works because the design of the blades relies mostly on lift, not drag. Once a wind turbine is spinning, the wind experienced by the front edge of the blade (called "apparent wind") is a combination of the natural wind direction and the wind created by the motion of the blade itself.

Determining Wind Speed

Figuring out what your wind resource is and the best place for a wind generator is vital and difficult. Without a reasonable estimate of the average wind speed at "tower top" (the height at which the turbine will sit), you'll be making a wild guess about the production of your wind generator. Estimating wind speed is much more complicated and volatile than solar energy predictions, since the resource varies dramatically between rooftop (where it is almost always negligible) to above the trees (where it may be worth capturing).

Short of a full-blown wind study—which is often hard to justify financially for residential sites—two primary resources are often used. First is wind mapping, which *might* give you reasonable data if you have the expertise to interpret it. Second is already-collected local data, which also needs interpretation, and can range from definitive to useless, depending on the source and duration.

See Access to learn more about wind site analysis. Meanwhile, remember that knowing the average wind speed on your site is crucial to predicting wind-generator energy production. And small differences in the wind speed can make a big difference in production. For instance, the energy available in a 12 mph wind is about 70% greater than the energy available in a 10 mph wind.

Courtesy Ian Woofenden

After reading this article, you'd be able to identify this as a three-bladed, upwind, direct-drive, permanent-magnet, side-furling wind turbine if you saw it in action.

Many different blade designs and configurations have been tried over the years, and most don't work terribly well. There are good reasons that support the successful designs. Look around—from sailboat wind generators to utility-scale machines—and you'll see the results of decades of engineering development. More information on aerodynamics can be found in many places. Hugh Piggott's book, *Windpower Workshop*, offers technically accurate, concise explanations.

Limits to Wind Energy

Wind is a *cubic* resource. The power available in the wind increases as the *cube* of the wind speed. If we shovel gravel twice as fast, we get twice as much gravel. If the atmospheric heat engine shovels moving air twice as fast, we get *eight* times as much energy (2^3, or 2 × 2 × 2).

This helps us understand wind generator design and siting. At the low end of the scale, it's important to know that anyone making significant performance claims at, say, 4 miles per hour is either clueless about the physics of wind or trying to pull the wool over your eyes. Do the math: Four times four times four is 64; 10 times 10 times 10 is 1,000. There just isn't very much energy at very low wind speeds. A wind generator doesn't start doing much until at least 10 mph.

On the other end of the scale, it's important to remember the forces we are dealing with. Forty times forty times forty

Bust a Myth!

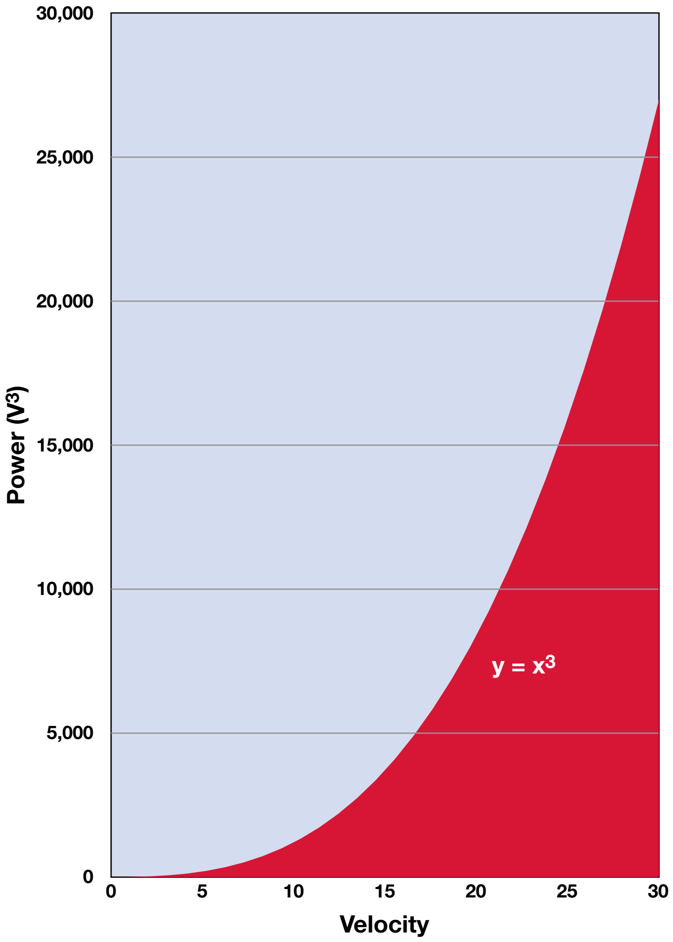
Are you wondering if the claims of a wind generator manufacturer, designer, or salesperson are legitimate or realistic? Apply a simple, generalized formula to get an idea of whether you're listening to a shyster or a reliable source.

Take the average wind speed used for the claim, cube it, divide it by 240, and that will equal the approximate kilowatt-hours (kWh) per month per square foot of rotor, at the Betz limit. Cut that number in half and you'll have a good number for a well-designed residential turbine.

For example, in a 9 mph average wind speed, a turbine operating at peak theoretical efficiency (the Betz limit) would give you 3 kWh per month per square foot of collector area [(9 × 9 × 9) ÷ 240 = 3]. If someone is claiming that a 15-square-foot turbine will deliver 90 kWh per month, they are claiming twice what is physically possible, and about four times more than the best turbines on the market.

For a different method that comes to similar conclusions, see Mike Klemen's page at www.ndsu.edu/ndsu/klemen/Perfect_Turbine.htm

Power as a Cube of Velocity



is 64,000. That's 64 times more energy than a 10 mph wind carries. You can see why wind turbines worth buying will protect themselves (govern) at 25 mph to 30 mph, shedding the rare high winds so they can stay alive for the next reasonable wind.

So there's a practical limit to how high of winds a wind generator is designed to capture. There's also a physical limit of how much of any wind you can capture. The Betz theorem states that you can only harvest a maximum of 59.3% of the wind before any attempt to take more will decrease what you get.

Think of it this way. A knife blade sticking up will take almost no energy out of the wind (only a little, due to friction). On the other end of the scale, a brick wall will try to take all of the energy out of the wind, blocking its path completely, but it won't turn any of it into useful motion. In the first case, the wind just passes by the "collector." In the second case, the wind backs up behind the collector, slows down, goes around, and just doesn't do any useful work.

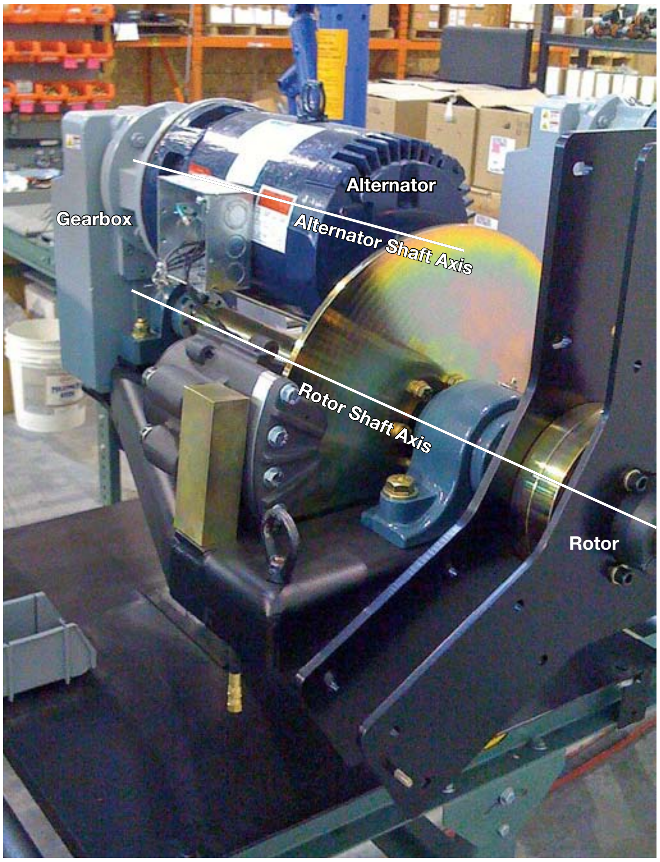
Somewhere in between, there's a sweet spot where we can capture some of the energy in the wind without slowing it down too much. We need to allow enough moving air through the collector to ensure adequate flow, and not back up too much wind against our collector, diminishing the return. Betz says that the maximum is about 60%. In real-world applications, a well-designed, modern utility-scale turbine might hit 50%, while residential turbines fall more in the 20% to 40% range.

Mechanical Transmission

Once we've taken our portion of the energy of that moving air and turned it into spinning motion in a shaft, we still need to spin the alternator. That shaft is spinning in a certain speed range, generally peaking at 150 to 900 rpm, depending on the machine's size and its design. (Low-rpm machines capture the same amount of energy from the wind as faster-turning ones, but the slower pace incurs less wear and tear and makes less noise.)

We can use a generator that works in the same speed range as the spinning shaft coupled to the blades (called the "rotor"). These are "direct-drive" machines, and they are the simplest and most efficient, *if* the blades and generating device are well-matched.

In some cases, a gearbox is warranted, to increase the shaft speed from the blades to a higher shaft speed for the generator. On home-designed machines, this is sometimes a relatively inefficient belt and pulley arrangement, which will waste a lot of energy. On manufactured machines, a gearbox is used to increase the rpm for the generator. A gearbox adds to the mechanics of the system, which means more wear and maintenance—regular oil changes and, eventually, gear replacement. But it may be a worthwhile trade-off—if you have a good wind resource—to get good matching and for using conventional and economical generators, designed for higher speeds than we want our blades spinning. (Larger-diameter blades need to spin slower so they don't self-destruct from centrifugal force.) Although mostly we see direct drive in home-scale turbines and, historically, more gear-driven utility-scale machines, more home-scale wind generators are using gearboxes.



Ian Woofenden

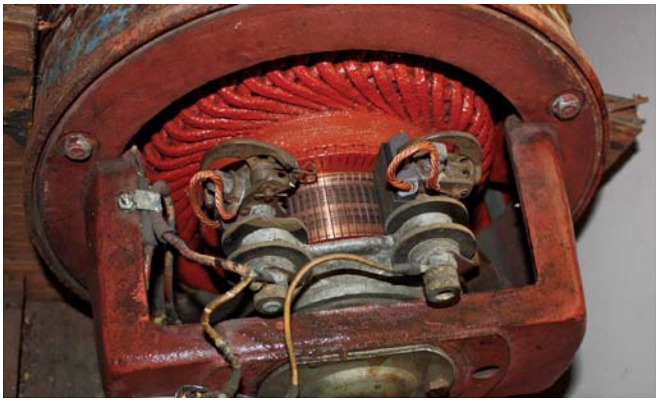
In some cases, a gearbox is necessary to optimize blade/rotor rpm with alternator rpm (also note this turbine's large disk brake).

Generating Devices

A generator or alternator moves magnetic fields past wire coils or vice versa, which makes electrons move in the wire. You may remember doing some science experiments as a child that showed this—it's not hard to measure voltage while waving a magnet past a loop of wire.

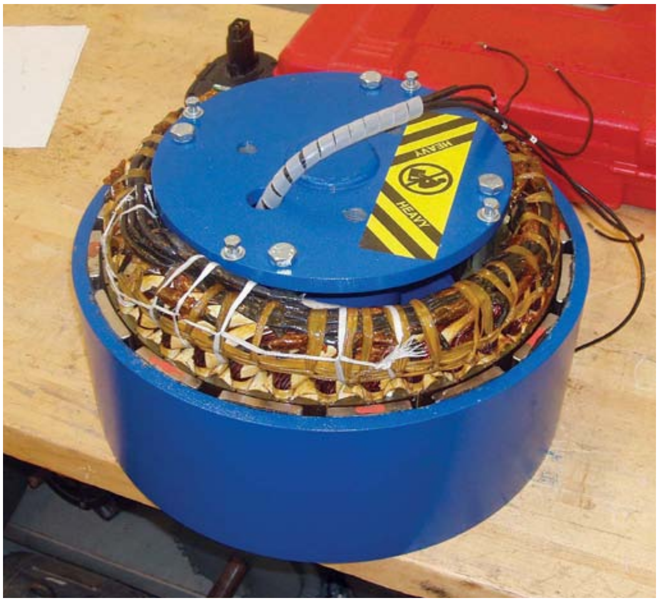
With generators, the goal is to move *lots* of magnetism past *lots* of wire to move *lots* of electrons. In one way or another, this is what generating devices are doing. There are three primary configurations, each of which has its own permutations and variations.

Wound-field alternators have a set of copper coils that are typically fixed (the "stator")—these are the coils we tap to harvest the electrical energy. They have another set of copper coils that are an electromagnet, and these coils typically spin past the fixed coils. These alternators are not very common today—we find them mostly in older designs. However, if they are well-designed, the magnetism ("field" or "excitation") can be very well matched to the wind speed. This means that the loading of the alternator can be matched with the available wind. One drawback of this design is that some of the wind energy is used to induce magnetism, so that energy is not available to make electricity.

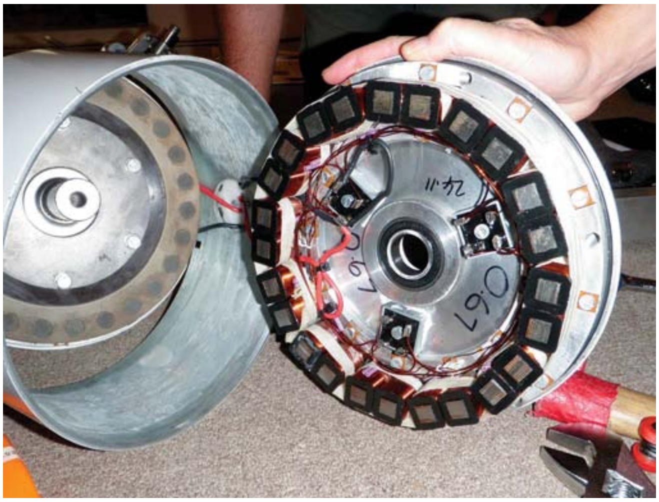


Courtesy Benjamin Root

This old Jacobs field-wound alternator requires brushes to supply energy to the electromagnetic field on the spinning rotor.



Permanent magnets on the outer rotor allow a simple brushless design. The windings are mounted on the inner immobile stator.



Courtesy Ian Woofenden (2)

This axial PM alternator has magnets on its rotor that spin past stationary coils face to face.

Permanent-magnet (PM) alternators follow the principle of moving magnetism past copper coils, but use permanent magnets—metallic materials that have stable magnetic properties. Older turbines use ferrite magnets; newer machines tend to use magnets of neodymium, a strongly magnetic material found primarily in China that commands very high prices.

PM alternators can be configured in a variety of ways, with coils spinning around magnets, magnets spinning around coils (most common), or in "axial" designs where the magnets and coils face each other in a disk-like arrangement, and the magnets typically spin.

Most home-scale wind turbines use PM alternators, which are simple, reliable, and economical. One minor drawback is that the magnetic strength is fixed, and not optimized for maximum power production at each wind speed. But lately, wind electronics engineers have been experimenting with voltage converters that adjust the balance between wind energy in and loading/generation, which overcomes this drawback somewhat to maximize production.

Induction generators use a cage, or conductive bars, spinning relative to groups of coils. A rotating magnetic field is created by feeding the stator coils with alternating current from the grid. This field interacts with the cage in the rotor to produce currents that make an opposing magnetic field, setting the rotor in motion. If the rotor is forced (by the wind) to turn faster than the magnetic field produced by the grid, then instead of drawing power, the device sends energy out to the grid.

These "generators" are the same as induction motors, and can be powered up by applying an electrical source to them. This is used in utility-scale and some home-scale machines to spin a turbine up to speed when the sensors and electronics show that there's enough wind to capture. Once the "motor" is going, the wind applied to the blades then pushes it beyond the amount of energy used just to generate energy.

One beauty of induction machines is that they need no inverter to connect to the utility grid. Electronics are necessary to facilitate and safeguard the connection, but the equipment is simpler and less costly than the inverter needed when you connect a wound-field or PM turbine to the grid.

Tail & Yaw

A wind generator needs to face the wind so that the blades are oriented to capture the wind efficiently. Home-scale horizontal-axis wind generators have a "yaw bearing," which allows the wind generator to swivel and face the wind—from whatever direction it is coming. This turning is called "yawing."

Yawing can be either active or passive. Larger home-scale machines and most utility-scale machines are active yaw, using motors and gears to turn the machine head around to face the wind, with wind vanes sensing the wind direction. Most home-scale machines have passive yawing, which uses the structural design of the machine to orient it into the wind.

Courtesy Ian Woofenden

Brushes transmit electricity from a yawing turbine down a stationary tower without twisting wires.

Courtesy Endurance Wind Power

Courtesy Proven Energy

Courtesy Endurance Wind Power

With upwind machines (blades are upwind of the tower), a tail sticks out behind the machine, and the force of the wind on it pushes the rotor into a position facing the wind. With downwind machines (blades are downwind of the tower), the rotor acts as the tail to yaw the machine properly.

Slip Rings & Transmission

Because a wind generator yaws, but its tower is fixed, we need a mechanism to transmit the electrical output from the rotating portion to the fixed. Utility-scale machines and some home-built machines allow the wires to be twisted, and either a motor or the owner periodically untwists them. To transmit the energy on most home-scale machines, slip rings—two or more bronze rings that are on the fixed portion of the machine/tower, and graphite brushes that ride on these rings—create a connection for the energy and allow swiveling without twisting wires.

Wires relay energy down the tower to the electronics, batteries (if used), home, and/or utility grid. Transmission may be DC, or as wild, multiphase AC. There's not a great deal of difference between the two in efficiency or cost; it is higher voltage that gives better efficiency. A big advantage to running AC down the tower is that the rectifiers that convert AC to DC are at ground level, where they are easier to troubleshoot and replace if needed.

Governing

A well-designed machine must be able to govern—shed wind in some way to reduce high winds' force on the turbine and tower. Shedding wind energy also reduces the speed of the turbine, avoiding mechanical or even electrical failure. There are three primary methods of governing, with variations in each.

Furling tilts the whole blade rotor either to the side, up like a helicopter, or in a combination of those two, to reduce the area exposed to the wind. This is a very common governing strategy, and is effective and easy to build. They're a bit of an art to design, and governing systems of this sort can be sluggish in responding to high wind.

Left: Centrifugal force on the blades works a linkage to change blade pitch on an old Jacobs generator. This complex but highly effective governor precisely regulates rpm.

Right: A side-furling governor uses the force of the wind on an off-center joint to pivot the blades out of the wind. In this case, mechanical furling is used to brake the machine during maintenance.

Pitch control changes the orientation of each individual blade in high winds, taking them out of their optimum aerodynamic position so they don't capture (or have to absorb) as much wind energy. This is typically accomplished with an arrangement with weights and springs. Governing happens incrementally as the rotational speed increases, and this strategy can be very precise, so it controls speed accurately and allows good production. This governing system may be more expensive than furling systems and is more prone to wear.

Stall is a speed-control method that relies on the inherent design of the blades, and results in poorer performance at high rotation. Stall regulation works by slowing down the blades in relation to the wind speed. If the rotational speed is constant (induction motor turbines, for example) and the wind speed increases, stall is inevitable—it just needs to be tuned to happen at the right wind speed.

Governing requires a delicate balance, regardless of what method is used, and relies on properly sizing and matching the various angles and offsets of the rotor and tail, the size and weight of blades, and the blade design. If any parameter is changed—making the blades longer or tail heavier, for example—you'll change the turbine's governing characteristics.

Braking

In addition to governing—which needs to happen automatically in high winds—wind generators need the ability to be stopped manually. We do this when we: need to repair them; think there's some problem; are expecting too-high winds; or when we simply don't need the energy (for instance, with a seasonal residence or a long vacation).

Mechanical brakes can be drum brakes or disk brakes, and are often activated by a hand winch at the tower base. A few turbines use manual furling with a tower-base winch to swing the rotor out of the wind—this at least slows it, if it doesn't fully stop the rotation.

Dynamic or electrical braking shorts the DC or wild AC output, stopping the turbine's rotation. Depending on the alternator design and wire run, this can be very effective. In other cases, it's iffy, and may not stop a machine in high winds, or hold it once stopped. Neodymium magnets have a more reliable effect for dynamic braking. Make sure you understand the limitations of dynamic braking for your particular machine.

Dynamic braking uses the alternator's electromagnetism against itself by shorting all three wires together.

Courtesy Ian Woofenden (3)

Electronics

A crucial part of a wind generator system is the electronics needed. Each machine will have its own electronic systems, which may include:

- Rectification to convert AC to DC.
- Maximum power point tracking (MPPT) to get the most output from the wind generator by matching the charging curve to the wind power curve. This relies on a programmed wind power curve for the particular turbine used.
- Charge controller to regulate battery charging (if used).
- Metering and data logging to monitor system performance.
- Circuit protection (breakers) is often included.

Making a Wise Choice

Understanding how a wind generator functions can help make wise buying and design decisions. Although wind generator specifics are discussed here, what you need is a whole system, which includes tower, transmission wire and conduit, electronics, and more. You need all the appropriate components, they need to be of high quality, and they need to be matched to each other. Usually, it's best to buy everything as one package to avoid surprises and problems.

Tapping that flow of moving air can be a lot of fun, but I'm here to tell you that it ain't easy. If you approach it sloppily or with a nickel-and-dime attitude, you're more likely to get poor and costly results. Investing in a good product and system and installing it with attention to detail will give you dependable renewable energy, now and over the long haul.

Access

Ian Woofenden (ian.woofenden@homepower.com) has been using, installing, fixing, consulting, and teaching about wind generators for more than 25 years in the Pacific Northwest. He is the author of *Wind Power for Dummies*, and one of the founders of the Small Wind Conference (www.smallwindconference.com).

Resources:

"Anatomy of a Wind Turbine" by Ian Woofenden & Hugh Piggott in *HP116*

"Estimating Wind Energy" by Hugh Piggott in *HP102*

"Wind Power Curves: What's Wrong, What's Better" by Ian Woofenden in *HP127*

"Understanding Wind Speed" by Ian Woofenden in *HP143*

"Estimating Obstruction Height" by Ian Woofenden in *HP141*

"Wind Turbine Transmission Wire Sizing" by Hugh Piggott in *HP134*

"Wind Electric System Basics" by Ian Woofenden in *HP110*

"Site It Right! An Interview with Wind Energy Consultant & Installer David Blecker" by Ian Woofenden in *HP115*

Installed by Palomar Solar in San Diego, CA

- All Aluminum, "Green" Solution
- Pre-Assembled Components
- No On-Site Fabrication
- Easy Assembly for Lower Labor Costs
- Low Part Count
- Locally sourced

HatiCon Solar™

Contact us at:
(866) 489-4472
info@haticonsolar.com
www.haticonsolar.com

MADE IN U.S.A.
MADE IN CANADA FABRIQUÉ AU CANADA