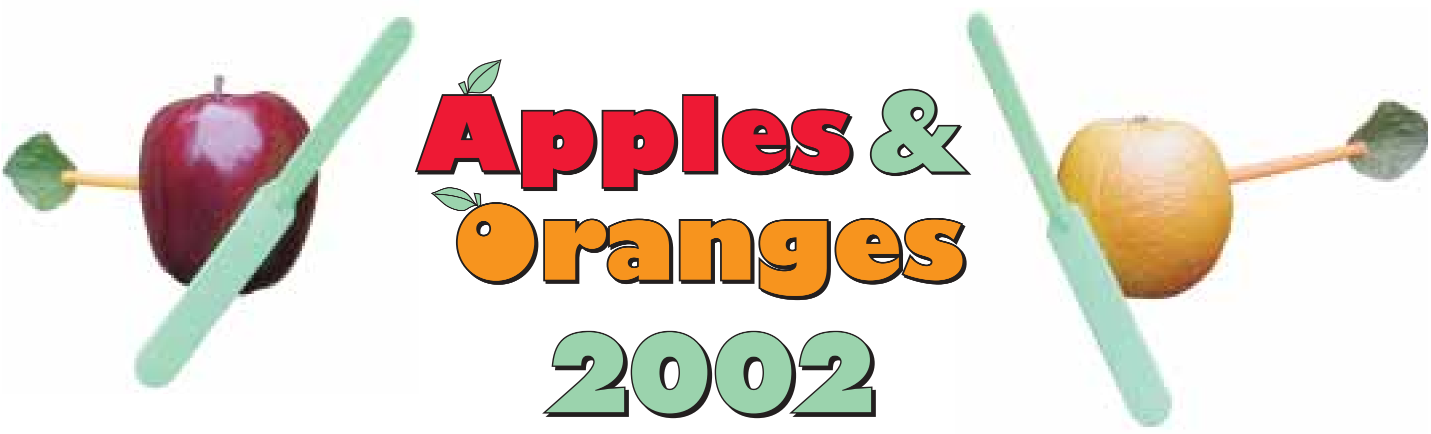

Apples & Oranges ’02 Technical Appendix

Mick Sagrillo

Apples & Oranges ’02 (A&O), in *HP90,* made a number of references to more detailed technical discussions of the topic on the Web. What follows are those miscellaneous discussions.

Monthly Energy Output Reality Check

The specifications in the table in A&O ’02 were all supplied by the manufacturers. An explanation is needed where KWH per month outputs have been starred (*) and labeled “estimated by author,” as with the Proven wind turbines. Proven provided me with a curve of annual energy outputs at various wind speeds. After repeatedly asking for actual numbers for the monthly energy outputs at various wind speeds, I was told to estimate the outputs from the curves. That’s what I did, which is why the table says “estimated by author.”

If you look at the KWH per month outputs in the table, the outputs appear to be all over the map. There doesn’t appear to be any correlation between swept area, peak turbine output, and KWH per month. So how do you make sense of this wild range of outputs?

Annual or monthly energy outputs are derived by the manufacturer using a rather complex set of calculations that incorporate the turbine power curve and the power density of various wind speeds over a range of statistical time, assuming given wind turbine component efficiencies. They also assume an ideal load, that is, one that can absorb all of the energy produced by the wind generator. While this is feasible with grid-intertied systems, battery charging wind turbines are another story.

Way back in physics class, the professor introduced problems with the phrase, “Assume we’re on a frictionless plane.” To a very great extent, that is what manufacturers do when deriving annual energy outputs for their products. A paper by National Renewable Energy Laboratory (NREL) small turbine engineers states, “Most small wind energy systems are initially evaluated with the use of computer-based models that assess the components to be considered….Although the models are useful in predicting component operation, dispatching, and performance, they may be over-predicting the actual production of renewable energy.” [1]

These calculations result in an ideal graph of outputs for the wind turbine. The resulting numbers are typically the energy outputs that are advertised by manufacturers, and the KWH per month outputs that were included in the table in A&O ’02. Because the ideal—the frictionless plane—will likely never be achieved in real world operation, I caution people with, “Your mileage may vary.”

To exacerbate the problem, there is no independent verification of home-sized turbine energy output. However, there is another way of ballparking energy outputs. This alternate method is based only on a turbine’s swept area at a given wind speed. While a somewhat simplistic method, it nonetheless results in what I consider to be far more realistic monthly energy outputs.

This formula also assumes an overall system efficiency, which is actually on the high end for a home-sized wind turbine across the range of wind speeds presented in the table. The equation for annual energy output (AEO) is:

$AEO = 0.01328 \times D^2 \times V^3$, where D is the rotor diameter and V is the wind speed. [2]

To make the AEO equation results match the A&O ’02 table’s monthly readings, I divided the annual outputs by 12 to yield monthly energy outputs (MEO) at various wind speeds, or:

$MEO = (0.01328 \times D^2 \times V^3) \div 12.$

Monthly Energy Outputs (in KWH)

Wind Speed (mph)	*Whisper H40*			*Bergey XL.1*			*Proven WT600*			*Whisper H80*		
	7.0 ft. Rotor Diameter			*8.2 ft. Rotor Diameter*			*8.4 ft. Rotor Diameter*			*10.0 ft. Rotor Diameter*		
	*Manu.'s Est.**	*Calc. Est.**	*Diff.**	*Manu.'s Est.**	*Calc. Est.**	*Diff.**	*Manu.'s Est.**	*Calc. Est.**	*Diff.**	*Manu.'s Est.**	*Calc. Est.**	*Diff.**
8	30	28	-7.5%	55	38	-30.7%	42	40	-4.8%	60	57	-5.6%
9	45	40	-12.2%	85	54	-36.2%	66	57	-13.8%	90	81	-10.4%
10	65	54	-16.6%	115	74	-35.3%	83	78	-5.9%	125	111	-11.5%
11	80	72	-9.8%	150	99	-34.0%	113	104	-8.0%	160	147	-7.9%
12	105	94	-10.8%	188	129	-31.6%	124	135	8.8%	190	191	0.6%
13	125	119	-4.7%	220	163	-25.7%	142	172	20.8%	215	243	13.1%
14	155	149	-4.0%	250	204	-18.3%	167	214	28.3%	265	304	14.6%

Wind Speed (mph)	*Proven WT2500*			*AWP 3.6*			*Jake Short Case*			*Jake Long Case*		
	11.1 ft. Rotor Diameter			*11.8 ft. Rotor Diameter*			*14.0 ft. Rotor Diameter*			*14.0 ft. Rotor Diameter*		
	*Manu.'s Est.**	*Calc. Est.**	*Diff.**	*Manu.'s Est.**	*Calc. Est.**	*Diff.**	*Manu.'s Est.**	*Calc. Est.**	*Diff.**	*Manu.'s Est.**	*Calc. Est.**	*Diff.**
8	167	70	-58.2%	75	79	5.2%	240	111	-53.7%	240	111	-53.7%
9	206	99	-51.7%	105	112	7.0%	300	158	-47.3%	300	158	-47.3%
10	292	136	-53.3%	130	154	18.5%	340	217	-36.2%	340	217	-36.2%
11	333	181	-45.5%	168	205	22.1%	410	289	-29.6%	440	289	-34.4%
12	417	236	-43.5%	192	266	38.7%	460	375	-18.5%	520	375	-27.9%
13	465	300	-35.6%	226	339	49.8%	500	477	-4.7%	610	477	-21.9%
14	542	374	-31.0%	246	423	71.9%	550	595	8.2%	700	595	-15.0%

Wind Speed (mph)	*Whisper 175*			*Proven WT6000*			*Bergey Excel-R*			*Bergey Excel-S*		
	15.0 ft. Rotor Diameter			*18.0 ft. Rotor Diameter*			*21.0 ft. Rotor Diameter*			*21.0 ft. Rotor Diameter*		
	*Manu.'s Est.**	*Calc. Est.**	*Diff.**	*Manu.'s Est.**	*Calc. Est.**	*Diff.**	*Manu.'s Est.**	*Calc. Est.**	*Diff.**	*Manu.'s Est.**	*Calc. Est.**	*Diff.**
8	170	127	-25.0%	417	184	-56.0%	340	250	-26.5%	240	250	4.1%
9	230	182	-21.1%	564	261	-53.7%	500	356	-28.8%	370	356	-3.8%
10	330	249	-24.5%	667	359	-46.2%	680	488	-28.2%	520	488	-6.1%
11	410	331	-19.2%	917	477	-48.0%	880	650	-26.2%	700	650	-7.2%
12	540	430	-20.3%	1,083	620	-42.8%	1,090	843	-22.6%	900	843	-6.3%
13	620	547	-11.8%	1,250	788	-37.0%	1,320	1,072	-18.8%	1,130	1,072	-5.1%
14	720	683	-5.1%	1,417	984	-30.6%	1,550	1,339	-13.6%	1,370	1,339	-2.2%

Wind Speed (mph)	*Jacobs 31-20*		
	31.0 ft. Rotor Diameter		
	*Manu.'s Est.**	*Calc. Est.**	*Diff.**
8	819	545	-33.5%
9	1,160	775	-33.2%
10	1,644	1,064	-35.3%
11	2,142	1,416	-33.9%
12	2,691	1,838	-31.7%
13	3,274	2,337	-28.6%
14	3,872	2,918	-24.6%

* Abbreviations:
Manufacturer's Estimate (KWH/ Month)
Calculated Estimate (KWH/ Month)
Difference (%)

Using the rotor diameters given in the table, and a range of monthly average wind speeds from 8 to 14 mph (3.6–6.3 m/s), we now get the KWH per month outputs in the table

The top line of each turbine's entry is the monthly output supplied by the manufacturer, as published in A&O '02. The second line is the calculated output based on the MEO equation above.

The third line is the percent deviation between the two. This was derived with the following equation:

(calculated MEO - manufacturer's output) ÷ manufacturer's output

A negative percentage means that the manufacturer's numbers are overstated compared to the calculated MEO, by the percent given. A positive percentage means that the manufacturer's numbers are understated compared to the calculated MEO, again by the percent given.

Wind Turbine Output Elevation Adjustment

Altitude (Feet above Sea Level)	*Output Correction*
0	100.0%
2,500	91.2%
5,000	83.2%
7,500	75.6%
10,000	68.7%

Some things immediately jump out in this comparison. First of all, the manufacturers' outputs for the Whisper H40 and H80, plus the Bergey Excel-S are all rather close to the MEO compared to the other turbines. This is great news for these three turbines! But a lot of questions come to mind.

Why are the other turbine outputs overestimated by anywhere from 30 percent to almost 60 percent? Why are the AWP 3.6's outputs so underestimated? Is the manufacturer of the African Wind Power more honest than the other manufacturers? Why is there so much variability from percentage to percentage for one manufacturer, from one manufacturer to another, and from one wind speed to another?

There are no simple answers to these questions. I spent considerable time trying to unearth the answers to these and other questions with Paul Gipe, author of *Wind Power for Home and Business,* and Trudy Forsyth and Jim Green, two of the top small wind turbine engineers at the National Renewable Energy Laboratory. While there is, and will continue to be, considerable debate on the topic of estimating wind turbine energy outputs, at least the four of us are more or less of the same opinion.

Paul Gipe has attempted to verify the power curves of small turbines by field testing them. One significant conclusion of Paul's is that home-sized wind turbines operate at a range of overall machine efficiencies of 23 percent down to 11 percent, depending on the wind generator and the wind speed.[3] The four of us agree that choosing a 20 percent conversion efficiency is a safe, albeit generous, estimate of overall turbine efficiency for determining MEO.[4]

In her research, Trudy Forsyth has found that two major factors influence a wind turbine's output—air density and turbulence.[4] Air density varies with temperature, something we have little control over. It also varies with elevation above sea level, and Trudy points out that people should know this when installing a turbine. We believe that all of the manufacturer's monthly energy outputs assume a standard temperature of 60°F (16°C) and an elevation above sea level of no more than 1,000 feet (305 m). If you live higher than about 1,000 feet above sea level, adjust your expected output according to the wind turbine output elevation adjustment table (left).

Unlike density, Trudy's second major concern, turbulence, can be controlled by the wind system owner. Turbulence is primarily a result of installing a wind generator on a short tower, so that ground clutter in the form of trees and houses disrupts the flow of the wind past the wind turbine rotor. This problem is easily overcome by simply making sure that the entire rotor of the wind turbine is at least 30 feet (9 m) above any obstacle on the landscape. Remember, the biggest variable that influences the output of a wind generator is the surface roughness and ground clutter in the form of trees and buildings around the tower.

All of the turbines listed in A&O '02 represent monthly energy outputs at the DC bus, except for the Bergey Excel-S and Jacobs 31-20 machines. Both of these wind generators are only available as grid-connected systems. "DC bus" means that the wind generator's energy output is measured before it enters the battery.

DC bus estimates do not take into consideration the inefficiencies and subsequent energy losses of the battery bank and balance of system components. As a result, battery charging systems will never reach the system efficiencies of grid-tied wind systems.[4] System efficiency losses as high as 25 percent have been documented by NREL tests of battery charging wind systems.[1] And this is with a laboratory that has the ability and resources to control variables.

In actual tests conducted by NREL on the Whisper H40, the manufacturer's calculated AEOs were 8 percent to 18.5 percent higher than test results for wind speeds ranging from 9 to 13.5 mph (4–6 m/s).[5] But remember that the Whisper H40 was one of the turbines with a manufacturer MEO close to my calculated outputs.

NREL engineers note, "In some cases, the energy capture of the wind turbines is only 40 percent of the amount expected based on the site wind speeds and published turbine power curves….field performance power curves typically do not match the published factory power curve…Reductions in energy capture as high as 59 percent bear this out."[1] According to NREL engineers David Corbus and Charles Newcomb, the major driver of this underperformance in the field is undersized battery capacity.[6] Besides amp-hour rating, factors such as battery age, condition, and any other situation that results in energy being dumped rather than used by the battery bank can contribute to this situation.

NREL's Jim Green points out, "Any single energy output estimate won't be right for any single turbine at any single site." The reason is a myriad of turbine and site variables, including:

- Rated wind speed of the wind turbine
- Wind power density
- Wind system availability
- Battery state of charge
- Battery age
- Battery capacity
- Battery condition
- Other loads on the wind generator besides the battery
- Controller settings
- The balance of system efficiency
- Alternator efficiency
- Airfoil efficiency
- The governing mechanism and how it's tuned

In addition, all of these variables interact with each other to exacerbate any one problem, or other variables, that you are trying to control. Finally, all of these factors vary with manufacturer, turbine, and wind speed.[4]

So, what do you do? Give up in despair? Not hardly. It's just that predicting wind turbine output is, at best, a moving target. On a frictionless plane!

I recommend that first and foremost, you minimize turbulence at your rotor by installing the system on a tall tower. This is a proven solution!

Next, rather than use the manufacturers' monthly estimated outputs given in the A&O '02 table, use the numbers presented in the above MEO table to size your wind energy system.

Estimate low, and be pleasantly surprised if your outputs are higher.

Number of Blades & Blade Chatter

While a number of manufacturers have offered two-bladed wind generators in the past, most no longer do. Since blades cost money, and a three-bladed rotor may cost 50 percent more than a two-bladed rotor, the question arises: why use three blades?

"Yaw" is a term that refers to a wind generator pivoting on its bearings around the tower top to follow the changing direction of the wind. A two-bladed rotor actually sets up a "chatter" as it yaws, which causes a strain on all of the wind generator's mechanical components.

Chattering occurs during yawing because of the continuous changing position of the two blades in the plane of rotation. When a two-bladed rotor has its blades in the vertical position (that is, in line with the tower) there is little resistance to the rotor yawing around the tower. However, when the blades rotate 90 degrees so that they are in the horizontal position (that is, at right angles to the tower, or parallel to the ground) they pose maximum resistance (or inertia) to any yawing motion. The result is a rhythmic starting and stopping of the yaw twice per revolution of the rotor. This starting and stopping of the yaw is what is called blade chatter.

Three-bladed rotors eliminate the chattering problem because there is never enough inertia from the one blade in the horizontal position to set up a blade chatter in the first place. The horizontal blade is more than counterbalanced by the other two blades working somewhere off on their own during yaw. In contrast to two-bladed rotors, well-balanced three-bladed rotors operate very smoothly, with no noticeable vibration or chatter.

Blade chatter will be transferred, not only to the wind generator itself, but to the entire tower. The result is additional stress and fatigue to the wind generator, the tower, and all welds and fasteners, potentially shortening the turbine's life. One former two-bladed wind turbine manufacturer lamented that "a two-bladed machine is essentially a two year machine." He switched his machines to three blades.

The Idiosyncrasies of Downwind Turbines

One advantage that downwind machines have is that, since they have no tail, you don't get charged for one. However, an interesting thing can happen with downwind machines. Mike Klemen of North Dakota has a Proven WT2500 on an 84 foot (26 m) tower. Mike reports that when the wind dies down and then shifts around 90 degrees from its previous direction, it sometimes takes a 12+ mph (5 m/s) wind to get the WT2500 reoriented into the wind. The reason is that downwind gennys do not have that long lever arm, the tail, which is useful in keeping the blades oriented into the wind.

Airfoils, Alternators, & Performance

"Airfoil" refers to the shape of the blade. The cross section of a blade looks much like an airplane wing, that is, curved on one side and more or less flat on the opposite side. The airfoil generates lift, which pulls the blades through the wind, causing the rotation that is needed to generate electricity.

The differences between wind turbine airfoils occur in three areas—manufacturing cost, noise, and performance. In terms of manufacturing processes, plastic airfoils are the easiest to manufacture, followed by pultrusions. Fiberglass blades require some hand work, but are not nearly as labor intensive as wood blades. As hand labor increases, so does the cost of replacement blades. See the A&O text sidebar on noise for a discussion of that issue.

Airfoil performance is all over the map. As tip speed ratio (see below) increases, so does performance, to an extent. The best performing airfoils have a tip speed ratio (TSR) of about 5 or 6 to 1. This means that the tip of the blade is moving five times faster than the wind driving the airfoil. In a 20 mph (9 m/s) wind, an airfoil with a TSR of 5 will be moving at 100 mph (45 m/s) at the blade tip. As TSR increases much beyond 7, drag also increases, which actually decreases an airfoil's performance. In addition, with increased TSR comes at least one downside—noise.

So, you ask, why would a manufacturer use a high TSR airfoil? The output of a generator is a function of a number of design parameters, two of which are rpm and the physical size of the generator. There is an inverse relationship between rpm and generator size. If you spin the generator faster, you can reduce the physical size of the generator and still get the same output at a given wind speed.

As rotor rpm increases due to increased TSR, generator size can decrease. For the manufacturer, this means less cost to fabricate their particular product, which translates to a more competitive spot in the marketplace. For the end user, it means a less expensive product. Everybody wins, right? Wrong! While the manufacturer wins by selling less expensive equipment, you the customer, with a high speed wind generator, will likely be the loser. Experience has shown that, for most wind turbine designs, wind generator life certainly seems to be inversely related to rotor TSR.

I'm actually quite cynical about high speed/higher performance airfoils. There are companies that invest a lot of money in developing these airfoils for their turbines in an attempt to increase output. The typical blade operates at about a 40 percent conversion efficiency, that is, its ability to convert moving air to rotational momentum required to turn the generator.

If a manufacturer can increase blade efficiency by 4 percent, this represents a 10 percent increase in conversion efficiency (from 40 percent to 44 percent) that can be incorporated into their product. But this efficiency comes at considerable research and development cost, which is passed on to you, the customer. The manufacturer, however, gets the bragging rights of having a more efficient airfoil than its competitors.

It turns out that these high speed airfoils operate at peak efficiency only when a variety of environmental parameters are met. If the blade is covered with dust or bugs, what happens to this almighty efficiency? It goes out the window. So where did it get us?

Let's try a different approach. Rather than increasing rotor efficiency by 10 percent, let's say we increase swept area by 10 percent. How much would we need to increase blade length to equal a 10 percent increase in efficiency? For our example, let's take the AWP 3.6, a midsized wind turbine in the A&O table.

The AWP has a blade length of 5.9 feet (1.8 m). Swept area of the rotor = $\pi \times r^2$, or $3.14 \times (5.9)^2 = 109$ square feet (10 m^2). A 10 percent increase in swept area would bring the AWP up to 120 square feet (11 m^2). Working backwards through our swept area equation, we would need to increase blade length to 6.2 feet (1.9 m). Three tenths of a foot—a mere 4 inches (10 cm) or 5 percent of the blade's length—increases the AWP swept area by 10 percent. In my opinion, increasing swept area is much more cost effective than expensive airfoil R&D. In addition, increasing swept area is not prone to airfoil derating by bugs or dust.

Generator & Alternator Designs

Electrical generators work by moving a wire (actually, many wires) through a magnetic field. The movement of the wire through the magnetic field induces current through the wire. It's the current that we want for our batteries and grid-intertied inverters.

Permanent magnet (PM) alternators use, as the name implies, permanent magnets for the magnetic field. PM alternators are lighter in weight than generators that use copper wire-wound fields. PM alternators produce three-phase wild alternating current (AC). "Wild AC" means that the frequency (and voltage) is variable with the wind speed. As rotor speed increases, so does the frequency. Wild AC cannot be used by standard 60 cycle appliances, and must be rectified to DC before it can be used in either a battery bank or a utility-tied synchronous inverter. DC generators simply produce direct current (DC).

Some manufacturers claim that PM alternators are better in wind systems than DC generators, primarily because there is less maintenance involved with an alternator than with a DC generator. DC generators have brushes, which have to be replaced periodically, maybe every six years or so. PM alternators do not have brushes. From my perspective, replacing brushes twice a decade can hardly be construed as a maintenance problem.

The real advantage of permanent magnets to a manufacturer is that using permanent magnets is relatively cheap. Remember that PM alternators are lighter in weight than wire-wound field generators and alternators. Weight costs money. Compared to the cost of the copper wire needed in a wound field, permanent magnets are a bargain! Cheaper materials, plus less labor, means that a manufacturer can be more competitive in pricing the product.

PM alternators also offer two advantages to the system owner. First, you may be able take advantage of dynamic braking, described under "shut-down mechanisms" in the A&O text. Second, PM alternators do not use some of their output to energize the fields, as do wire-wound field generators.

However, PM alternators do have one disadvantage compared to DC generators and brushless alternators with a wound field. (I'm going to simplify this greatly, so all you electrical engineers out there, please don't drop your teeth!) Because the magnets in a PM alternator are permanent, the amount of magnetism they exude, or their flux density, is fixed at the magnet's maximum amount. The amount of flux density in a wire-wound field magnet, however, is proportional to the current through it, and somewhat, to the amount of voltage present. In other words, the higher the voltage present in a wire-wound field, the stronger the current, and the stronger the magnetic flux will be. As the rotor speeds up, the flux density of the field also increases.

The nice thing about this arrangement is that the magnets in a wire-wound field generator or brushless alternator put very little magnetic drag on the spinning armature when little wind is blowing. But there's plenty of magnetic drag available when the wind is cranking and the generator is peaking.

The power curve of a DC wire-wound field generator or brushless alternator nicely follows the power available in increasing wind speeds. (Remember V^3?) That's just the way it should be. PM alternators, on the other hand, always have maximum magnetic drag on the alternator's current-generating stator. This means that performance is at its peak at only one spot on the entire power curve. All other points on the power curve are a compromise.

This can have a considerable impact on the performance of a wind generator. At the low wind speed end of the power curve, the part of the curve where the wind system spends most of its life, blades are sometimes fighting the magnetic flux of the PM, resulting in less output. To overcome this problem, manufacturers using PM alternators have to design more torque into their blades just to get the rotor spinning in low winds.

At the other end of the power curve, some wind turbines seem to reach a "breakaway speed," a point where the rpm of the rotor really takes off. This is due to insufficient magnetic flux of the PM relative to the power at the blades. Once the breakaway speed has been reached and rpm picks up, the rotor can get very noisy, especially when governing. Interestingly, this is not a problem with either the Proven wind turbines, or the AWP wind genny, both of which use PM alternators, because both use very low speed alternators.

So while PM alternators are simpler (no brushes) and cheaper to build than DC generators or brushless alternators, the simplicity comes at a price. To be fair, however, it should be noted that DC generators and brushless alternators are more expensive than PM alternators. And since generator brushes will need changing periodically, they do require a bit more maintenance.

Brushless alternators offer the best of both worlds. The fields are wire-wound rather than permanent magnet, and there are no brushes to replace. Their power curve is similar to a DC generator. On the downside, brushless alternators are considerably more complicated, and more expensive to replace or repair than either DC generators or PM alternators.

A Suggestion to Improve Disc Brakes

The Proven WT2500, WT6000, and Jacobs 31-20 all use a mechanical disc brake that slows the rotor to a stop on their wind turbines. A winch cranks a cable, which engages the brake. In high winds, it can be tough to get the Jacobs 31-20 rotor to stop with the disc brake. Unfortunately, with both the Jacobs 31-20 and Provens, the failure mode (due to a broken cable, for example) is no brake, and the rotor takes off.

Actually, these systems could easily be modified by changing the compression springs on the disc brake (which force the brake pads open when the cable is released) to pull-type springs (which work like a screen door spring). With a pull-type spring, winching the cable would pull against the springs, releasing the brake pads from the brake disc. The failure mode for this type of system would be pressing the brake pads against the disc, stopping the rotor. (Hey manufacturers—hint, hint.)

Access

Mick Sagrillo, Sagrillo Power & Light, E3971 Bluebird Rd., Forestville, WI 54213 • Phone/Fax: 920-837-7523 msagrillo@itol.com

Notes

1. Corbus, David, E. Ian Baring-Gould, Seth Friedly, and Charles Newcomb, "Analysis Of Reduced Energy Capture Mechanisms For Small Wind Systems," presented at the American Wind Energy Association's Wind Power 2002 Conference, June 2002.

2. The actual equation for annual energy output comes from Paul Gipe's book *Wind Power Basics* (page 19), and was simplified by Jim Green.
3. E-mail from Paul Gipe 7/9/02 and 7/14/02.
4. Telephone conference calls with Trudy Forsyth, Paul Gipe, and Jim Green.
5. E-mail from Trudy Forsyth, 7/10/02.
6. Phone conversation with David Corbus and Charles Newcomb, 7/25/02.