Hot technologies: **energy**

LOW COST, PLENTIFUL, CLEAN, AND, IN ALL OTHER RESPECTS, "GREEN." THESE WORDS DESCRIBE WIND POWER IN A NUTSHELL. SO, WHY IS IT SO UNPOPULAR? THE DEVIL IS IN THE DETAILS, ALONG WITH OUR RELUCTANCE TO ADOPT AN UNKNOWN TECHNOLOGY. WITH FOSSIL-FUEL PRICES ON THE RISE, THEIR SUPPLY INCREASINGLY UNSTABLE, AND GLOBAL-WARMING EFFECTS GROWING, HOWEVER, THE WIND-TURBINE ALTERNATIVE IS GARNERING OVERDUE ATTENTION.

CUTTING THE CARBON-ENERGY CORD: IS THE ANSWER BLOWIN' IN THE WIND?

BY BRIAN DIPERT • SENIOR TECHNICAL EDITOR

The debate on global warming is over, according to *Scientific American* (**Reference 1**). With those no-holds-barred words, the respected journal introduced the theme of its September 2006 special issue, "Energy's Future: How to Power the Economy and Still Fight Global Warming." Diminishing but still lingering debate within the scientific community hasn't completely settled the question of whether—and, if so, to what degree—increased carbon dioxide and other greenhouse-gas concentration in the earth's atmosphere have caused global warming (**Figure 1**). But *Scientific American*'s Special Projects Editor Gary Stix seems convinced that a material link exists: "Present levels of carbon dioxide—nearing 400 ppm in the earth's atmosphere—are higher than they have been at any time in the past 650,000 years and could easily surpass 500 ppm by 2050 without radical intervention. ... Almost all of the 20 hottest years on record have occurred since the 1980s. No one knows exactly what will happen if things are left unchecked—the exact date when a polar ice sheet will complete a phase change from solid to liquid cannot be foreseen with precision. ... But no climatologist wants to test what will arise if carbon-dioxide levels drive much higher than 500 ppm" (**Reference 1**).

Even if you're not a fan of the "fossil-fuels-equal-global-warming" theories, plenty of other good reasons exist to seriously consider weaning yourself from carbon-based—that is, coal, natural-gas, and petroleum—economy. A simple visit to the local gas station will suffice as motivation. First, let's analyze the supply-side reasons for the recent price increases. In the near term, the unstable political situation in the Middle East, home to an estimated two-thirds of the world's oil reserves, has disrupted supply lines. In the longer term, an increasing number of analysts are warning that we're nearing the Peak Oil threshold—that is, the point beyond which, the Hubbert Peak Theory predicts, earth's oil production will begin to decline (**Reference 2**). We won't immediately feel the impact of this decay; "Even if oil production peaks soon—a debatable contention given Canada's oil sands, Venezuela's heavy oil, and other reserves—coal and its derivatives could tide the earth over for more than a century," says *Scientific American*. But beyond Peak Oil, whenever it happens, the supply decline will be unrelenting.

The magazine goes on to address demand: "The United States holds less than 5% of the world's population but produces nearly 25% of carbon emissions." (Note: The US population passed the 300 million threshold just two months ago.) And what about demand trends in the future? "The torrid economic growth of China and India will elicit calls from industrial nations for restraints on emissions, which will again be met by even more adamant retorts that citizens of Shenzhen and Hyderabad should have the same opportunities to build their economies that those of Detroit and Frankfurt once did." Infrared-radiation retention and supply/demand anxieties combine with a third primary carbon-based-fuel concern: pollution. As *The New York Times* points out, "Coal ... is causing acid rain and respiratory ailments while contributing to global warming. China accounted for 79% of the world's growth in coal consumption last year, and India used 7% more" (**Reference 3**).

In the face of such gloomy news, energy-redirection efforts around the world are increasing in number and pace, with two primary objectives: the near-term goals of minimizing the emissions of carbon-centric-fuel sources and minimizing worldwide energy demands and the long-term goal of developing alternatives to carbon-based energy. *Scientific American*'s article lists five high-confidence candidates, along with a host of tier-two alternatives: nuclear power, solar cells, bio-fuels, hydrogen, and wind turbines. Wind power is a topic near and dear to the hearts of many in Silicon Valley, who live and work near California's largest wind-farm collective, Altamont Pass, which California built after the 1970s energy crisis and which state tax credits funded (**Figure 2**). Southern California residents may be more familiar with the state's two other large wind farms: San Gorgonio Pass near Palm Springs and Tehachapi Pass, which links the San Joaquin Valley and the Mojave Desert.

AT A GLANCE

- Greenhouse-gas-induced global-warming worries aren't the only reasons to consider a power-grid shift to wind power.
- Thorough wind-farm-location planning is key, both for maximizing efficiency and power output and for addressing wildlife-safety concerns.
- Horizontal- and vertical-axis wind turbines both have advantages and disadvantages; second-tier design trade-offs also bear consideration.
- Wind's unpredictable nature forces utility operators to think differently about power generation.
- Sea- and high-altitude-based turbines present different sets of benefits and complications, and homeowners can also exploit wind's power potential.

Wind power isn't a California-only phenomenon; the largest stand-alone farm in the United States lies along the Oregon/Washington border, and, while traveling this year, I observed a number of massive wind turbines on both sides of Minnesota's Highway 90, as well as their predecessors, windmills, all across the country. Wind power isn't a United States-only occurrence, either; according to Wikipedia and other sources, 69% of the world's end-of-2005 wind-power production occurred outside the United States (**Reference 4**). Germany alone produced 32% of the world's 58,982 MW of wind energy, and wind generated 6% of Germany's electricity, versus 1% of the world's electricity and 0.4% of electricity in the United States, representing roughly 1.6 million homes' demand. Denmark's wind-energy generation was only fifth in the world in absolute capacity, yet it satisfied more than 20% of the energy demands of its citizens, the highest percentage in the world. Between Germany with 18,428 MW in 2005 and Denmark with 3128 MW in absolute capacity were Spain with 10,027 MW, the United States with 9149 MW, and India with 4430 MW.

At first glance, wind power might seem to be a "perfect" energy source; It is clean, greenhouse-gas-mitigating, abundant, infinitely renewable, domestically produced, low-priced in many locations, widely distributed, and supportive of rural economies. But, like any other technology, it involves trade-offs. A combination of technical, economic, political, and aesthetic factors has muted

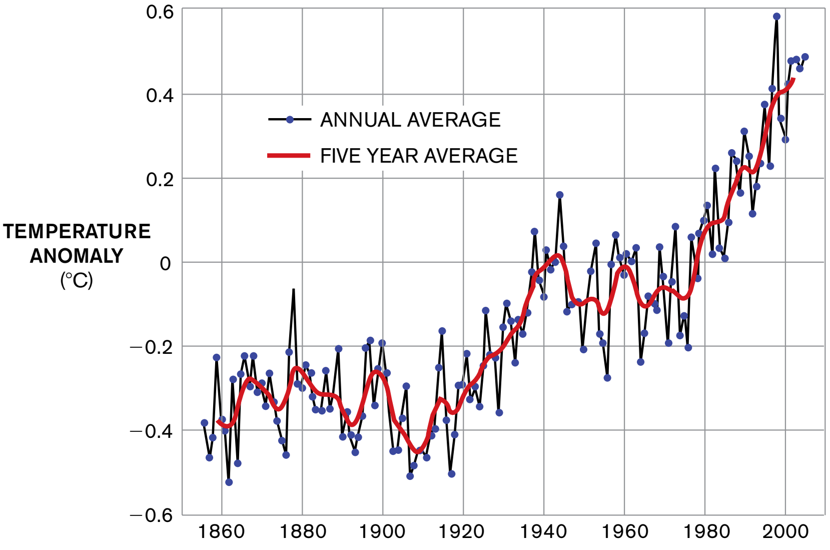

Figure 1 In some graph versions, this 150-year-spanning "hockey stick" of global temperatures, based on instrument-measurement records, further expands into the past using "proxy" records, such as, according to Wikipedia, the width of tree rings; the amount of snowfall over glacial sites; the isotopic composition of snow, corals, and stalactites; the time of crop harvests; the tree line in various locations; and other historical records (courtesy the Climatic Research Unit of the University of East Anglia and the Hadley Centre of the UK Meteorological Office).

Figure 2 You'll find the three largest wind-farm collectives in California on Altamont Pass, San Gorgonio Pass, and Tehachapi Pass.

the initial enthusiasm for wind power that nations exhibited at the height of the 1970s OPEC (Organization for the Petroleum Exporting Countries) crisis. But with enough time, effort, and money, countries can surmount most if not all of wind power's issues. And, as the world grapples with another cyclical spike in carbon-based fuel prices, the motivation to surmount those issues is once again on an upward climb.

LOCATION, LOCATION, LOCATION

The three most important factors in real-estate value—location, location, location—also hold true for wind energy. A turbine's location is critically important to its subsequent power-generation success. As Wikipedia states, you must pay attention to "micro-siting"—the exact positions of the turbines—because a difference of 30m can sometimes mean a doubling in output. The US Department of Energy developed **Figure 3**, which shows wind-energy potential across the United States. Specifically, this data targets terrestrial-based wind turbines; the picture differs dramatically when you broaden the options to include ocean-based and high-altitude wind-generation equipment (see **sidebars** "Up in the air" and "Out of sight, out of mind?"). A historical rule of thumb suggests that a site isn't ideal for wind-farm usage unless it exhibits average wind speeds of 10 mph or higher, but turbine advancements are steadily lowering the palatable wind-speed threshold (see **sidebar** at "More at EDN.com").

Altamont Pass, one of the earliest wind farms in the United States, provides a case study of both location strengths and location shortcomings. Wikipedia points out that "under hot inland (Central Valley) conditions, a thermal low is developed that brings in cool coastal marine air, driving the tur-

UP IN THE AIR

In its introduction to the topic of wind power, Wikipedia notes that, "An estimated 1 to 3% of energy from the sun that hits the earth is converted into wind energy. This is about 50 to 100 times more energy than is converted into biomass by all the plants on earth through photosynthesis. Most of this wind energy can be found at high altitudes where continuous wind speeds of over 160 km/h (100 mph) occur." And, in its September 2005 edition, which classifies high-altitude wind-energy generation as a Plan B technology, *Scientific American* notes that according to New York University physicist Martin I Hoffert, "roughly two-thirds of the total wind energy on this planet resides in the upper trophosphere, beyond the reach of today's wind farms" (Reference A).

Here's more from *Scientific American*: "Ken Caldeira of the Carnegie Institution of Washington once calculated how wind power varies with altitude, latitude, and season. The mother lode is the jet stream, about 10,000 meters (33,000 feet) up between 20 and 40 degrees latitude in the Northern Hemisphere. In the skies over the United States, Europe, China, and Japan–indeed, many of the countries best prepared to exploit it–wind power surges to 5000 or even 10,000 watts a square meter. The jet stream does wander. But it never stops."

Atmospheric-wind-farm architects would need to tether an aerial turbine to the ground, both to hold it in position and to facilitate power transfer to terrestrial stations. To enable the turbine to rise to and maintain altitude, researchers have proposed three primary power schemes: adjustable-pitch counter-rotating blades; helium; and solar cells, which batteries would supplant for overnight and cloudy-weather operation. Maintenance costs, such as periodically refilling the helium, and durability in the face of turbulence, wind gusts, lightning strikes, moisture, and other factors are practical issues that energy providers must address before they can tap the tremendous energy potential of the trophosphere. Also, although high-altitude wind farms consume much less ground area than their terrestrial counterparts, they require civilian- and military-aviation-agency-regulatory approval.

REFERENCE

A **Gibbs, Wayne B, "Plan B for Energy," *Scientific American*, September 2006, pg 106.**

bines at a time of maximum electricity demand” (**Reference 5**). In an analogous experience, while driving from Palm Springs to Los Angeles in late May, I struggled against the resistance of an extremely powerful wind stream; the midafternoon sun was heating the high desert to the east, while a cool, wet fog swathed the Los Angeles Basin on the west side of San Gorgonio Pass. Beyond exploiting air pressure and temperature variance, both passes’ turbine farms, like the one at Tehachapi Pass, also take advantage of another Wikipedia-described wind phenomenon; “Onshore turbine installations tend to be on ridgelines … to exploit so-called topographic acceleration. The hill or ridge causes the wind to accelerate as it is forced over it. The additional wind speeds gained in this way make large differences to the amount of energy that is produced.”

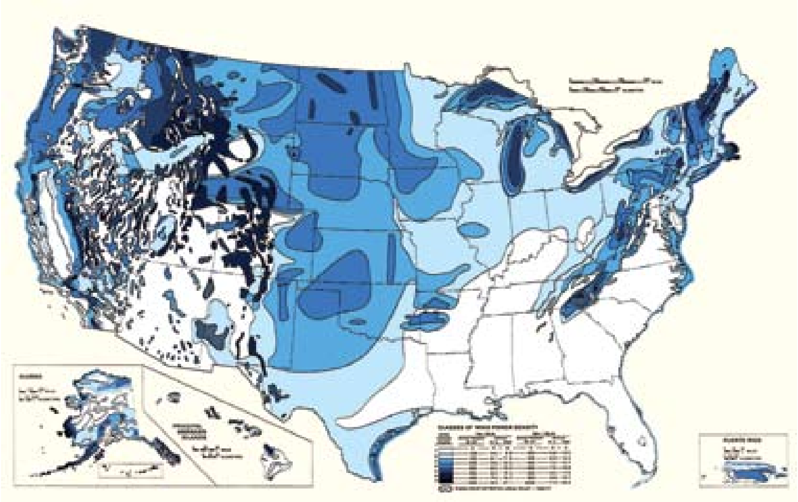

Figure 3 Areas of the United States with Class 4 and higher wind ratings are suitable for farming in conjunction with advanced turbine technology (courtesy United States National Renewable Energy Laboratory).

Yet Altamont Pass isn’t a perfect site. Part of the reason is weather-related. According to Wikipedia, the area sometimes exhibits an inland high-pressure condition, meaning that the entire region can be both hot and windless. At these times, backup natural-gas-powered turbine plants must pick up the slack. Another part of the reason that Altamont Pass is imperfect is that birds and bats can become caught and die in the turbine rotors. This problem is the crux of many environmentalists’ uneasy embrace of wind power, but careful site selection can minimize it. In the *IEEE Institute*, J Charles Smith, executive director of the Utility Wind Integration Group, notes of Altamont Pass that,

OUT OF SIGHT, OUT OF MIND?

I admit it: I find wind farms and the turbines contained within them attractive. (Granted, though, I don’t live near one.) They mesmerize me every time I drive by or through Altamont Pass. But not everyone agrees with me, thereby explaining part of the appeal of offshore wind-farm alternatives. Their distance from population centers also mitigates any potential noise concerns and, because the winds are stronger and obstacles are fewer at sea, the turbines can be shorter (as measured from the water’s surface) than their onshore alternatives.

The continuous presence of strong, sustained winds is a key advantage of offshore wind farms. Stephen Connors, the director of the Massachusetts Institute of Technology’s (www.mit.edu) Analysis Group for Regional Energy Alternatives at the Laboratory for Energy and the Environment, points out that, 100 miles off the northeast coast of the United States, the wind is 50% stronger to twice as strong as it is onshore (Reference A). But the news isn’t all good; marine environments, with their caustic salt and moisture, extremes of temperature, and wind gusts, can impact turbine reliability and usable life. And there’s the issue of how to get the power back to shore; the farther the wind farm is from the coastline, the more expensive the undersea cable.

Finally, there’s the practical issue of how to solidly secure the turbines in inherently nonsolid water. In countries such as Denmark and Scotland, which have long extended continental shelves, it’s possible to secure wind turbines to the sea floor; a prototype 5-MW turbine 10 miles off the coast of Moray Firth, Scotland, for example, sits in 150 ft of water. The US coastline drops off much faster, however, and for that reason MIT has developed a 5-MW prototype in which the turbine tower connects to a 100-ft-diameter underwater platform, which then attaches to concrete anchors stretching up to 650 ft farther to the ocean floor.

And, if even the thought of offshore turbines sticking out of the water is aesthetically unpleasant to you, consider this: Several companies are developing turbines that locate below the water and tap into the periodic tide flow for energy generation. However, the potential impact on marine life, analogous to wind turbines’ prospective effect on avian populations, is a perhaps obvious hurdle to the practical implementation of such a scheme.

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A Stauffer, Nancy, “Deep-sea oil rigs inspire MIT designs for giant wind turbines,” MIT Laboratory for Energy and the Environment, Aug 29, 2006, web.mit.edu/newsoffice/2006/wind.html.

“This wind farm used old high-speed turbines right in a flyway, surrounded by open scrub grass with lots of ground squirrels to attract raptors. Now, we know more about avian flyways; we study each site for about a year” (**Reference 6**).

What other areas make good locations for wind farms? Wikipedia points out that “Seashores also tend to be windy areas and good sites for turbine installation, because a primary source of wind is convection from the differential heating and cooling of land and sea over the course of day and night. Winds at sea carry somewhat more energy than winds of the same speed in mountainous areas because the air at sea level is more dense.” Hilltops and seashores might be ideal locales from a wind-profile standpoint, but they’re anathema to folks who see wind turbines as eyesores. Looking again at **Figure 3**, you’ll note that plenty of the ideal wind-generation sites in the United States are removed from large population centers. The US Department of Energy estimates that, by harnessing just 6% of the US land area for wind energy, it would be possible to supply 1.5 times the country’s current electricity-consumption needs, thereby opening the door to further pollution- and greenhouse-gas-reducing steps, such as a wholesale population conversion to electric vehicles (**Reference 7**). Unfortunately, though, locating wind farms far away from population centers increases the cost and complexity of transferring generated power to those population centers.

DIVERSE DESIGN OPTIONS

Once you find an ideal site for your wind farm, what sort of turbines should you place there? As usual, no easy answers exist, as a visit to Altamont Pass and its plethora of turbine shapes and sizes suggest. **Figure 4** shows the guts of a traditional multiblade, nacelle-housed, horizontal-axis turbine design. The gearbox translates the blades’ 30- to 60-rpm rotational speed to the 1200 to 1500 rpm necessary to operate a generator. These turbines come in both downwind- and upwind-pointing variants: The upwind versions are more common, because towers produce turbulence behind them, which causes fatigue failure with downwind-turbine blades. However, the upwind versions are also more mechanically complex, each requiring a wind vane and yaw drive to keep them facing into the wind.

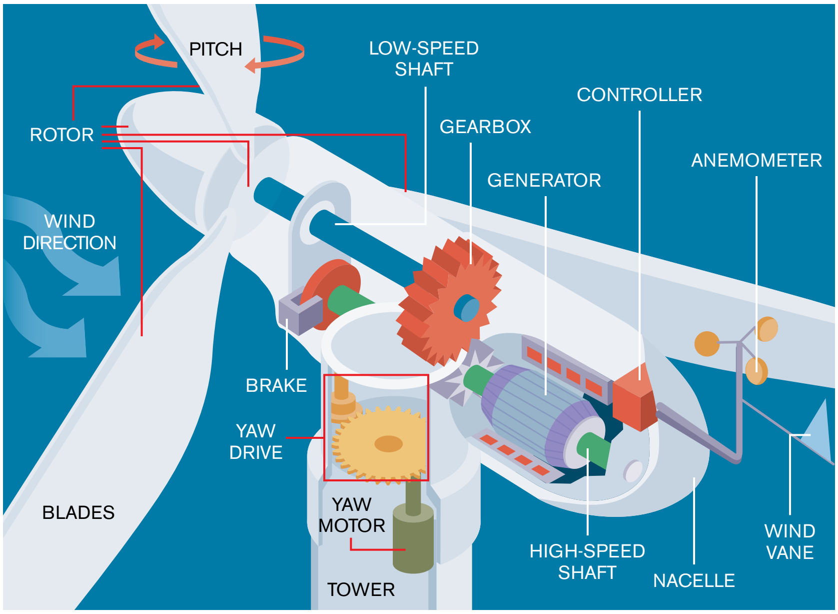

Figure 4 A traditional upwind horizontal-axis turbine design includes, at its heart, a gearbox that translates the relatively slow blade-rotation speed to a higher speed shaft rotation suitable for electricity generation (courtesy US Department of Energy).

Your next questions are: How tall should your turbine be, and how many blades should it house? Once again, you have a number of factors to consider, which Wikipedia addresses. “The wind blows faster at higher altitudes because of the reduced influx of drag of the surface (sea or land) and the reduced viscosity of the air. The increase in velocity with altitude is most dramatic near the surface and is affected by topography, surface roughness, and upwind obstacles such as trees or buildings. Typically, the increase of wind speeds with increasing height follows a logarithmic profile that can be reasonably approximated by the wind profile power law, using an exponent of one-seventh, which predicts that wind speed rises proportionally to the seventh root of altitude. Doubling the altitude of a turbine, then, increases the expected wind speeds by 10% and the expected power by 34%.”

So, the taller the turbine, the better, both because the wind is stronger and because you can make the blades longer. But the taller-is-better argument holds true only to a point. The taller the turbine, the more expensive it is to build and maintain, and, at some point, you need to worry about interfering with air traffic. Next, how many blades should the turbine have: one with counterbalance, two, three, or more? The variance in wind velocity with altitude causes the force and, therefore, torque on a horizontal-axis turbine blade to be greatest at the upper reach of its arc (**Reference 8**). The resultant cyclic twist, a reliability issue that you can design around, is worse with even-blade-count turbines, because one blade is at its maximum, or straight up, while another is at its minimum, or straight down. All other factors being equal, higher blade counts bring lower vibration intensity, generally lower noise and wear, and generally higher efficiency. On the other hand, small, high-blade-count turbines suffer decreased efficiency due to blade-to-blade turbulence effects. Also, turbine cost generally increases with increased blade count, regardless of turbine size.

Visit a wind farm, and you might also see strange-looking vertical-axis turbines, reminiscent in appearance of an eggbeater (**Figure 5**). These Darrieus or Gorlov wind turbines have higher efficiency than their horizontal-axis counterparts. The turbines’ names derive from their inventors: respectively, French aeronautical engineer Georges

(continued on pg 50)

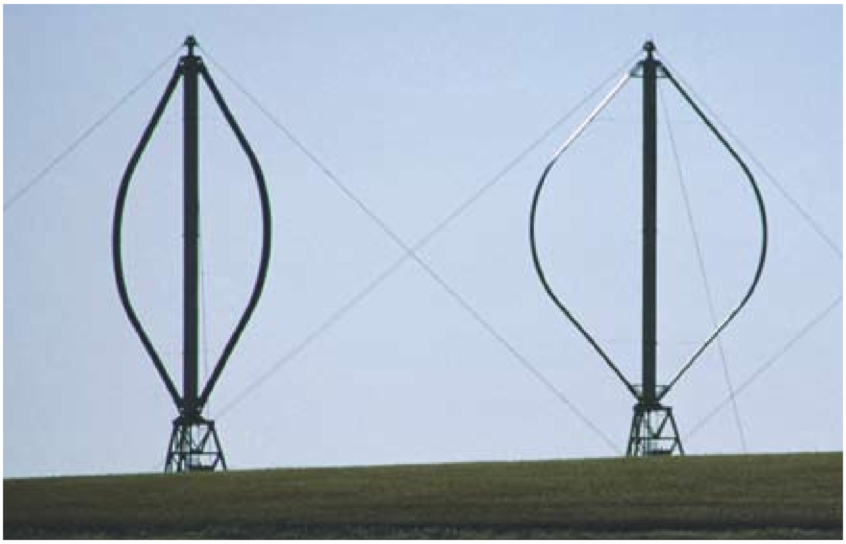

Figure 5 Vertical-axis Darrieus wind turbines can operate at higher efficiencies than their horizontal-axis peers; a simpler construction and immunity from wind-direction shifts are other advantages.

Jean Marie Darrieus, who patented his version in 1931, and Russian-born US mechanical engineer Alexander Gorlov, whose design won the Thomas A Edison Patent Award from the American Society of Mechanical Engineers in 2001. Quoting Wikipedia, "Albert Betz, a German physicist, determined in 1919 that a wind turbine can extract at most 59% of the energy that would otherwise flow through the turbine's cross section. The Betz limit applies regardless of the design of the turbine. More recent work by Gorlov shows a theoretical limit of about 30% for propeller-type turbines.

"Actual efficiencies range from 10 to 20% for propeller-type turbines and are as high as 35% for 3-D vertical-axis turbines, such as Darrieus or Gorlov turbines." Darrieus turbines tend to be simpler to build, because the gearbox and other subsystems are at the base of the turbine, not crammed into a nacelle on top of a tower. They also don't need to point directly into—or away from—the wind. Unfortunately, Darrieus turbines aren't universal panaceas; they have their downsides, too. Variable-direction wind-induced high stress on the vertical axis decreases reliability. Also, their low starting torque necessitates the inclusion of a supplemental rotor or separate power source to start them turning. And, because they generally reside on towers, they're constrained by the slower, more turbulent, and less efficient airflow near the ground.

Design innovation continues for both horizontal- and vertical-axis turbines. Department of Energy documentation on turbine design, for example, points out that "the gearbox is a costly (and heavy) part of the wind turbine, and engineers are exploring direct-drive generators that operate at lower rotational speeds and don't need gearboxes" (**Reference 9**). Wikipedia notes, "Newer wind turbines often turn at whatever speed generates electricity most efficiently. The variable-frequency current is then converted to dc and then back to ac, matching the line frequency and voltage. Although the two conversions require costly equipment and cause power loss, the turbine

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can capture a significantly larger fraction of the wind energy."

The IEEE Power Engineering Society devoted its November/December 2005 issue to the subject of wind power. Smith's editorial, which introduced a five-article series, made the following comments about wind-farm-fed power-plant design: "Wind plants have benefited from steady advances in technology that have been made over the past 15 years. Much of the advance has been made in the components dealing with the utility interface, the electrical machine, the power electronic converter, and the control capability. We have come a long way from the days of the simple induction generator with soft start. We can now control the real and reactive power output of the machine within some design range subject to fuel availability, limit the positive ramp rate of the machine, control voltage, limit power output, and design for low-voltage ride-through. Soon, we will be able to provide governor functions and controlled ramp-down during high wind speed events" (**Reference 10**).

MANAGING IMPERMANENCE

Perhaps the biggest challenge—and opportunity—to those evaluating the implementation of wind turbines and equipment running on energy from those turbines is wind's inherent unpredictability. This randomness, Wikipedia explains, results from the fundamental fact that the sun provides heat unevenly to the earth; hence, the poles receive less energy from the sun than the equator does. Also, the dry land heats up and cools down more quickly than the seas do. "The differential heating powers a global atmospheric convection system reaching from the earth's surface to the stratosphere, which acts as a virtual ceiling," says the online reference. On average, wind tends to be stronger in winter than summer and at night than during the day. Note that this situation is the exactly opposite profile of two other green power sources: hydroelectric and solar power. The approaches often neatly counterbalance each other.

Wind's night-and-winter preference is good news if you want your wind farm to supply a community's electrical-heating needs; it's bad news if you expect wind power to feed your customers' air conditioners. Although each wind farm's output is variable over less than a one-year time frame, a multifarm grid spanning multiple geographic regions can moderate some of this inconsistency. Meteorologists can often accurately predict and account for weather patterns that might affect wind-farm output, bringing online other power sources well before the weather's manifestation. Electrical pricing can also act as an effective catalyst for consumers to change their behavior. If consumers know that electricity costs more at certain times of day and less at others and that the price varies depending on wind-farm-output patterns, they might, for example, do laundry or charge their electrical cars overnight versus in the middle of the day. And, adopting a more long-term perspective, a given wind farm's year-to-year output variation is usually no more than a few percentage points up or down. Ironically, global-warming trends are most likely to affect that variation.

To flatten out some of the turbine-to-turbine output variability that occurs within a farm throughout the day, as well as to extract the maximum energy from a plot of land, a plant designer might be tempted to cram as many turbines as possible into the available space. The more-turbines-are-better strategy works, but only up to a point. Just as blade-to-blade turbulence can decrease intraturbine efficiency, placing turbines too closely together decreases interturbine turbulence efficiency, thus decreasing the entire farm's performance. Wikipedia notes that ideally "turbines are spaced three to five rotor diameters apart perpendicular to

FOR MORE INFORMATION

Carnegie Institution
www.carnegieinstitution.org

General Electric
www.ge.com

The Massachusetts Institute of Technology's Analysis Group for Regional Energy Alternatives at the Lab for Energy and the Environment
http://web.mit.edu/agrea/

National Renewable Energy Laboratory Wind Technology Center
www.nrel.gov/wind/

New York University
www.nyu.edu

Southwest Windpower
www.windenergy.com

Toyota
www.toyota.com

United States Department of Energy Wind Energy Program
www.eere.energy.gov

Utility Wind Integration Group
www.uwig.org

the prevailing wind and five to 10 rotor diameters apart in the direction of the prevailing wind to minimize efficiency loss." In these optimum configurations, "the wind park effect loss can be as low as 2% of the combined nameplate rating of the turbines."

On wind compared with traditional fuel sources that utility companies can quickly bring online whenever demand warrants, Smith comments, "A wind plant is generally an energy resource, not a capacity resource. We live in a capacity world, and we have to think about a wind plant differently. It supplies cheap energy when it is available, and it is a valuable contribution to a well-designed system. A number of investigators have pointed out that a wind plant should be viewed [in] an unconventional way, as load (negative load, that is, and not generation). An examination of the statistics of wind production shows that it behaves much more like load than generation. Instead of talking about firming up the wind to make it look like something that it is not, accept it for what it is and deal with the net load accordingly. We're used to dealing with the aggregate load, which has a large degree of random behavior and uncertainty, so let's begin to think about dealing with this new net load in the same way. We don't try to balance each load on the system, so let's not try to balance each wind generator on the system. It is the net system load that's important."

The US space program, which federal budget resources primarily finance, is a tangible example of how significantly a strong government backing can advance a technology's capabilities, decrease its costs, and spur ancillary technologies. The US-government-sponsored rural-electrification program of the 1950s, which connected most US homes and businesses to a central power grid and, in doing so, ironically closed the book on the windmill's role as a power provider for farms, showed how strong government backing can radically transform a culture. Wind power, along with other renewable resources, will benefit from similar strong government backing, as the downsides of a fossil-fuel-dependent culture become increasingly evident.

Ironically, Smith also mentions the US space program in a call to arms that closes his wind-power treatise. "The electric-power system is the most complex machine ever devised, more complex even than the manned space-flight program. The design and operation of such a machine could only be carried out by an incredibly talented, capable, intelligent group of people. That group is the long list of scientists, engineers, technicians, mathematicians, computer scientists, and other people who have dedicated their lives to the development, care, and feeding of this machine. I submit that this group is still the most creative, talented, intelligent, and dedicated group of professionals in the world. We have been faced with challenges and problems throughout the history of our industry, and we have always risen to the occasion, solved the problems, and moved on. I have every reason to believe that we will continue to do the same."**EDN**

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