CHAPTER 12

Large-Scale Renewables: Wind and Solar

12.1 Renewable Electric Power Systems

Locating generation on the customer's side of the meter has a significant economic advantage: it allows photovoltaic (PV) and other self-generation systems to compete against the retail price of electricity. It is much harder for renewables to compete against conventional central power stations in wholesale markets because wholesale prices are often one-half to one-third of retail rates. The most advanced, and cost-effective, renewable electricity generation systems are wind turbines with economics that can compete, toe-to-toe, with other large central stations at the wholesale level. Much of this chapter is devoted to these systems.

In addition to wind systems, concentrating solar power (CSP) systems are also making inroads into the marketplace for central power stations. These CSP systems convert sunlight into heat, which is then used to drive a heat engine coupled to an electrical generator. These solar-thermal systems include reflective parabolic troughs that concentrate sunlight onto a focal line containing a circulating heat-transfer fluid used to generate steam to run a rather conventional steam-cycle power plant. The largest such system, some 354 MW, has been operating in the desert in southern California for more than two decades. More recently, an even larger solar-dish array has been proposed that will use arrays of parabolic dish concentrators to focus heat onto electricity-generating Stirling engines of the sort described in Chapter 10.

12.2 Historical Development of Wind Power

Wind has been utilized as a source of power for thousands of years for such tasks as propelling sailing ships, grinding grain, pumping water, and powering factory machinery. The world's first wind turbine used to generate electricity was built in 1891 by a Danish inventor and school principal, Poul la Cour. It is especially interesting to note that la Cour experimented with electrolysis to produce hydrogen for gas lights in his schoolhouse (records include reference to a number of windows that had to be replaced as a result of his tinkering). In that regard, we could say that he was one hundred years ahead of his time—the concept of using renewable sources of electricity to electrolyze water to power fuel cells has re-emerged as an intriguing possibility for the twenty-first century.

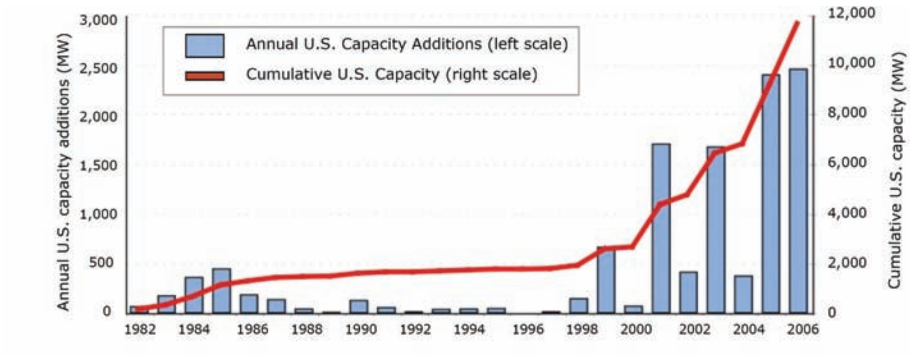
In the United States, the classic multibladed, water-pumping wind turbines used to be ubiquitous across the Great Plains. Indeed, it can be argued that they enabled the crucial first steps in the expansion of farming, ranching, and human settlements into that vast stretch of relatively arid country. Those turbines were ideal for water pumping because their multiblade design produces high torque even at low wind speeds—just what is needed to overcome the friction and weight of that heavy pumping rod that moves up and down in the well. The strong winds in those Great Plains states also stimulated the development of small wind-electric systems for rural areas not yet served by the electricity grid. Hundreds of thousands of these fast spinning, two- and three-bladed turbines used to dot the landscape in the 1930s and 1940s, but they disappeared as soon as the more reliable and economic utility grid spread across the landscape. The role that wind once played in the economic development of these windy states seems now on the verge of being repeated as wind farms begin to create employment, tax revenues, and hefty royalty payments that are providing a much-needed jolt to many local economies.

The oil shocks of the 1970s, which heightened awareness of our energy problems, coupled with substantial financial and regulatory incentives for alternative energy systems, stimulated a renewal of interest in wind power in the United States. California became the proving ground for dozens of manufacturers who installed thousands of new wind turbines in the Altamont Pass region just east of San Francisco, the Tehachipi Pass near Barstow, and San Gorgonio Pass just north of Palm Springs. Many of these early machines did not perform very well, and their very location in mountain passes often put them directly in the path of migrating birds. Their location coupled with their small-diameter, high-speed blades, created the image that these were lethal "bird cuisinarts." When lucrative tax incentives were terminated in the mid-1980s, the U.S. wind industry nearly collapsed as well.

Lack of interest in wind in the United States was reflected in the lackluster growth in installed capacity in the decade between 1988 and 1998. By contrast, between 2000 and 2006 it grew at an average annual rate of 23%, reaching a total of just under 14,000 MW in 2007—enough to satisfy the entire electricity demand of 3.5 million homes. The 2500 MW of new wind projects brought on line in 2006 was 19% of that year's rated-power additions to the U.S. grid and represented a $3.7 billion investment in new installations (Wiser, et al., 2007). As shown in Figure 12.1, these later years have been characterized by a boom-and-bust cycle of construction, which reflects the on-again, off-again, short-term extensions of a federal production tax credit (PTC) that as of 2007 provides a ten-year, $0.019/kWh incentive for wind projects.

The U.S. wind industry stalled from the late 1980s to the mid-1990s, but wind technology development continued unabated in Europe—especially in Denmark, Germany, and Spain—and they entered the market with larger, less costly, more efficient, more reliable turbines that created the global sales boom in the late 1990s. By the turn of the century it was possible to make the case that wind, in good locations, was as cheap as any other source of electricity (Jacobson and Masters, 2001). Figure 12.2 presents a comparison of the average price of wind power in recent years with the range of wholesale prices paid for bulk power in the United States. On a cumulative basis, wind has consistently been priced at or below the low end of the wholesale power price range.

figure 12.1



Installed capacity of wind turbines in the United States and net annual additions. Irregular net additions illustrate the impact of unpredictable tax credits.

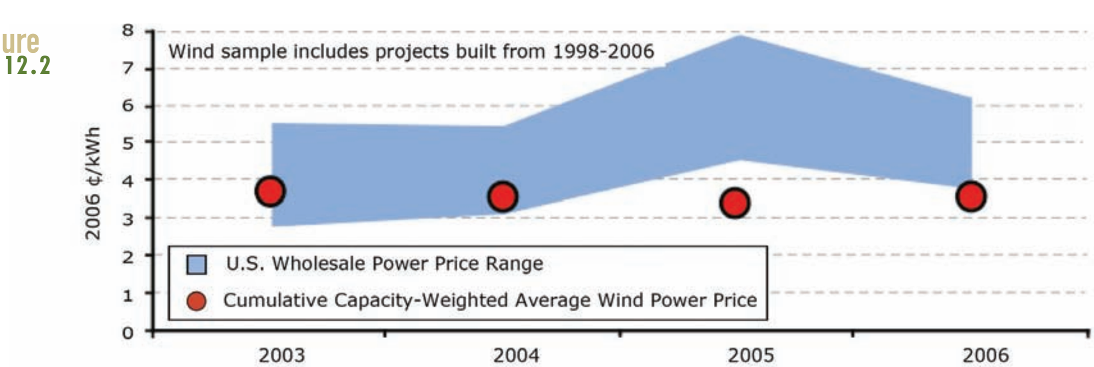
Source: Wiser, et al., 2007

Globally, the cumulative installed capacity of wind turbines grew at a fairly steady rate of 25% per year between 1996 and 2006, reaching just over 74,000 MW in 2006. As shown in Figure 12.3, the country with the largest total installed wind capacity in 2006 was Germany (28%) followed by Spain and the United States, each with 16%. The largest increases in capacity in 2006 were in those same three countries, with the United States in the lead at 2.4 GW of added capacity. As an interesting comparison, the new installed capacity of wind around the globe in 2006 (15 GW) was about 6 times the increase of photovoltaic installations (2.5 GW), but the rate of growth of PVs was higher (40% versus 26%).

12.3 The Wind Resource

How much power and energy is available in the wind? To help answer that question, the National Renewable Energy Laboratory (NREL) defines the wind power classification scheme

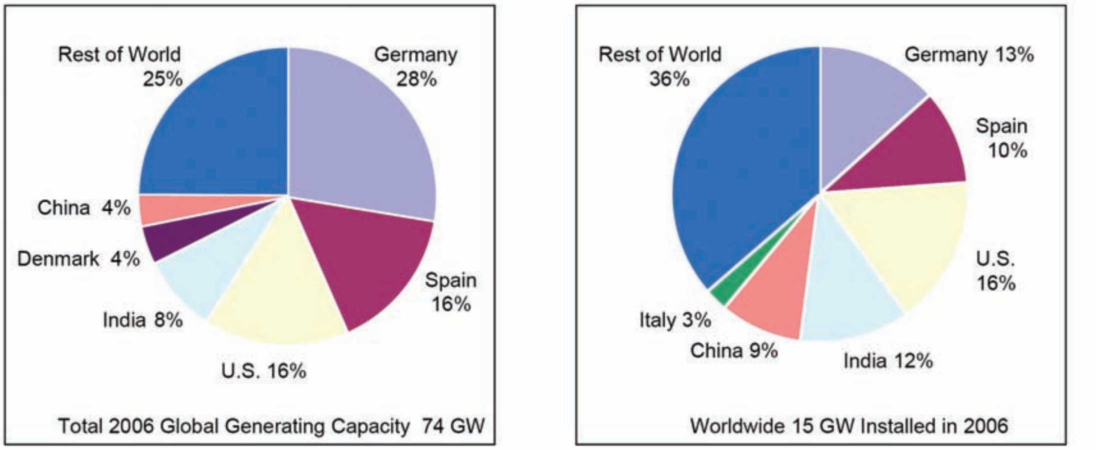
figure 12.2



The cumulative capacity-weighted average wind price in the United States compared with conventional generation wholesale power prices.

Source: Wiser, et al., 2007

figure 12.3



Worldwide installed capacity of wind turbines and net annual additions. Installed capacity grew at 25% per year for the decade from 1996 to 2006.

Source: data from GWEC, 2006

table 12.1 Standard Wind Power Classification Scheme*

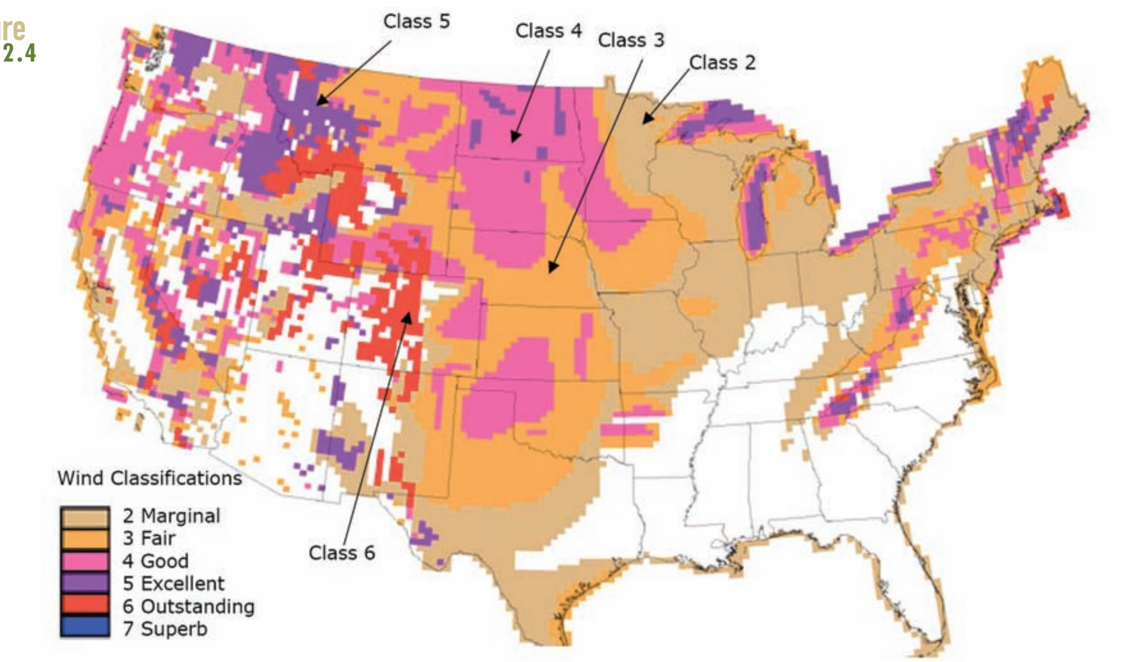
Wind Power Classification	Resource Potential	Wind Power Density (W/m²)	Average Wind Speed (m/s)	Average Wind Speed (mph)
2	Marginal	200–300	5.6–6.4	12.5–14.3
3	Fair	300–400	6.4–7.0	14.3–15.7
4	Good	400–500	7.0–7.5	15.7–16.8
5	Excellent	500–600	7.5–8.0	16.8–17.9
6	Outstanding	600–800	8.0–8.8	17.9–19.7
7	Superb	> 800	> 8.8	> 19.7

* Average wind speeds for each category are based on Rayleigh statistics (see Sidebar 12.1).

shown in Table 12.1. For example, Class-4 winds (referred to as "Good") have between 400 and 500 watts of power per square meter of cross-sectional area, which correlates to an average wind speed of 15.7 to 16.8 mph and is often thought of as the threshold of economic viability for wind power.

Wind quality varies with geography, so NREL has developed a continuously improving series of national and regional maps that apply this wind power classification scheme, such as the one shown in Figure 12.4. These have traditionally been based on wind evaluations at an assumed elevation of 50 meters, which was roughly the hub height for turbines at the time the maps were first made. With wind turbines getting ever larger, mounted on taller and taller towers, new maps are being developed that show the resource at 80 meters, which is closer to the current hub height of large turbines (Archer and Jacobson, 2005). At that higher elevation, wind

figure 12.4



U.S. wind resources organized by wind classifications at an elevation of 50 meters.

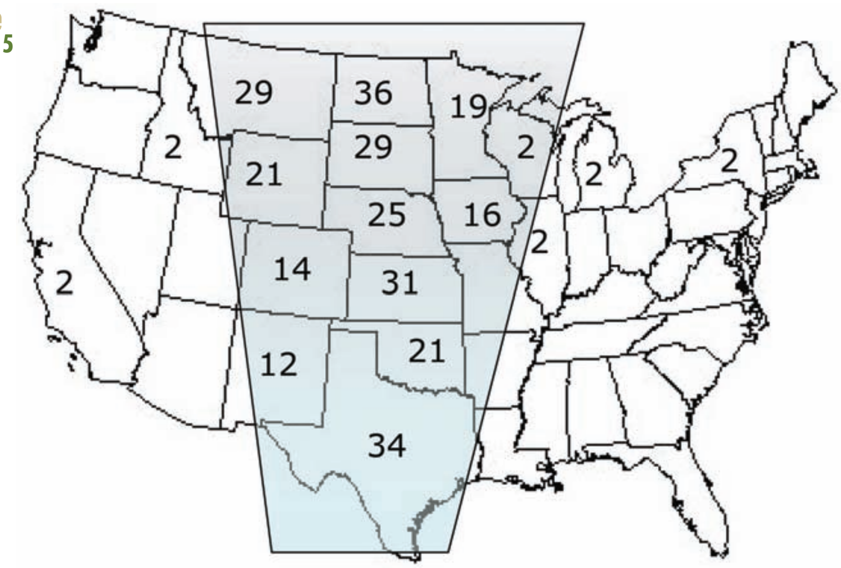
Source: NREL, 1987

speeds increase enough to often bump the wind regime upward by one classification (e.g., from class 3 to class 4), making available an even larger wind resource base than previously estimated.

Wind maps such as those shown in Figure 12.4 can be used as a starting point for estimates of the electrical energy that wind turbines can potentially deliver in a given region. To make such estimates, significant land use questions must be evaluated. Flat grazing lands would be easy to develop, and the impacts on current usage of such lands would be minimal. On the other hand, developing sites in heavily forested areas or along mountain ridges, for example, would be much more difficult and environmentally damaging. Urban areas and highly sensitive lands such as national parks also need to be excluded from consideration. Economic viability of remaining areas will often be closely tied to the proximity to transmission lines with available capacity as well as load centers near enough to take advantage of the available power.

Land-use constraints play a major role in siting wind power systems. Estimates of their effect on U.S. wind energy potential have been made by the Pacific Northwest Laboratory. In one assessment the exploitable wind resource at 50 meters was estimated to be 16,700 billion kWh/yr with no land-use restriction, but decreased to 4600 billion kWh/yr under the most severe constraints (Elliott, 1991). By comparison, the total electricity generated by all power plants in the United States in 2005 was 4340 billion kWh, which suggests the wind resource is theoretically sufficient to meet the entire U.S. demand. That, of course, seems highly unlikely because wind doesn't always blow at exactly the right time and the cost of energy storage to buffer the mismatch between instantaneous supply with current demand

figure 12.5



Estimated percentage of U.S. electricity demand that could be met with the wind resource in the windiest states. North Dakota or Texas alone could theoretically supply more than one-third of national demand. Based on data from Elliott (1991) for winds of class 3 or better at 50 meters.

seems prohibitive. The fraction of U.S. demand that could actually be met with wind power in the future is highly uncertain.

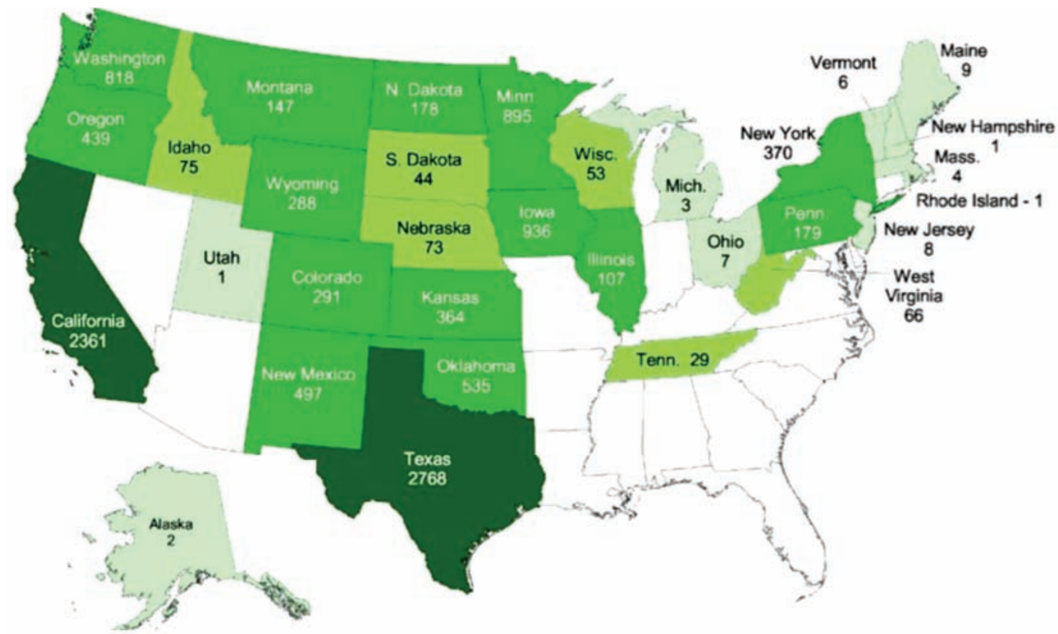
Another important difficulty in supplying a high fraction of U.S. power by wind is the disparity between where the wind blows and where the major load centers are located. As Figure 12.5 suggests, the best winds tend to be located along a wedge of states from Montana and Minnesota in the north, down to Texas in the south. The wind resource in one state alone, North Dakota, is thought to be sufficient to supply over one-third of all U.S. electricity. Some have dubbed the Great Plains region “the Saudi Arabia of wind” because of the great, untapped potential. California, which ranks seventeenth in terms of wind resource, used to have more installed capacity than any other state. However, in 2006, Texas, which has abundant wind resources, overtook California as the number one state (Figure 12.6).

12.4 Wind Turbine Technology

Wind turbines are characterized by the axis about which the blades rotate, the number of blades, and whether they face into the wind or away from it. Figure 12.7 illustrates these distinctions.

The only vertical-axis machine that has had any commercial success is the Darrieus rotor, named after its inventor, French engineer G. M. Darrieus, who first developed the turbines in the 1920s. The shape of the blades is that which would result from holding a

figure 12.6

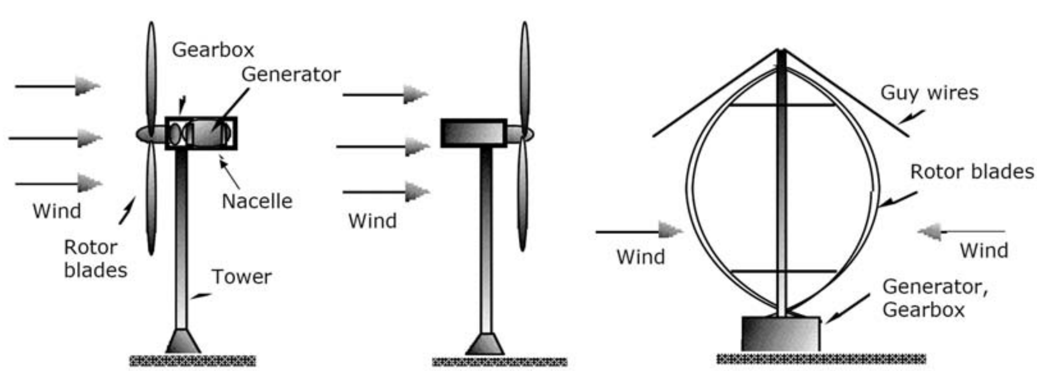


Distribution of the 11,600 MW of installed wind turbine capacity by state as of January 2007.

SOURCE: National Renewable Energy Laboratory

rope at both ends and spinning it around a vertical axis, giving it a look not unlike a giant eggbeater. There are a number of potential advantages of vertical-axis machines over their horizontal-axis counterparts. They always point into the wind, which eliminates the need for special yaw (left-right directional) controls. The heavy machinery contained in the *nacelle*

figure 12.7



Horizontal-axis wind turbines are either upwind machines (a) or downwind machines (b). Vertical-axis wind turbines accept the wind from any direction (c). Most turbines these days are three-bladed, horizontal-axis, upwind machines.

(the housing around the generator, gearbox, etc.) is at ground level so the support structure for the turbine doesn't need to be nearly as strong. Moreover, the blades in a Darrieus rotor are almost always in pure tension, which means that they can be relatively lightweight and inexpensive because they don't have to handle the constant flexing associated with blades on horizontal-axis machines. On the other hand, the best winds are higher up, which means these low-to-the-ground rotors don't have nearly the wind resource to tap into compared to their horizontal counterparts, which tend to be mounted on tall towers.

Vertical-axis machines do remain intriguing, but the industry has pretty much abandoned the concept and virtually all turbines are now horizontal-axis machines. The next key design question is whether to make them upwind machines, in which the wind hits the blades before it reaches the tower, or the other way around, as downwind machines. Downwind machines have the advantage of automatic yaw control as the wind pushes the blades away from the tower, but the wind-shadowing effect of having the tower in front of the blades causes blade flexing every time the blades swing behind the tower. This flexing not only has the potential to cause blade failure due to fatigue, but it also reduces power output while increasing blade noise. The result is that the wind industry has adopted horizontal-axis, upwind machines as the standard.

The remaining question is how many blades the turbine should have. The classic multibladed farm windmill has a large area of rotor blades facing into the wind, which provides the high torque needed for simple water pumping. They don't spin very fast, so the turbulence caused by one blade on the following blade is relatively unimportant. For electricity generation, however, the tip speed of the blades is very high and the turbulence caused by one blade on another can significantly reduce overall efficiency, which suggests the fewer the number of blades, the better. Most new turbines have two or three blades. Three-bladed rotors run smoother than their two-bladed counterparts because the impact of tower interference as well as the variation of wind speed with height are more evenly transferred from rotors to drive shaft. Most wind turbines now have three blades.

The number of blades affects the overall rotor efficiency as a function of a quantity called the *tip-speed ratio* (TSR), as illustrated in Figure 12.8. The tip-speed ratio is the speed at which the outer tip of the blade is rotating divided by the wind speed. For the American multiblade windmill so common in the 1930s and 1940s, the optimum TSR is less than one, whereas for a typical three-bladed wind turbine the tip speed is about four times the speed of the wind. The maximum theoretical efficiency of a rotor is the *Betz limit*. Albert Betz was a German physicist who in 1919 showed that the maximum possible rotor efficiency occurs when the blades slow the wind by two-thirds, which results in a maximum possible efficiency of 59.3%. Solution Box 12.1 illustrates the use of TSR to estimate the rpm of the rotor.

Figure 12.9 shows an artist's rendition of the inner workings of the 3.6-MW wind turbine manufactured by GE. The main components inside the nacelle are the generator, gearbox, and yaw drive system. The three-bladed rotor hub includes pitch drive mechanisms to vary the pitch of the blades to control speed.

Turbine manufacturers have exploited the economies of scale that come with building larger and larger turbines. Most turbines built before 2000 were rated at less than 1 MW

SOLUTION

SOLUTION BOX 12.1

How Fast Does the Turbine Spin?

One of the first impressions you are likely to have when you see a modern wind turbine is how slowly it seems to turn. Imagine a three-bladed turbine with a blade diameter of 102 meters that generates 3.6 MW of power when exposed to 14 m/s wind speeds. If we assume a tip-speed ratio of 4, estimate how fast the turbine spins.

Solution:

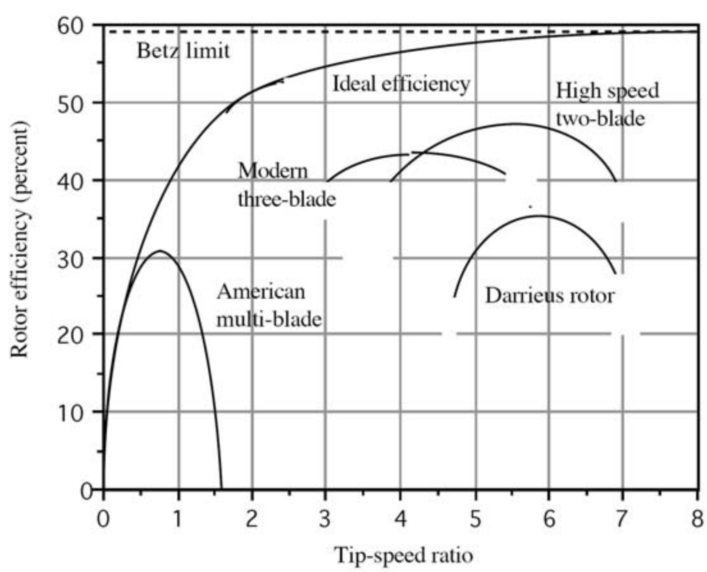
Begin with the definition of TSR.

$$\text{Tip-speed-ratio (TSR)} = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{(\text{rev/min}) \times \pi D\ (\text{m/rev})}{V_w\ (\text{m/s}) \times 60\ (\text{s/min})}$$

$$\text{rev/min} = \frac{60\ V_w}{\pi D} = \frac{60\ (\text{s/min}) \times 14\ (\text{m/s}) \times 4}{\pi \times 102\ (\text{m/rev})} = 10.5\ \text{rpm}$$

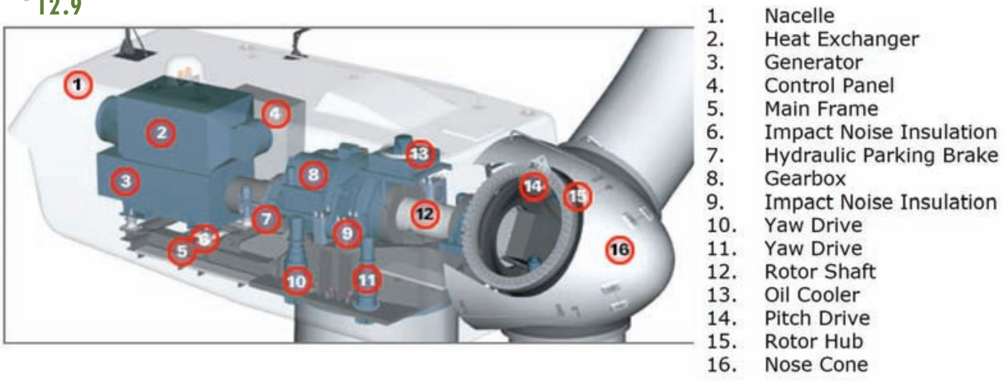
That is about 5.7 seconds per revolution. Although that looks very slow, the tip of the blades would be moving at 4 × 14 m/s = 56 m/s, which is about 125 miles per hour.

figure 12.8



Rotor efficiency depends on the number of blades and tip-speed ratio. The theoretical maximum, called the Betz limit, is 59.3%.

figure 12.9 **An Inside View of the 102-meter, 3.6-MW GE Wind Turbine**

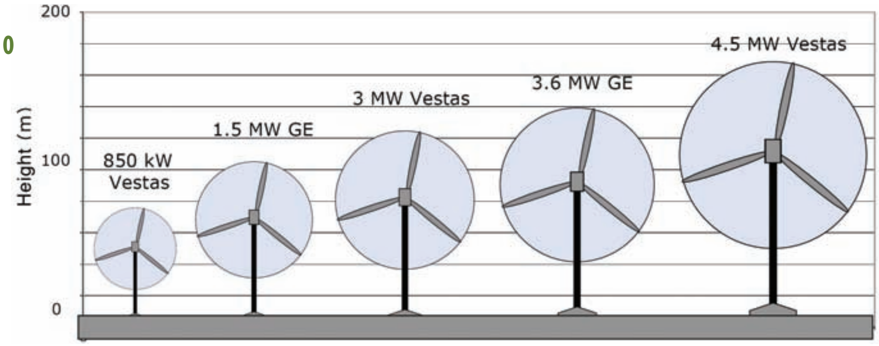


each; those are now considered small machines. New turbines are several megawatts each and some under development are as large as 4.5 MW. Figure 12.12 shows how big these new machines are becoming. The 4.5-MW turbine being developed by Vestas Wind Systems for the offshore market will have a blade diameter of 120 meters (longer than a football field), and by the time it is placed on its tower the top of the sweep of its blades will be over 160 meters (roughly the height of a fifty-story building).

12.5 Energy from the Wind

Just how much power is in the wind and how much can we imagine the turbine being able to extract? The answers, of course, depend on how fast the wind is blowing, the swept area of the blades, and the detailed characteristics of the turbine. The starting point is the power in the wind itself.

figure 12.10

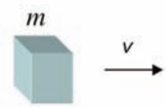


Showing the evolution of turbine sizes. The 4.5-MW Vestas turbine will be as tall as a fifty-story building.

12.5.1 Instantaneous Power in the Wind

Consider a "piece" of air with mass m moving at a speed v. Its kinetic energy (K.E.) is given by the familiar relationship described in Section 4.3 of this book:

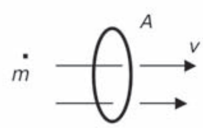
Eq. 12.1



$$\text{K.E.} = \frac{1}{2} m v^2$$

Because power is energy per unit of time, the power represented by a mass of air moving at velocity v through area A will be

Eq. 12.2



$$\text{Power through area } A = \frac{\text{Energy}}{\text{Time}} = \frac{1}{2}\left(\frac{\text{Mass}}{\text{Time}}\right) v^2$$

The mass flow rate $\dot{m}$, through area A, is the product of air density ρ (which is a function of temperature and atmospheric pressure), wind speed v, and cross-sectional area A.

Eq. 12.3

$$\dot{m} = \frac{\text{mass passing through } A}{\text{time}} = \rho A v$$

Combining Equation 12.2 with 12.3 gives us an important relationship:

Eq. 12.4

$$P_W = \frac{1}{2} \rho A v^3$$

In S.I. units,

P_w = power in the wind (watts)
ρ = air density, which is 1.225 kg/m^3 at 15°C and 1 atm
A = cross-sectional area through which the wind blows (m^2)
v = wind speed (m/s); note: 1 m/s = 2.237 mph

The important thing to note from Equation 12.4 is that power in the wind increases as the cube of wind speed. That is, doubling the wind speed increases the power eight-fold. Another way to look at it is, for example, 1 hour of wind blowing at 20 mph carries as much energy as 8 hours at 10 mph, or 64 hours (2.7 days) of wind blowing at 5 mph. What really matters for a wind turbine is its ability to capture those faster winds. In fact, most big turbines aren't even turned on for low-speed winds. Another thing to note from Equation 12.4 is that power goes up as the swept area increases, which means a doubling of the blade diameter increases the available power by a factor of four.

SOLUTION

SOLUTION BOX 12.2

Average Power in the Wind—Be Careful!

Suppose the wind blows for 10 hours at 8 m/s and 10 hours at 4 m/s. What would be the total energy and average power per square meter of area over those 20 hours?

Solution:

Applying Equation 12.4 to each wind regime:

$$\textbf{Energy} = \frac{1}{2}\rho v^3(\text{W/m}^2) \times \Delta t\ (\text{hr})$$

$$\textbf{Energy (10 hr @ 8 m/s)} = 0.5 \times 1.225 \times 8^3 \times 10 = 3136\ \text{Wh/m}^2$$
$$\textbf{Energy (10 hr @ 4 m/s)} = 0.5 \times 1.225 \times 4^3 \times 10 = 392\ \text{Wh/m}^2$$
$$\textbf{Total} = 3136 + 392 = 3528\ \text{Wh/m}^2$$

Notice how insignificant the energy contributed by those low-speed, 4 m/s winds is. The average power over those 20 hours is 3528 Wh/20 hr = 176.4 Wh/m^2.

Suppose we had simply plugged the average wind speed of 6 m/s into Equation 12.4. What would we have gotten for average power?

$$\textbf{Average Power} = \frac{1}{2}\rho\left(\bar{v}\right)^3 = 0.5 \times 1.225 \times 6^3 = 132.3\ \text{W/m}^2$$

Our 132.4 W/m^2 estimate using average wind speed in Equation 12.4 is 25% lower than the correct answer of 176.4 W/m^2.

12.5.2 Average Power in the Wind

Although Equation 12.4 correctly provides the instantaneous power in the wind, the nonlinear relationship between wind speed and power tells us we need to be cautious about using it to estimate the average power in winds that have variable speeds. Just plugging the average wind speed into Equation 12.4 will underestimate the average power by a significant amount (as we shall see later, the error may be close to 50%).

Even the very simple example shown in Solution Box 12.2 shows the need to have some idea of the distribution of wind speeds at a site if we want to estimate the average power or total energy that a wind turbine will produce. For a real wind project, a lot of data need to be collected over a considerable period of time to try to determine the typical number of hours each year that the wind will blow at 1 m/s, 2 m/s . . . and so forth. From this data, an analysis similar to that shown in Solution Box 12.2 can be worked out.

There are some shortcuts that are often taken, however, the most common of which begins with a simple estimate of the average wind speed at the site. Average wind speed is easy to measure using an inexpensive anemometer, which is used as a "wind odometer" to measure miles of wind that pass by as indicated by the number of revolutions of the spinning anemometer cups. Dividing by the hours it took to record those miles gives an average wind speed in miles per hour. Coupling average wind speed with an assumption about the distribution of wind speeds about that average enables us to find the average power in the wind. The mathematics is a little tricky, so we're putting the analysis in Sidebar 12.1 for those who are interested in such details. Later we will summarize the conclusions.

12.5.3 Energy from a Turbine Using Average Power in the Wind

If we can make some assumptions about the efficiency of a wind turbine, we can quickly estimate the power and energy that will be delivered if we assume Rayleigh winds with some average wind speed. Table 12.2 uses Equation 12.8 to assemble a convenient conversion from average wind speed to average power in the wind.

Although wind turbine efficiencies vary depending on the wind regime in which they are placed, in good winds they tend to operate with an overall efficiency of somewhere between 25% and 35%. Those state-by-state estimates of wind energy potential shown in Figure 12.5, for example, assumed average turbine efficiencies of 25%, which is on the low side for today's modern turbines.

To illustrate this simple procedure, suppose we want to estimate the energy delivered from a 30%-efficient 2000 kW wind turbine with 80-meter blades if it is located in an area with an average wind speed of 7 m/s (the beginning edge of class-4 winds). From Table 12.2, the average power in the wind is 401 W/m^2 so the average power that the turbine would deliver would be

$$P_{avg} = \eta_{Turbine} \times A_{Rotor}\ (\mathrm{m}^2) \times P_{Wind}\ (\mathrm{W/m}^2) = 0.30 \times \frac{\pi}{4} \times 80^2 \times 401 = 604{,}693\ \mathrm{W}$$

Over a year's time (8760 hours), the output would be about

$$\textbf{Energy delivered} = 604.7\ \mathrm{kW} \times 8760\ \mathrm{hr/yr} = 5.3 \times 10^6\ \mathrm{kWh/yr}$$

12.5.4 Wind Turbine Capacity Factors

All power plants, whether they be nuclear, hydroelectric, coal, or whatever, have a *rated power* output, P_R, which tells us how many kilowatts or megawatts they deliver when running at full power. A conventional power plant may operate at full, or near-full, output most of the time, but that is not the case for wind turbines because they are so dependent on available winds. This means, for example, that a 100-MW base-load, coal plant will be likely to deliver many more

SIDEBAR

SIDEBAR 12.1

Rayleigh Statistics

The distribution of wind speeds at a site is often assumed to follow a Rayleigh probability density function described by the following equation:

Eq. 12.5 $$f(v) = \frac{\pi v}{2(v_{avg})^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{v_{avg}}\right)^2\right]$$

where v_{avg} = average wind speed

Figure 12.11 shows what this looks like.

What we would like to find is the average power in the wind. That is, we want

Eq. 12.6 $$P_{avg} = \left(\frac{1}{2}\rho A v^3\right)_{avg} = \frac{1}{2}\rho A \cdot (v^3)_{avg}$$

Using some notions from statistics, we can evaluate Equation 12.6 with the following:

Eq. 12.7 $$P_{avg} = \left(\frac{1}{2}\rho A v^3\right)_{avg} = \frac{1}{2}\rho A \cdot (v^3)_{avg}$$
$$= \frac{1}{2}\rho A \int_0^\infty v^3 f(v)\,dv$$

If we plug the Rayleigh probability density function given in Equation 12.5 into Equation 12.7 and do some fancy calculus, we get the following interesting result:

Eq. 12.8 $$P_{avg} = \frac{6}{\pi} \cdot \frac{1}{2}\rho A \cdot (v^3)_{avg} = 1.91 \cdot \frac{1}{2}\rho A\,(v^3)_{avg}$$

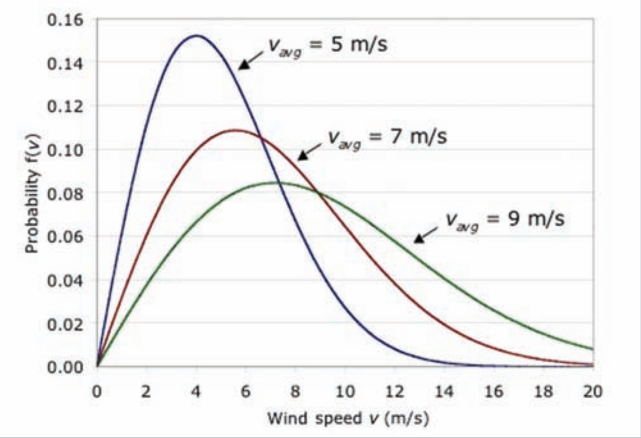
That is, if we just plug the average wind speed into the usual equation for power in the wind and then multiply the result by $6/\pi = 1.91$ we get the average power in the wind if the wind distribution follows Rayleigh statistics.

For example, in Table 12.1 the threshold of class-4 winds is an average wind speed of 7.0 m/s that supposedly creates an average power in the wind of 400 W/m^2. We can test that combination using Equation 12.8:

Eq. 12.9 $$P_{avg}\,(@v_{avg} = 7\text{ m/s}) = \frac{6}{\pi}\left(\frac{1}{2} \times 1.225 \times 7^3\right)$$
$$= 401\text{ W/m}^2$$

which pretty closely agrees with the wind classification table.

figure 12.11



The Rayleigh probability density function for varying average wind speeds.

table 12.2 Average Power in the Wind Assuming Rayleigh Statistics

Average Wind Speed (m/s)	Average Wind Speed (mph)	Average Power in Wind (W/m^2)
3	6.7	32
4	8.9	75
5	11.2	146
6	13.4	253
7	15.7	401
8	17.9	599
9	20.1	853

kWh per year than a 100-MW wind farm—perhaps as much as three times as much! Therefore, we have to be very careful comparing the two to be sure we aren't overstating the case for wind.

If a power plant operated at full power all 8760 hours per year (24 hr/day × 365 day/yr), its annual energy output would be P_R (kW) × 8760 hr/yr. Because power plants don't operate at full output all of the time, we can describe their annual output using an overall average capacity factor (CF) such that

Eq. 12.9

$$\text{Annual energy (kWh/yr)} = P_R \text{ (kW)} \times 8760 \text{ hr/yr} \times \text{CF}$$

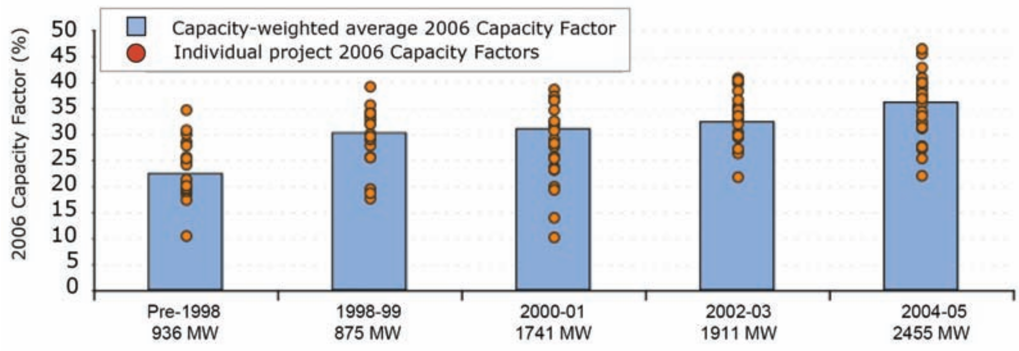
For example the 2000 kW wind turbine in the previous example delivered 5.3×10^6 kWh/yr, which means its CF would be

$$\text{CF} = \frac{5.3 \times 10^6 \text{ kWh/yr}}{2{,}000 \text{ kW} \times 8760 \text{ hr/yr}} = 0.302 = 30.2\%$$

That's a pretty typical CF for modern turbines operating on the edge between class-3 and class-4 winds. Most wind plants installed today are in class-4 and class-5 sites, resulting in CFs of roughly 30%–40%, with some as high as 45% (Figure 12.12). For comparison, base-load coal plants often operate with capacity factors of 80%–90%.

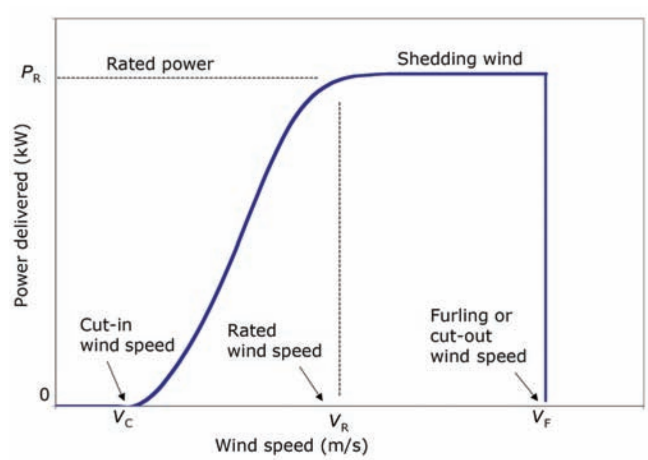
Wind turbine CFs are affected both by the wind regime and the turbine's power curve, which is a graph of its power output as a function of wind speed. An example of an idealized power curve is shown in Figure 12.13. For winds below the *cut-in wind speed*, V_C, the turbine isn't even turned on because the power that would be generated isn't enough to offset generator losses. Above the cut-in wind speed, the power output climbs rapidly, more or less as the cube of wind speed, until it reaches the point at which the generator is delivering as much power as it can, namely its rated power P_R. The *rated wind speed*, V_R, that goes with the rated power isn't a very clearly defined number for real turbines because the power curve is usually somewhat rounded as shown in the figure. Above the rated wind speed, the pitch of the turbine blades is adjusted to shed some of the wind to keep from overpowering the generator. Finally, at some point, called the *furling* or *cut-out wind speed*, V_F, the winds are just too high and too dangerous, so the turbine shuts down.

figure 12.12 **2006 Capacity Factors for U.S. Wind Farms by Date of Installation**



Source: Wiser, et al., 2007

figure 12.13 **An Example Wind-Turbine Power Curve**

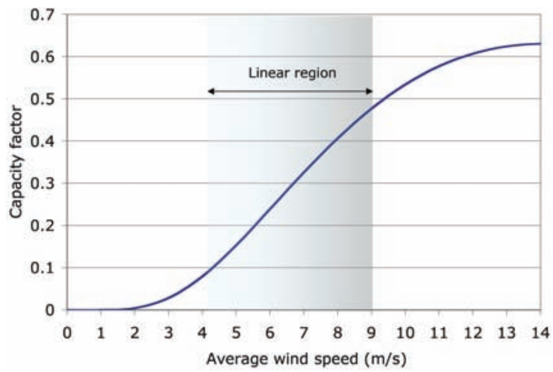


No power is generated below V_C. Above V_R the output remains relatively constant at P_R. Above V_F the turbine is shut down.

The CF for a wind turbine depends on the interaction between its power curve and the distribution of wind speeds to which it is exposed. In fact, the CF, as a function of average wind speed, will have a similar shape to the turbine's power curve, as is suggested in Figure 12.14. The CF will be very low if a lot of the wind is below the cut-in wind speed. On the other hand, when a lot of the wind is above the rated wind speed the CF saturates, and in fact, can begin to decrease when winds include some above the furling wind speed.

The most interesting aspect of Figure 12.14 is the fact that within the range of average wind speeds (e.g., about 4–9 m/s) to which a turbine is likely to be exposed, the CF is quite linear. This may seem quite surprising because earlier we talked about how power in the wind

figure 12.14



For turbines in good sites (e.g., average wind in the 4–9 m/s range), capacity factors are fairly linear with increasing average wind speeds.

itself increases as the cube of wind speed. However, once we include the characteristics of actual turbines, which include discarding low-speed winds and shedding much of the available power at higher wind speeds, the energy delivered by an actual turbine seems to increase in a straight-line fashion with increasing average wind speed. In fact, based on correlating CFs for a number of actual turbines with simple turbine characteristics, the following very handy relationship has been derived (Masters, 2004).

Eq. 12.10

$$\mathrm{CF} = 0.087V_{\mathrm{avg}} - \frac{P_{\mathrm{R}}}{D^2}$$

where CF = turbine capacity factor
V_{avg} = average wind speed (m/s) assuming Rayleigh statistics
P_{R} = rated power of the turbine (kW)
D = rotor diameter (m)

Be aware that Equation 12.10 is a simple correlation that was not derived from fundamental principles, so the units don't cancel. To make it work, you must use the units specified above. The example in Solution Box 12.3 illustrates its use.

12.6 Economics of Wind Power

One of the key advantages of newer wind turbines is the reduction in capital cost per kW of installed capacity as economies of scale kick in, Reasons for this reduction include the following:

- Cost of a rotor is roughly proportional to its diameter, but power delivered is proportional to diameter squared.

SOLUTION

SOLUTION BOX 12.3

Estimating the Energy Delivered by a Wind Turbine

Let's return to the example of a 2-MW, 80-meter wind turbine in Rayleigh winds with average wind speed equal to 7 m/s. Use Equation 12.10 to estimate its CF and annual electricity production.

Solution:

From Equation 12.10 the capacity factor is

$$\mathrm{CF} = 0.087V_{avg} - \frac{P_R}{D^2} = 0.087 \times 7 - \frac{2000}{80^2} = 0.297$$

From Equation 12.9 the annual energy delivered is estimated to be

$$\text{Energy} = \mathrm{CF} \times P_R \times 8760 = 0.297 \times 2000\ \text{kW} \times 8760\ \text{hr/yr} = 5.2 \times 10^6\ \text{kWh/yr}$$

Pretty simple.

- Taller towers reach into higher winds, which increases energy faster than tower cost.
- Labor to assemble the components for larger machines is not that much higher than for small ones.
- Planning, permitting, site preparation, and installation costs don't increase much when size increases.
- Servicing large turbines isn't much different from servicing small ones and newer turbines are designed to need less servicing in the first place.

As a result, capital costs for U.S. projects dropped by about 85% in the last two decades to about $1200/kW. Since then, prices have begun to rise slightly in part due to the rising cost of materials (somewhat due to the surge in all types of construction in China), a weakening dollar compared to the Euro (because a significant fraction of turbines are imported), and a shortage of turbines (due to explosive growth in demand). Offshore installations at about $1600/kW are more expensive, but the strength and consistency of winds there can offset that initial cost disadvantage.

There are a great many financial considerations that go into an actual analysis of a wind project, including things such as loan interest rates, the desired return on any equity investment in the plant, tax advantages associated with accelerated depreciation of capital equipment, property taxes and income taxes, and various incentives provided by government agencies and utilities. A special tax incentive, called the *production tax credit* (PTC), has been an especially important and somewhat problematic factor in the economics of wind. The PTC was enacted in 1992 to provide a 1.5¢/kWh, tax credit that would be inflation adjusted over the years (1.9¢/kWh in 2006). Although the credit does provide a significant financial incentive, Congress has several times allowed the credit to expire, causing the boom-and-bust cycle in construction shown in Figure 12.1. Just before each expiration, construction booms as the industry tries to get plants installed in time to take advantage of the credit, after which the industry virtually shuts down while it waits for the next renewal.

To find a levelized cost estimate for energy delivered by a wind turbine, we need to divide annual costs by annual energy delivered. We just learned how to find annual energy, and in Section 9.5.1 we described annual costs in terms of a fixed charge rate on capital along with annual operations and maintenance (O&M) costs. The example in Solution Box 12.4 illustrates how these factors combine to determine the cost of energy (COE).

The 5.5¢/kWh cost of energy from the example wind plant analyzed in Solution Box 12.4 is actually somewhat on the high side. When accelerated depreciation of the capital investment is included, most wind projects are able to make profits while selling electricity on the wholesale market for around 4¢/kWh. For comparison purposes, consider the cost of a natural-gas-fired efficient, combined-cycle power plant. Assuming a heat rate of 7500 Btu/kWh and natural gas at the 2006 price of around $7 per million Btu, the cost of fuel alone would be over 5¢/kWh. The levelized cost of new coal-fired power plants is around 4¢/kWh. The bottom line suggests that new wind plants in good locations compare favorably against any other new generation source. Moreover, wind avoids the risk of future increases in prices for conventional fuels and likely future carbon taxes, which adds a valuable "hedge value" to wind.

Other economic attributes add value to wind plants. Because turbines are compatible with traditional farming and ranching, land lease revenues of thousands of dollars per year per turbine can provide a real income boost to farmers and ranchers, which can make the difference between just getting by and prosperity. Wind farms also add a new and significant contribution to the local tax base, which helps fund local schools, hospitals, and all the other services that county governments provide. Construction of wind farms and ongoing maintenance provides local jobs, while adding significantly to the local tax base.

12.7 Environmental Impacts of Wind

Wind turbines have many environmental benefits as well as some negative attributes. On the positive side of course, wind turbines generate electricity without the CO_2, SO_2, NO_x, particulate matter, and mercury air pollutants that conventional power plants emit in great quantities. The American Wind Energy Association (AWEA) estimates that the development of just 10% of the wind potential in the ten windiest states in the United States would provide more than

SOLUTION

SOLUTION BOX 12.4

Simple Levelized Cost of Wind Energy

Suppose a 2-MW, 80-m turbine is set up in an area with an average wind speed of 7 m/s. Suppose the complete system cost of \$2.4 million (\$1200/kW) is amortized using a 14%/yr fixed charge rate (FCR). Annual O&M costs are estimated to be \$48,000/yr (2% of capital costs). An additional royalty revenue of \$5000/yr is to be paid to the local rancher on whose land the turbine sits. Finally, the system is eligible for a PTC of \$0.019/kWh. Find the COE.

Solution:

First, we'll amortize the capital cost using Equation 9.4.

$$\textbf{Annual fixed costs (\$/yr) = Capital cost (\$) × FCR (\%/yr)}$$
$$= \$2.4 \times 10^6 \times 0.14/\text{yr} = \$336{,}000/\text{yr}$$

Add in the O&M and royalty payments to get an annual cost of the project

$$A = \$336{,}000 + \$48{,}000 + \$5{,}000 = \$389{,}000/\text{yr}$$

These are the same turbine and wind conditions already analyzed in Solution Box 12.3, which we calculated would deliver 5.2 million kWh/yr. Dividing annual cost by annual energy gives

$$\text{Cost of electricity} = \frac{\$389{,}000/\text{yr}}{5.2 \times 10^6\ \text{kWh/yr}} = \$0.075/\text{kWh}$$

Reducing this by the production tax credit yields a final

$$\text{COE of } \$0.075 - \$0.019 = \$0.055/\text{kWh}$$

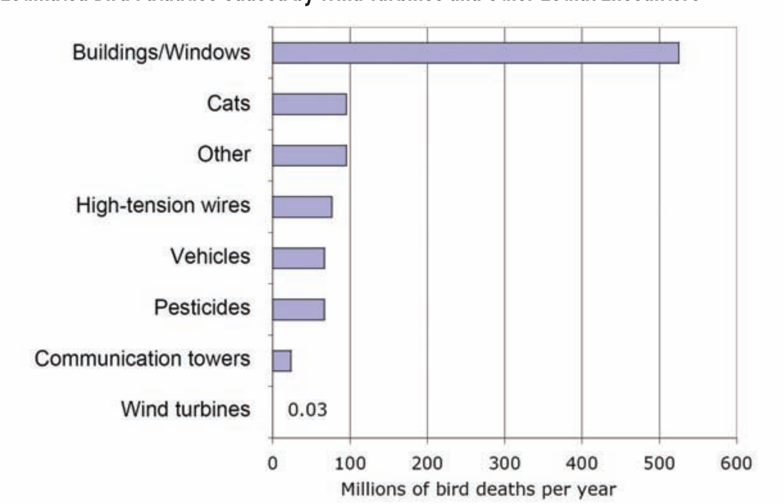
enough energy to displace emissions from the nation's coal-fired power plants and eliminate the nation's major source of acid rain, reduce total U.S. emissions of CO_2 by almost one-third, and help contain the spread of asthma and other respiratory diseases aggravated or caused by air pollution in this country. In addition, wind turbines don't need water for cooling and hence can be located in arid areas without using up that precious resource. Whereas a nuclear or coal-fired power plant consumes through evaporation more than 500 gallons of water per MWh, a wind turbine requires about one gallon (mostly for cleaning turbine blades).

Much of the negative impact of wind turbines has been associated with avian collisions—especially with birds in the Altamont Wind Resource Area about 50 miles east of San Francisco and with bats in Appalachia. These two locations in particular seem to stand apart from most of the potential wind sites in the rest of the country. The northern California wind farms are located along ridges and in mountain passes through which the winds blow and the birds fly. The high concentration of turbines (more than 5000 of them); the fact that many of them are older, smaller machines with blades that spin much faster and reach closer to the ground; coupled with older, lattice towers that provide convenient resting and nesting spots for birds, all contribute to the high mortality rate. Moreover, the year-round abundance of prey in the area leads to an unacceptably high mortality rate of birds the public cares most about—raptors. California, with about 20% of U.S. wind turbine installed capacity, has been estimated to be the site of over 90% of turbine-caused raptor deaths. These circumstances are not common, and wind farms with more sensitive siting and taller, slower turbines have greatly reduced bird death rates.

An interesting comparison of bird deaths caused by wind turbines with other causes of mortality is provided in Figure 12.15. Turbines are thought to cause on the order of 30,000 bird deaths per year; feral and domestic cats kill 100 million each year; and bird collisions with buildings over 500 million.

On the other side of the country, a wind farm in the mountains of eastern West Virginia and another in Pennsylvania have been implicated in the deaths of a large number of bats. Although bats are not perceived by the public in the same way that eagles and hawks are, their deaths are worrisome in part because they have lower reproductive rates than birds and their populations are more vulnerable to blade impacts. A 2005 Government Accounting Office survey indicates that bat death rates may be more of a problem in the Appalachian Mountains,

figure 12.15 **Estimated Bird Fatalities Caused by Wind Turbines and Other Lethal Encounters**



Source: based on Erickson, et al., 2002

where annual fatality rates may be as high as 38 bats per turbine compared with other areas where the numbers range from 0 to 4.3 deaths per year.

Another environmental concern is noise. Again, newer turbines are much better than older ones. Most now are upwind machines, which avoids the thumping sound caused when downwind blades flex as they pass behind their towers. And newer blades have improved aerodynamic characteristics that make them much quieter. For most of us who might stop along the highway to look at a wind farm, turbine noise is insignificant in comparison to the sound of cars and trucks whizzing by. Standing next to a turbine, the sound is a gentle "whup, whup, whup" that is masked in large part by the sound of the wind itself. And a few hundred meters away, turbine sound levels have been compared to that encountered in the reading room of a library.

Perhaps the most troublesome environmental impact of wind turbines is in the eye of the beholder. For some, wind farms are a blight on the landscape, comparable to oil derricks, whereas for others they are welcomed as an elegant, fascinating symbol of a modern, pollution-free energy future. As Martin Pasqualetti (2004) points out, negative attitudes often change dramatically a few years after turbines are installed. In Palm Springs, for example, after thousands of turbines were installed in San Gorgonio Pass just north of the city limits, the community reacted with alarm at the perception that turbines were destroying the aesthetic appeal of the very thing that drew tourists to the area's fancy resorts in the first place. A few years later, influenced somewhat by the financial windfall that local tax revenues were producing, attitudes abruptly changed and wind farms began to pop up in advertisements and postcards as a major tourist attraction.

The major test case for wind aesthetics is being played out in Nantucket Sound where a proposed $500–$700 million Cape Wind project is being proposed that would include 130, 400-foot-tall turbines as close as 5 miles from the shore. The project has split the community with some taking the side of preserving an astonishingly beautiful marine environment (i.e., their view), with others describing it as a classic example of a "Not in My Back Yard" (NIMBY) objection. Perhaps, as Pasqualetti suggests, wind developers should consider a fresh approach and avoid such conflicts, at least for the time being, by focusing their attention on regions where wind would be welcomed as a boon to the local economy—replacing NIMBYs with PIMBYs ("Please, in My Back Yard").

The bottom line for wind power systems is their bottom line. They are essentially pollution-free sources of low-cost electricity that can compete with any other source of electricity.

12.8 Concentrating Solar Power (CSP) Technologies

Although wind systems are the fastest growing renewable energy technology for large-scale generation, there are other solar energy systems that are beginning to enjoy a resurgence of attention as potential electricity sources for wholesale markets. CSP technologies convert sunlight into thermal energy, which is transformed into mechanical power in the form of