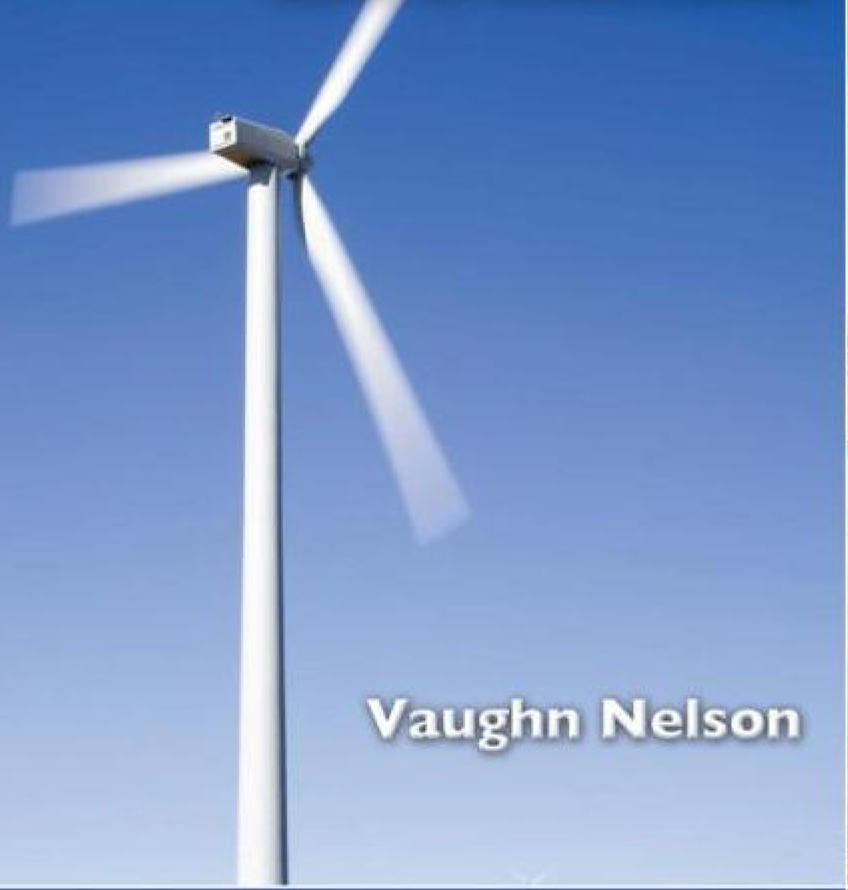
WIND ENERGY

Renewable Energy and the Environment



Vaughn Nelson

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Series Preface

By 2050 the demand for energy could double or even triple as the global population grows and developing countries expand their economies. All life on Earth depends on energy and the cycling of carbon. Energy is essential for economic and social development and also poses an environmental challenge. We must explore all aspects of energy production and consumption, including energy efficiency, clean energy, the global carbon cycle, carbon sources, and sinks and biomass, as well as their relationship to climate and natural resource issues. Knowledge of energy has allowed humans to flourish in numbers unimaginable to our ancestors.

The world's dependence on fossil fuels began approximately 200 years ago. Are we running out of oil? No, but we are certainly running out of the affordable oil that has powered the world economy since the 1950s. We know how to recover fossil fuels and harvest their energy for operating power plants, planes, trains, and automobiles; this leads to modifying the carbon cycle and additional greenhouse gas emissions. The result has been the debate on availability of fossil energy resources; peak oil era and timing for anticipated end of the fossil fuel era; price and environmental impact versus various renewable resources and use; carbon footprint; and emissions and control, including cap and trade and emergence of "green power."

Our current consumption has largely relied on oil for mobile applications and coal, natural gas, and nuclear or water power for stationary applications. In order to address the energy issues in a comprehensive manner, it is vital to consider the complexity of energy. Any energy resource, including oil, coal, wind, and biomass, is an element of a complex supply chain and must be considered in its entirety as a system from production through consumption. All of the elements of the system are interrelated and interdependent. Oil, for example, requires consideration for interlinking of all of the elements, including exploration, drilling, production, water, transportation, refining, refinery products and byproducts, waste, environmental impact, distribution, consumption/application, and, finally, emissions.

Inefficiencies in any part of the system have an impact on the overall system, and disruption in one of these elements causes major interruption in consumption. As we have experienced in the past, interrupted exploration will result in disruption in production, restricted refining and distribution, and consumption shortages. Therefore, any proposed energy solution requires careful evaluation and, as such, may be one of the key barriers to implementing the proposed use of hydrogen as a mobile fuel.

Even though an admirable level of effort has gone into improving the efficiency of fuel sources for delivery of energy, we are faced with severe challenges on many fronts. These include population growth, emerging economies, new and expanded usage, and limited natural resources. All energy solutions include some level of risk, including technology snafus, changes in market demand, and economic drivers. This is particularly true when proposing an energy solution involving implementation of untested alternative energy technologies.

There are concerns that emissions from fossil fuels will lead to changing climate with possibly disastrous consequences. Over the past five decades, the world's collective greenhouse gas emissions have increased significantly—even as increasing efficiency has resulted in extending energy benefits to more of the population. Many propose that we improve the efficiency of energy use and conserve resources to lessen greenhouse gas emissions and avoid a climate catastrophe. Using fossil fuels more efficiently has not reduced overall greenhouse gas emissions for various reasons, and it is unlikely that such initiatives will have a perceptible effect on atmospheric greenhouse gas content. Although the correlation between energy use and greenhouse gas emissions is debatable, there are effective means to produce energy, even from fossil fuels, while controlling emissions. Emerging technologies and engineered alternatives will also manage the makeup of the atmosphere, but will require significant understanding and careful use of energy.

We need to step back and reconsider our role in and knowledge of energy use. The traditional approach of micromanagement of greenhouse gas emissions is not feasible or functional over a long period of time. More assertive methods to influence the carbon cycle are needed and will be emerging in the coming years. Modifications to the cycle mean that we must look at all options in managing atmospheric greenhouse gases, including various ways to produce, consume, and deal with energy. We need to be willing to face reality and search in earnest for alternative energy solutions. Some technologies appear to be able to assist; however, all may not be viable. The proposed solutions must not be in terms of a "quick approach," but rather as a more comprehensive, long-term (10, 25, and 50+ years) approach based on science and utilizing aggressive research and development. The proposed solutions must be capable of being retrofitted into our existing energy chain. In the meantime, we must continually seek to increase the efficiency of converting energy into heat and power.

One of the best ways to define sustainable development is through long-term, affordable availability of resources, including energy. There are many potential constraints to sustainable development. Foremost of these is the competition for water use in energy production, manufacturing, and farming versus a shortage of fresh water for consumption and development. Sustainable development is also dependent on the Earth's limited amount of soil; in the not too distant future, we will have to restore and build soil as a part of sustainable development. Hence, possible solutions must be comprehensive and based on integrating our energy use with nature's management of carbon, water, and life on Earth as represented by the carbon and hydrogeological cycles.

Obviously, the challenges presented by the need to control atmospheric greenhouse gases are enormous and require "out of the box" thinking, innovative approaches, imagination, and bold engineering initiatives in order to achieve sustainable development. We will need to exploit energy even more ingeniously and integrate its use with control of atmospheric greenhouse gases. The continued development and application of energy is essential to the development of human society in a sustainable manner through the coming centuries.

All alternative energy technologies are not equal; they have various risks and drawbacks. When evaluating our energy options, we must consider all aspects, including performance against known criteria, basic economics and benefits, efficiency, processing and utilization requirements, infrastructure requirements, subsidies and credits, and waste and the ecosystem, as well as unintended consequences such as impacts on natural resources and the environment. Additionally, we must include the overall changes and the emerging energy picture based on current and future efforts to modify fossil fuels and evaluate the energy return for the investment of funds and other natural resources such as water.

A significant driver in creating this book series focused on alternative energy and the environment and was provoked as a consequence of lecturing around the country and in the classroom on the subject of energy, environment, and natural resources such as water. Water is a precious commodity in the West in general and the Southwest in particular and has a significant impact on energy production, including alternative sources, due to the nexus between energy and water and the major correlation with the environment and sustainability-related issues. The correlation among these elements, how they relate to each other, and the impact of one on the other are understood; however, integration and utilization of alternative energy resources into the energy matrix has not been significantly debated.

Also, as renewable technology implementation grows by various states nationally and internationally, the need for informed and trained human resources continues to be a significant driver in future employment. This has resulted in universities, community colleges, and trade schools offering minors, certificate programs, and, in some cases, majors in renewable energy and sustainability. As the field grows, the demand increases for trained operators, engineers, designers, and architects able to incorporate these technologies into their daily activity. Additionally, we receive daily deluges of flyers, e-mails, and texts on various short courses available for parties interested in solar, wind, geothermal, biomass, and other types of energy. These are under the umbrella of retooling an individual's career and providing the trained resources needed to interact with financial, governmental, and industrial organizations.

In all my interactions in this field throughout the years, I have conducted significant searches for integrated textbooks that explain alternative energy resources in a suitable manner that would complement a syllabus for a potential course to be taught at the university and provide good reference material for parties getting involved in this field. I have been able to locate a number of books on the subject matter related to energy; energy systems; and resources such as fossil nuclear, renewable energy, and energy conversion, as well as specific books on the subjects of natural resource availability, use, and impact as related to energy and environment. However, books that are correlated and present the various subjects in detail are few and far between.

We have therefore started a series in which each text addresses specific technology fields in the renewable energy arena. As a part of this series, there are textbooks on wind, solar, geothermal, biomass, hydro, and other energy forms yet to be developed. Our texts are intended for upper level undergraduate and graduate students and informed readers who have a solid fundamental understanding of science and mathematics. Individuals and organizations that are involved with design development of the renewable energy field entities and interested in having reference material available to their scientists and engineers, consulting organizations, and reference libraries will also be interested in these texts. Each book presents fundamentals as well as a series of numerical and conceptual problems designed to stimulate creative thinking and problem solving.

I wish to express my deep gratitude to my wife, Maryam, who has served as a motivator and intellectual companion and too often has been the victim of this effort. Her support, encouragement, patience, and involvement have been essential to the completion of this series.

Abbas Ghassemi, PhD

The Series Editor

Dr. Abbas Ghassemi is the director of Institute for Energy and Environment (IE&E) and professor of chemical engineering at New Mexico State University. In addition to teaching and research, he oversees the operations of WERC: A Consortium for Environmental Education and Technology Development, the Southwest Technology Development Institute (SWTDI), and the Carlsbad Environmental Monitoring and Research Center (CEMRC) and has been involved in energy, water, risk assessment, process control, pollution prevention, and waste minimization areas for a number of industries throughout the United States for the past 20 years. He has also successfully led and managed a number of peer-reviewed scientific evaluations of environmental, water, and energy programs for the U.S. Department of Energy, the U.S. Environmental Protection Agency, national laboratories, and industry. Dr. Ghassemi has over 30 years of industrial and academic experience in risk assessment and decision theory; renewable energy; water quality and quantity; pollution control technology and prevention; energy efficiency; process control, management, and modification; waste management; and environmental restoration. He has authored and edited several textbooks and many publications and papers in the areas of energy, water, waste management, process control, sensors, thermodynamics, transport phenomena, education management, and innovative teaching methods. Dr. Ghassemi serves on a number of public and private boards, editorial boards, and peer-review panels and holds an MS and PhD in chemical engineering, with minors in statistics and mathematics, from New Mexico State University, and a BS in chemical engineering, with a minor in mathematics, from the University of Oklahoma.

Preface

The big question: How do we use science and technology such that Spaceship Earth will be a place for all life to exist? We are citizens of the planet Earth, and within your lifetime there will be major decisions over the following: energy (including food), water, minerals, space, and war (which I can state will happen with 99.9% probability). The previous statements were written over 20 years ago when I first taught introductory courses on wind and solar energy. Since then the United States has been involved in Grenada, Panama, Somalia, the Gulf War, the Balkans, Afghanistan, and now Iraq, so the prediction on war was easily fulfilled. I refer to two of the wars as Oil War I (the Gulf War) and Oil War II (Iraq War).

We are over 6 billion and heading toward 11 billion people. Renewable energy is part of the solution for the energy problem, and wind energy is one of the cost-effective options for the generation of electricity. By the end of 2007, there were around 100,000 wind turbines installed in wind farms (also called parks or plants), with an installed capacity of 94,000 megawatts, which generated around 300 terawatt-hours in a year. Wind energy is now part of national policies for generation of electricity.

I was very fortunate to work in a new field, which allowed research, publication and travel, and interaction with scientists, engineers, manufacturers, policy makers, and students that has enriched my life. I enjoyed visiting the wind farms, installations, universities, and institutes in many parts of the world. It is a pleasure to get paid for something you like to do.

I am deeply indebted to colleagues, present and past, at the Alternative Energy Institute (AEI); West Texas A&M University (WTAMU); the Wind Energy Group at the Agricultural Research Service; the U.S. Department of Agriculture (USDA), Bushland, Texas; and the students in my classes and those who have worked at AEI who have provided insight and feedback. There are many others who have worked with us at AEI and USDA, especially the numerous international researchers and interns. Thanks also to the Instruction Innovation and Technology Laboratory, WTAMU, for the computer drawings. I want to express gratitude to my wife, Beth, who has put up with me all these years. Even though if you have seen one wind turbine or wind farm, you have seen them all, she does not complain when we make side trips to take more photos.

The Author

Dr. Vaughn Nelson has been involved with wind energy since the early 1970s, is the author of five books (four books on CD), has published over fifty articles and reports, was the principal investigator on numerous grants, and has given over sixty workshops and seminars on the local to international level. His primary work has been on wind resource assessment, education and training, applied R&D, and rural applications of wind energy. Presently, he is a research professor with the Alternative Energy Institute (AEI), West Texas A&M University (WTAMU). He was director of AEI from its inception in 1977 through 2003 and retired as dean of the graduate school of Research and Information Technology, WTAMU, in 2001. He has served on State of Texas committees, most notably the Texas Energy Coordination Council during its 10 years. He has received three awards from the American Wind Energy Association, one of which was the Lifetime Achievement Award in 2003, and served on the board of directors for state and national renewable energy organizations.

Dr. Nelson's degrees are a PhD in physics, University of Kansas; an EdM, Harvard University; and a BSE, Kansas State Teachers College, Emporia. He was at the Departamento de Física, Universidad de Oriente, Cumana, Venezuela for 2 years and then at WTAMU from 1969 to the present.

1 Introduction

Industrialized societies run on energy, and as third world countries industrialize, especially China and India with their large populations, the demand for energy is increasing. Economists look at monetary values (dollars) to explain the manufacture and exchange of goods and services. However, in the final analysis, the physical commodity is the transfer of energy units. While industrialized nations comprise only one-fourth of the population of the world, they use four-fifths of the world's energy. Most of these forms of energy are solar energy, which are subdivided into two classifications;

Stored solar energy: Fossil fuels—coal, oil, and natural gas, which are finite and therefore depletable.

Renewable energy: Radiation, wind, biomass, hydro, and ocean thermal and waves. Many people discount renewable solar energy, some even calling it an exotic source of energy. However, presently it is the source of all food, most fiber, and in many parts of the world, heating and cooking [1].

Other forms of energy are tidal (due to gravitation), geothermal (heat from the earth), and nuclear (fission and fusion). In reality, geothermal is a form of renewable energy, because as heat is removed from the earth's surface, it is replenished from heat from further down.

The main source of energy in industrialized nations is fossil fuels, and when that factor is combined with the increasing demand and increasing population of the world, a switch to other energy sources is imminent. Whether this change will be rational or catastrophic depends on the enlightenment of the public and their leaders.

1.1 HISTORY

The use of wind as an energy source begins in antiquity. Vertical-axis windmills for grinding grain were reported in Persia in the tenth century and in China in the thirteenth century [2]. At one time wind was a major source of energy for transportation (sailboats), grinding grain, and pumping water. Windmills, along with water mills, were the largest power sources before the invention of the steam engine. Windmills, numbering in the thousands, for grinding grain and pumping drainage water were common across Europe, and some windmills were even used for industrial purposes, such as sawing wood. As the Europeans set off colonizing the world, windmills were built across the world [3].

Except for sailing, the main long-term use of wind has been for pumping water. Besides the Dutch windmills, another famous example was the sail wing blades for pumping water for irrigation on the island of Crete. One of the blades had a whistle on it to notify the operator to change the sail area when the winds were too high.

1.1.1 Dutch Windmill

At one time there were over 9,000 windmills in the Netherlands. Of course there were different designs, from the earlier post mill to the taller mills where only the top rotated to keep the blades perpendicular to the wind. Today, the Dutch windmills are a famous attraction in the Netherlands (Figure 1.1). The machines for pumping large volumes of water from a low head were as large as 25 m in diameter and were almost all wood. Even the helical pump, an Archimedean screw, was made of wood (Figure 1.2). They were quite sophisticated in terms of the aerodynamics of the blades. The miller would rotate (yaw) the top of the windmill from the ground with a rope attached to a wooden beam on the cap,

FIGURE 1.1 Dutch windmills, World Heritage Site, Kinderdijk, The Netherlands.

so the rotor would be perpendicular to the wind. Others would have a small fan rotor to yaw the big rotor. The rotational speed and power were regulated by the amount of sail that was on the blades. The miller and his family lived in the bottom of the windmill, and the smoke from the fireplace was vented to the upper floors to control insects. For the thatched windmill, fire was a major hazard.

1.1.2 Farm Windmill

Farm windmills were one of the primary factors in the settlement of the Great Plains of the United States [4]. From 1850 on water pumping windmills were manufactured in the tens of thousands. The early wood machines (Figure 1.3) have largely disappeared from the landscape, except for an isolated farmhouse or in museums.

By 1900, almost all windmills were made of metal, still with multiblade vanes, and the fan or blades were 3–5 m in diameter (Figure 1.4). Although the peak use of farm windmills was in the 1930s and 1940s, when over 6 million were in operation, these windmills are still being

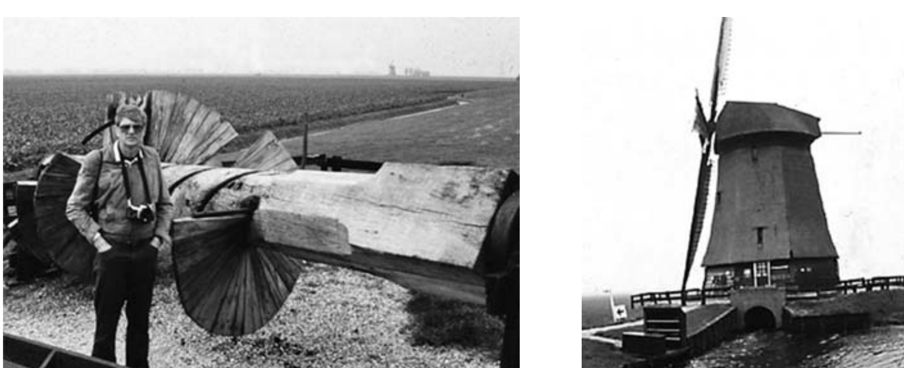

FIGURE 1.2 Thatched Dutch windmill. Notice water flow at bottom of windmill into the canal. Author in much younger days next to helical pump.

FIGURE 1.3 Historical farm windmills at J. B. Buchanan farm near Spearman, Texas. Windmills have been moved to museum at Spearman.

manufactured and are being used to pump water for livestock and residences. The American Wind Power Center in Lubbock, Texas, has an outstanding collection of farm windmills.

Most of the farm windmills are in Africa, Argentina, Australia, Canada, and the United States. As the farm windmill is fairly expensive, there has been a resurgence of design changes to create a less expensive system. Another major change is the development and commercialization of stand-alone, electric-electric systems for pumping enough water for villages or irrigation, or both [5].

FIGURE 1.4 Farm windmill in the Southern High Plains, United States.

The farm windmill proves that wind energy is a valuable commodity, even though the size is small. For example, there are an estimated 30,000 operating farm windmills in the Southern High Plains of the United States. Even though the power output is low, 0.2–0.5 kilowatts (kW), they collectively provide an estimated output of 6 megawatts (MW). If these windmills for pumping water were converted to electricity from the electric grid, it would require around 15 MW of thermal power at the generating station and over $1,000 million for the transmission lines, electric pumps, etc. This does not count the dollars saved in fossil fuel with an energy equivalent of 130 million kilowatt-hours (kWh) per year (equivalent to 80,000 barrels of oil per year). Because many of these windmills are 30 years old or older and maintenance costs are $250–400 per year, farmers and ranchers are looking at alternatives such as solar water pumping rather than purchasing new farm windmills.

In 1888, Brush built a windmill to generate electricity, which was based on the rotor (large number of slats) and tail vane of a large farm windmill. The wooden rotor (17 m diameter) was connected to a direct current generator through a 50:1 step-up gearbox to produce around 12 kW in good winds. The unit operated for 20 years; however, the low rotational speed was too inefficient for the production of electricity. For example, a wind turbine with the same-diameter rotor would produce around 100 kW.

1.1.3 Wind Chargers

As electricity became practical, isolated locations were too far from generating plants and transmission lines were too costly. Therefore, a number of manufacturers built stand-alone wind systems for generating electricity (Figures 1.5 and 1.6), based on a propeller type rotor with two or three blades. Most of the wind chargers had a direct current generator, 6 to 32 volts (V), and some of the later

FIGURE 1.5 Windcharger, 100 W, direct current, with flap air brakes. At USDA-ARS wind test station, Bushland, Texas.

FIGURE 1.6 Jacobs, 4 kW, direct current generator. It was still in use in the 1970s on a farm near Vega, Texas.

models were 110 V. The electricity was stored in batteries, and these wet-cell, lead-acid batteries required careful maintenance for long life.

These systems with two or three propeller blades are quite different from the farm windmill, which had a large number of blades covering most of the rotor swept area. The farm windmill is well engineered for pumping low volumes of water; however, it is too inefficient for generating electricity because the blade design and large number of blades means slow rotational speed of the rotor.

The wind chargers became obsolete in the United States when inexpensive electricity (subsidized) became available from rural electric cooperatives in the 1940s and 1950s. After the energy crisis of 1973, a number of these units were repaired for personal use or to sell. Small companies also imported wind machines from Australia and Europe to sell in the United States during the 1970s.

1.1.4 Generation of Electricity for Utilities

There were a number of attempts to design and construct large wind turbines for utility use [6–11]. These designs centered on different concepts for capturing wind energy (Figure 1.7): airfoil-shaped blades with the axis of the rotor being horizontal or vertical, Savonius, and Magnus effect. With a vertical axis there are no orientation problems of the rotor due to different wind directions.

A rotating cylinder in an airstream will experience a force or thrust perpendicular to the wind, the Magnus effect. In 1926 Flettner built a horizontal-axis wind turbine with four blades, where each blade was a tapered cylinder driven by an electric motor. The cylinders (blades) were 5 m long and 0.8 m in diameter at the midpoint. The rotor was 20 m in diameter on a 33 m tower, with a rated power of 30 kW at a wind speed of 10 m/s.

Madaras proposed mounting vertical rotating cylinders on railroad cars, which would travel around a circular track propelled by the Magnus effect. The generators were to be connected to the

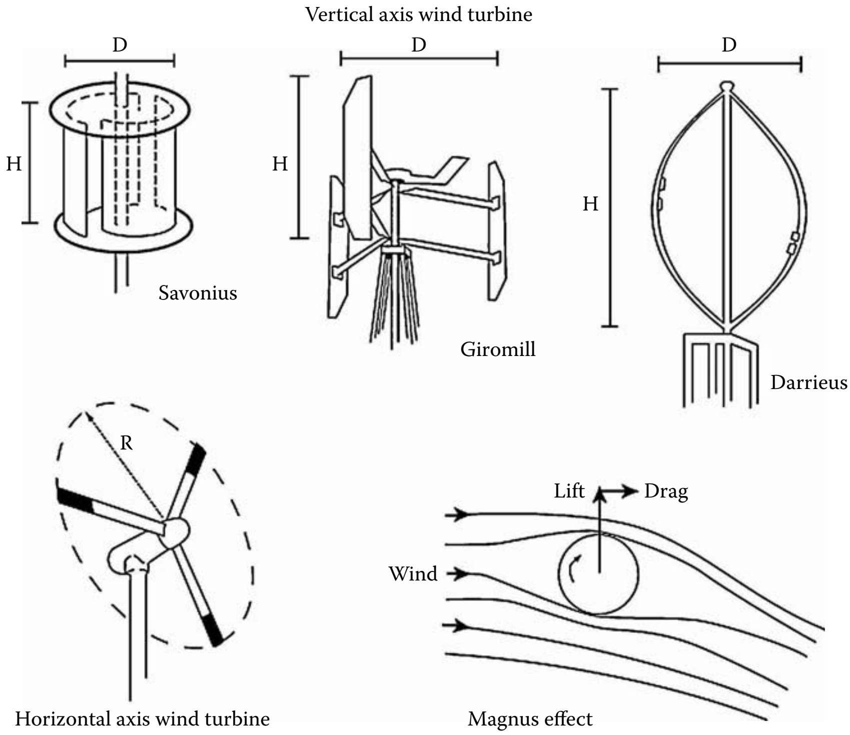

FIGURE 1.7 Diagram of different rotors.

axles of the railroad cars. In 1933, a prototype installation, which consisted of a cylinder 29 m tall and 8.5 m in diameter mounted on a concrete base, was spun when the wind was blowing and the force was measured. Results were inconclusive and the prospect was abandoned.

The Magnus effect has been used for ships, called Flettner rotors [12, 13], and one ship operated using rotors for fuel savings from 1926 to 1933. In 1984 the Costeau Society had a sailing ship, *Alcyone*, built that used two fixed cylinders with an aspirated turbosail [14].

In Finland, Savonius built S-shaped rotors, which were similar to two halves of a cylinder separated by a distance smaller than the diameter. In 1927, Darrieus invented a wind machine where the shape of the blade was similar to a jumping rope. His patent also covered straight vertical blades, a giromill. Later the Darrieus design was reinvented by researchers in Canada [15].

In 1931 the Russians built a 100 kW wind turbine near Yalta on the Black Sea. The rotor was 30 m in diameter on a 30 m rotating tower. The rotor was kept facing into the wind by moving the inclined supporting strut that connected the back of the turbine to a carriage on a circular track. The blade covering was galvanized steel and the gears were of wood. The adjustable angle (pitch) of the blades to the rotor plane controlled the rotational speed and power. Annual output was around 280,000 kWh/year.

The Smith–Putnam wind turbine (Figure 1.8) was developed, fabricated, and erected in 2 years, 1939–1941 [6]. The turbine, which was located on Grandpa's Knob, Vermont, was connected to the grid of Central Vermont Public Service. The rotor was 53 m in diameter on a 38 m tower. Blades were stainless steel with a 3.4 m chord, and each weighed 8,700 kg. The generator was synchronized with the line frequency by adjusting the pitch of the blades. At wind speeds above 35 m/s the blades were changed to the feathered position (parallel to the wind) to shut the unit down. Rated power output was 1,250 kW at 14 m/s. The rotor was on the downwind side of the tower and the blades were free to move independently (teeter, perpendicular to the wind) due to wind loading.

FIGURE 1.8 Smith–Putnam wind turbine, 1250 kW. (Photo from archive files of Carl Wilcox. With permission.)

Testing of the wind turbine started in October 1941, and in May 1942, after 360 h of operation, cracks were discovered in the blades near the root. The root sections were strengthened and the cracks were repaired by arc welding. A main bearing failed in February 1943, and it was not replaced until March 1945 because of a shortage of materials due to World War II. After the bearing was replaced, the unit was operated as a generating station for 3 weeks when a blade failed due to stress at the root. Total running time was only around 1,100 h. Even though the prototype project showed that a wind turbine could be connected to the utility grid, it was not further pursued because of economics. The industrial photos of the construction of the Smith–Putnam wind turbine are available online [16].

Percy Thomas, an engineer with the Federal Power Commission, pursued the feasibility of wind machines. He compiled the first map for wind power in the United States and published reports on design and feasibility of wind turbines [7].

After World War II, research and development efforts on wind turbines were centered in Europe. E. W. Golding summarized the efforts in Great Britain [8], and further efforts are reported in the conference proceedings of the United Nations [9]. The British built two large wind turbines. One wind turbine was built by the John Brown Company on Costa Hill, Orkney, in 1955. The John Brown unit was rated at 100 kW at 16 m/s, with a rotor diameter of 15 m on a 24 m tower. The wind turbine was connected to a diesel-powered grid and only ran intermittently in 1955 due to operational problems.

The other unit was built by Enfield, based on a design by the Frenchman Andreau, and was erected at St. Albans in 1952. The Enfield–Andreau wind turbine rotor was 24 m in diameter on a 30 m tower, with a rated power of 100 kW at 13 m/s. This unit was quite different in that the blades were hollow, and when they rotated, the air flowed through an air turbine, connected to an alternator at ground level, and out of the tip of the blades (Figure 1.9). This unit was moved to Grand Vent, Algeria, for further testing in 1957. Frictional losses were too large for this unit to be successful.

The French built several prototype wind turbines from 1958 to 1966. A 800 kW wind turbine was located at Nogent Le Roi, which had a rotor diameter of 31 m and was operated at constant rotor speed connected to a synchronous generator. The top weighed 162 metric tons and was mounted on

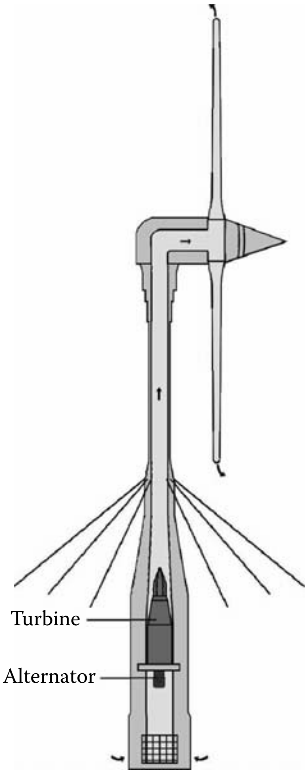

FIGURE 1.9 Diagram of Enfield–Andreau wind turbine, 100 kW.

a 32 m tower. This unit fed electricity into the national grid from 1958 to 1963. Two other units were located at St. Remy-Des-Landes. The smaller Neyrpic machine had a rotor diameter of 21 m on a 17 m tower, and the asynchronous generator produced 130 kW at 12 m/s. The larger unit had a rated power of 1,000 kW at 17 m/s and operated for 7 months, until operation ceased in June 1964 due to a broken turbine shaft. Even though the prototypes clearly showed the feasibility of connecting wind turbines to the electric grid, the French decided in 1964 to discontinue further wind energy research and development.

During the 1950s, Hütter of Germany designed and tested wind turbines that were the most technologically advanced for that time and for the next two decades. The rotors had lightweight fiberglass blades (Figure 1.10) mounted on a teetered hub with pitch control and coning since the rotors were downwind. A 10 kW unit was developed and tested, which culminated in a larger unit, 34 m diameter, that produced 100 kW at 8 m/s [17]. This unit had around 4,000 h of operation from 1957 to 1968; however, the experiments proceeded slowly due to lack of funds and problems with blade vibration.

In Denmark, several hundred systems based on the design by La Cour [18] were built, with rated power from 5 to 35 kW. The units had rotor diameters around 20 m, four blades, which had a mechanical connection to a generator on the ground. By 1900, there were around 30,000 wind turbines for farms and homes, and in 1918, some 120 local utilities in Denmark had a wind turbine, typically 20–35 kW for a total of 3 MW. At that time, these turbines produced around 3% of the Danish electricity. Danish interest waned in subsequent years, until a crisis of production of electricity during World War II. Since the Danes did not have any fossil fuel resources, they looked at connecting wind turbines into their national grid, and the Danish government started a program to

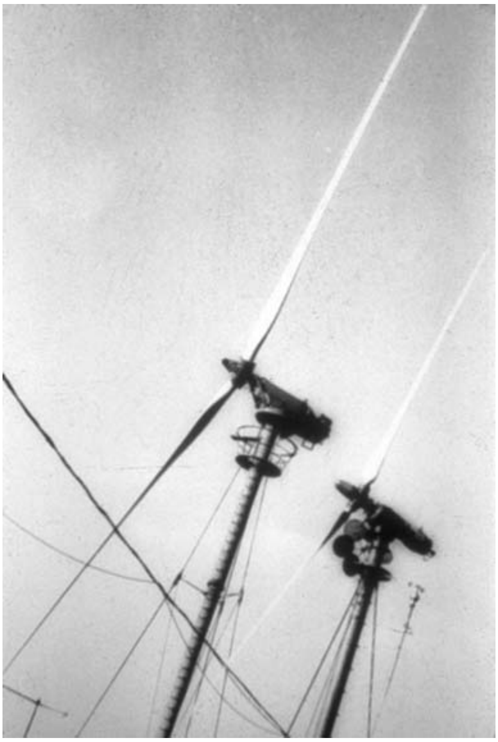

FIGURE 1.10 German wind turbines: left, 100 kW; right, 10 kW. (Photo provided by NASA-Lewis.)

develop large-scale wind turbines for producing electricity. During World War II, a series of wind turbines in the 45 kW range were developed with direct current (DC) generators. These units produced around 4 million kWh per year during this period.

The Danes had the only successful program, which began in 1947 with a series of investigations on the feasibility of using wind power, and continued until 1968 [9, pp. 229–240]. A prototype wind turbine of 7.5 m diameter was built and remained in operation until 1960, when it was dismantled. A wind turbine at Bogo, originally constructed for DC power in 1942, was reconstructed for alternating current (AC) in 1952. Rotor diameter was 13.5 m with a 45 kW generator. The results of the two experimental wind turbines were encouraging and culminated in the Gedser wind turbine (Figure 1.11). This unit was erected in 1957, and during the period 1958–1967 it produced 2,242 MWh. It was shut down in 1967 when maintenance costs became too high. The rotor was 35 m in diameter and the tower, 26 m height, was prestressed concrete. The rotor was upwind of the tower, and the blades were fixed pitch with tip brakes for overspeed control. The wind turbine had an asynchronous generator (rated power of 200 kW at 15 m/s), which provided stall control, and it had an electromechanical yaw mechanism. Denmark and the United States furnished money to place the Gedser wind turbine in operation for a short time period in 1977–1978 for research, which included tests for aerodynamic performance and structural loads.

The successful program of the Danes was overshadowed by the failure of other large machines. The machines failed due to technical problems, mainly stresses due to vibration and control at high wind speeds. Others were economic failures. Everyone agreed there were no scientific barriers to the use of wind turbines tied to the utility grid. In the 1960s development of wind machines was abandoned since petroleum was easily available and inexpensive.

FIGURE 1.11 Danish wind turbine, Gedser, 200 kW. (Photo from Danish Wind Industry Association. With permission.)

1.2 WIND FARMS

Wind farms began in California in 1982 as a result of U.S. federal laws and incentives and mandates on avoided costs set by the California Energy Commission. At end of 2007 the installed capacity in the world was estimated at 95 gigawatts (GW), most of which, 94 GW, was in wind farms (Figure 1.12), with the major amount being installed in the European Union. The size of turbines

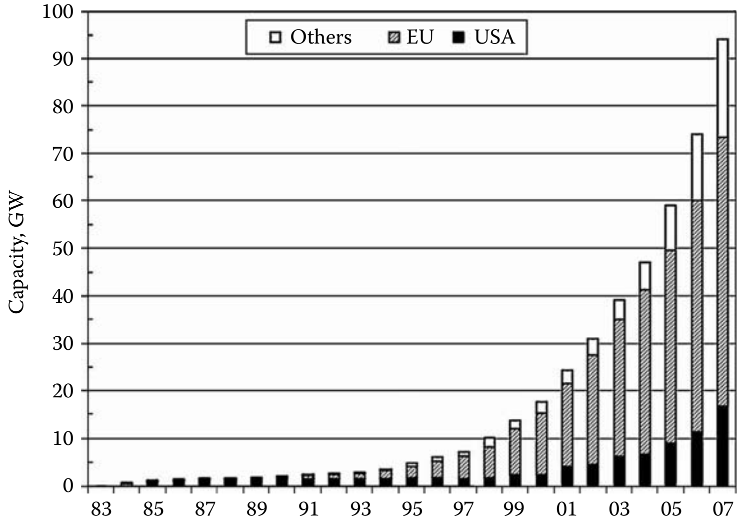

FIGURE 1.12 World installed capacity of wind turbines, primarily wind farms.

TABLE 1.1
Number of Small Wind Systems in the World

Application	Number
Total, electric generation	600,000
Village power; wind, wind hybrid, wind-diesel	1,800?
Telecommunications	200?
Farm windmill	300,000

has increased from 25–100 kW, 10–20 m diameter, to megawatt units, 60–100 m diameter, on towers of 80 to over 100 m. Over 1 GW has been installed in offshore wind farms. Production of electricity from wind farms is the cheapest source of renewable energy and is even less expensive than new coal and nuclear power plants. Wind power has grown at around 25% per year for the past few years, and global installation is predicted to reach 240 GW by 2012.

1.3 SMALL SYSTEMS

Small systems (Table 1.1), in general, are wind turbines of watts to 100 kW. Most small systems are not connected to the grid and have battery storage, and the largest percentage is in the size range of 50–300 W. However, in the United States and other parts of the developed world a fairly large market has developed for small wind systems, 1–10 kW, connected to the grid through inverters. The telecommunications systems need high reliability, so they are hybrid systems with wind, photovoltaic (PV) and battery storage, and diesel. Some of these locations are only accessible by helicopter.

As one-fourth of the world's population does not have electrical power, and as costs of diesel generation have increased, there have been a number of installations of village power systems. Most are hybrid systems, wind/PV, and a few with only wind, and both with battery storage. Another system is wind/diesel, where some of the wind/diesel systems have storage and other systems have wind turbines added to an existing diesel power plant [19]. The wind/diesel systems range in size from less than 100 kW, with one or more wind turbines, to hundreds of kilowatts, with multiple wind turbines.

LINKS

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Danish Wind Industry Association, www.windpower.org/en/pictures/index.htm. History of wind turbines.

Darrel Dodge, http://telosnet.com/wind. An illustrated history of wind power development. This is a very good overview.

Erik Grove-Nielsen, www.windsofchange.dk. Winds of change, 25 years of wind power development on planet earth. A story in photos from the years 1975 to 2000. Site also has brochures of wind turbines.

European Wind Energy Association, www.ewea.org/fileadmin/ewea_documents/documents/publications/WD/2007_september/wd-sept-focus.pdf. *Wind directions*, 25th anniversary. *The Road to Maturity*, September/October 2007.

Farm windmills, http://windmillersgazette.com/index.html.

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2 Energy

2.1 PHILOSOPHY

Scientists have been very successful in understanding and finding unifying principles. Many people take the resulting technology for granted and do not understand the limitations of humans as being part of the physical world. There are moral laws (or principles), civil laws, and physical laws. Moral laws have been broken, such as murder and adultery, and everybody has broken some civil law, such as driving over the speed limit. However, nobody breaks a physical law. Therefore, we can only work with nature, and we cannot do anything that violates the physical world. Another way of stating this: you cannot fool mother nature.

2.1.1 Advantages/Disadvantages of Renewable Energy

The advantages of renewable energy are that it is sustainable (nondepletable), ubiquitous (found everywhere across the world in contrast to fossil fuels and minerals), and essentially nonpolluting. Wind turbines and photovoltaics (PV) do not use water in the production of electricity, which is another major advantage in dry areas of the world, such as the southwest and most of the west of the United States. This is in contrast to thermal electric plants, including nuclear power, which use large quantities of water.

The disadvantages of renewable energy are low density and variability, which results in higher initial cost because of the need for large capture area and storage or backup power. For different forms of renewable energy, other disadvantages or perceived problems are visual pollution, odor from biomass, avian and bats with wind farms, and brine from geothermal. In addition, wherever a large facility is to be located, there will be perceived and real problems to the local people. For conventional power plants using fossil fuels, for power plants using nuclear energy, and even for renewable energy, there is the problem of not in my backyard. In the United States there is considerable opposition to a wind farm offshore of Cape Cod, and there are areas off limits for drilling for oil and natural gas, such as the coasts of Florida. Also notice the infrastructure problems associated with transmission lines for electricity and pipelines for oil and gas.

2.1.2 Economics

Business entities always couch their concerns in terms of economics. The following statements are common:

We cannot have a cleaner environment because it is uneconomical.
Renewable energy is not economical.
We must be allowed to continue our operations as in the past because if we have to install new equipment for emission reduction, we cannot compete with other energy sources.
We will have to reduce employment, jobs will go overseas, etc.

The different types of economics to consider are pecuniary, social, and physical. Pecuniary is what everybody thinks of as economics, dollars. Social economics (sometimes called externalities) are those borne by everybody, and the externalities may be negative or positive. Many businesses want the general public to pay for their environmental costs. A good example is the use of coal in China, as any city of any size has major problems with air pollution. They have laws (social) for clean air, but they are not enforced. The cost will be paid in the future in terms of health problems, especially for today's children. If environmental problems affect someone else today or in the future, who pays? The estimates of the pollution costs for generation of electricity by coal range from \$0.005 to 0.10/kWh.

Physical economics is the energy cost and efficiency of the process, energetics. Others refer to energetics as energy returned on energy invested. A system for producing energy must be a net energy gainer. What is the energy content at the end use versus how much energy is used in the production, transport, and transmission? Therefore, the energetics of the process has to be calculated over the life of the system, and the energetics must be postive.

There are fundamental limitations in nature due to physical laws. In the end mother nature always wins, or the corollary, pay now or probably pay more in the future. On that note, we should be looking at life cycle costs, rather than our ordinary way of doing business—low initial costs and then payments over time.

Finally, we have to look at incentives and penalties for the energy entities. Each energy entity wants incentives (subsidies) for itself and penalties for its competitors. Incentives come in the form of reduced or no taxes, not having to pay social costs on a product, and the government paying for research and development, while penalties come in the form of taxes and environmental and other regulations. It is estimated that we use energy sources in direct proportion to the incentives that the source has received in the past. There are many examples of incentives for fossil fuels and nuclear power. At one time in the United States, there was a hugh incentive for the production of oil, a 27.5% depreciation allowance taken off the bottom line of taxes.

2.2 DEFINITION OF *ENERGY* AND *POWER*

To understand renewable energy and the environment, the definitions of *energy* and *power* are needed. *Work* is the force on an object moved through some distance. Work is equal to force times distance:

$$W = F * D, \text{ Joule (J) = Newton (N) * meter (m)} \tag{2.1}$$

A number of symbols will be used, and problems can be solved using personal computers, spreadsheets, and calculators. Examples are supplied for illustration and understanding.

Many people have a mental block as soon as they see mathematical symbols, but everybody uses symbols. Ask any person what *piano* means and he or she understand the symbol, but to a South Seas islander, a piano is "a big black box, you hit him in teeth and he cries." By the same token, Equation 2.1 can be understood as a shorthand notation for the words and concepts written above it.

To move objects, do work, and change position of objects requires energy, so energy and work are measured by the same units. Some units of energy are Joule, calorie, British thermal unit (BTU), kilowatt-hour (kWh), and even barrels of oil.

Calorie = amount of energy required to raise 1 g of water 1°C
BTU = amount of energy required to raise 1 lb of water 1°F
Some conversion factors for energy are:
1 calorie = 4.12 J
1 calorie = kilocalorie = 1,000 calories, the unit used in nutrition
1 BTU = 1,055 J
1 barrel of oil (42 gallons) = $6.12 * 10^9$ J = $1.7 * 10^3$ kWh
1 metric ton of coal = $2.5 * 10^7$ BTU = $2.2 * 10^{10}$ J
1 cubic foot of natural gas = 1,000 BTU
1 therm = 10^5 BTU = 100 ft^3 of natural gas
1 quad = 10^{15} BTU
1 kWh = $3.6 * 10^6$ J = $3.4 * 10^3$ BTU
1 kW = 1.33 horsepower

Natural gas is sold by the mcf (which is 1,000 cubic feet) and it has an energy content of around 10^6 BTU. You need to be careful when comparing energy from coal with other sources, because 1 metric ton = 1,000 kg = 2,200 lb, 1 ton or long ton = 2,400 lb, and 1 short ton = 2,000 lb. Metric tons will be used unless noted. Also, different types of coal have different energy contents. A barrel of oil (160 L, 42 gallons) is refined to around 166 L (44 gallons) of components, of which 72 L (19 gallons) is gasoline.

Objects in motion can do work; therefore, they possess energy, kinetic energy (KE):

$$KE = 0.5\ m\ v^2 \tag{2.2}$$

where m is the mass of the object and v is its speed.

EXAMPLE 2.1

A car with a mass of 1,000 kg moving at 15 m/s has kinetic energy.

$$KE = 0.5 * 1{,}000 * 15 * 15 = 112{,}500\ J = 1.1 * 10^5\ J \text{ to two significant figures}$$

Because objects interact, for example, by gravity or electromagnetics, then due to their relative position they can do work or have energy, potential energy (PE). To raise a 1 kg mass, 2 m high, requires 20 J of energy. Then at that upper level, the object has 20 J of potential energy. Energy from fossil fuels is chemical energy, which is the potential energy due to the electromagnetic interaction.

Power is the rate of energy use or production and is equal to energy divided by time.

$$P = E/t,\ \text{watt} = \text{J/s} \tag{2.3}$$

If either power or energy is known, then the other quantity can be calculated for any time period. Always remember, a kilowatt (kW) is a measure of power and a kilowatt-hour (kWh) is a measure of energy.

$$E = P * t \tag{2.4}$$

EXAMPLE 2.2

A 5 kW electric motor that runs for 2 h consumes 10 kWh of energy.

EXAMPLE 2.3

Ten 100-watt lightbulbs that are left on all day will consume 24 kWh of energy.

Heat is another form of energy, thermal energy. Heat is just the internal kinetic energy (random motion of the atoms) of a body. Rub your hands together and they get warmer. As you heat your home, you are increasing the speed of the particles of air and other materials in the home. Heat and temperature are different. Heat is energy, and temperature is the potential for transfer of heat from a hot place to a cold place. Do not equate temperature to heat (energy).

2.3 FUNDAMENTALS CONCERNING ENERGY

A major unifying concept is energy and how energy is transferred. The area of physics that deals with heat is called thermodynamics. Part of today's understanding of energy can be embodied in the following laws or principles of thermodynamics:

1. Energy is conserved. Energy is not created or destroyed, only transformed from one form to another. In laymen's terms, this means that all you can do is break even. A number of patents have been issued for a perpetual motion machine [1], a device that produces more

energy than the energy needed to run the machine. A number of people have invested money in such machines, but needless to say, the money was lost since the devices contradict the first law of thermodynamics.

2. Thermal energy, heat, cannot be transformed totally into work. In laymen's terms, you cannot even break even. In every transformation there is an energy efficiency that will be less than 100%. So it takes energy to move heat from a cold place to a hot place (refrigerator, heat pump for house in the winter time). Another way of looking at it is that systems tend toward disorder, and in transformations of energy, disorder increases. In succinct terms, entropy is increasing.

Therefore, some forms of energy are more useful than other forms. For example, the energy in a liter of gasoline is not lost but only transformed into heat by a car. However, after the transformation, that energy is dispersed into a low-grade form (more entropy) and cannot be used to move the car. So the efficiency from energy input to end product, energetics, needs to be calculated. Fuel cells have a much higher efficiency than the internal combustion engine, so why aren't the highways filled with cars powered by fuel cells.

2.4 ENERGY DILEMMA IN LIGHT OF THE LAWS OF THERMODYNAMICS

There is not an energy crisis, as energy cannot be created or destroyed, only transformed to another form. We have an energy dilemma in the use of finite energy resources and their effect on the environment, primarily due to the burning of fossil fuels. The first and primary objective of any energy policy must be conservation and efficiency. It is the most economical form for alleviating our energy problems.

2.4.1 Conservation

Conservation means if you do not need it, do not turn it on or use it. Admonitions to reduce the thermostat setting and reduce speed limits are conservation measures. High prices and shortages of energy increase conservation; for example, in the California electrical crisis of 2000–2001, consumption of electricity was reduced. In general, utility and energy companies like to sell more electricity and energy rather than have customers reduce the use of energy.

2.4.2 Efficiency

Efficiency is the measure of energy for the function or product divided by the energy input:

$$\text{Efficiency} = (\text{energy out})/(\text{energy in}) \tag{2.5}$$

Energy can be used to do work (mechanical energy) or heat an object or space (thermal energy), can be transformed to electrical energy, or can be stored as potential or chemical energy. In each transformation, physical principles can determine an upper limit on efficiency. In thermal processes, the temperatures of the hot and cold reservoirs determine this efficiency:

$$\text{Eff} = \frac{T_H - T_C}{T_H} \tag{2.6}$$

where T_H and T_C are the temperatures of the hot and cold reservoirs, respectively. Temperatures must be in Kelvin, and the conversion is $T_K = T_C + 273$. Thermal electric power plants have efficiencies of 35–40%. In other words, 40% is converted into electricity and 60% of the chemical (or nuclear) energy is rejected as waste heat.

EXAMPLE 2.4

An electrical generating plant uses steam at 700°C (973K), and on the downside the steam is cooled by water to 300°C (573K). The maximum efficiency possible is around 0.41 or 41%.

Since efficiency is always less than 1, for a system or device to continue to operate, energy must be obtained from outside the system. For a series of energy transformations there is a total efficiency, which is the product (multiply) of the individual efficiencies.

EXAMPLE 2.5

Efficiency of incandescent lights in your home from a coal-fired plant:

Transformation	Efficiency, %
Mining of coal	96
Transportation of coal	97
Generation of electricity	38
Transmission of electricity	93
Incandescent bulb (electricity to light)	5
Overall efficiency (coal to light)	1.6

You can see why fluorescence lights, efficiency 15–25%, for commercial buildings and compact fluorescence lights for your home are so important. Now light-emitting diodes (LEDs), efficiency 25–50%, are available. Countries, states, and even cities are setting regulations to phase out incandescent lighting. This also says that day lighting can save money, especially during the summer, as you do not need air conditioning to reduce the heat given off by the lights.

In the physical world, subsidies or economics (dollars) do not change the final outcome, all they do is tilt consumption or use in favor of different energy resources. For example, at some point in the future it will take more energy to drill for oil than the amount of energy in the oil produced. At that point, it is foolish to subsidize the drilling for oil as an energy source. It might be that the product is so useful as a liquid fuel or as a feedstock for other products that it could be subsidized by other energy sources. Another example is that a glass of orange juice is a net energy loser in temperate climates. What is the energetics of producing ethanol from corn?

Prior to the oil crisis of 1973, industry and business maintained that efficiency was not cost-effective and that the gross domestic product (GDP) was tied directly to the amount of energy used. However, industry changed and the United States saved millions (10^9) of dollars since 1973 by increased efficiency in industry and higher efficiency for transportation. However, much more conservation and efficiency has to be done in the coming decades.

Every U.S. president since 1973 has called for energy independence, primarily in reaction to the importation of foreign oil. In 2006, President G. W. Bush's energy policy maintained that we have to drill for more oil and gas, and as in the past, the automobile industry was fighting against increasing fuel efficiency. The automobile industry's argument is couched in terms of economics—we cannot compete with foreign manufacturers of small cars, consumers will not buy fuel-efficient cars (advertising pushes large motors, acceleration and power, and SUVs)—and safety. In past discussions with students, they stated that gasoline in the United States would have to be around $1/L ($4/gallon) before they would buy a fuel-efficient vehicle. Of course, Europeans have been paying those prices for quite a long period, and it is not surprising that with oil over $100/bbl in 2008, the sale of fuel-efficient vehicles has increased. The safety issue means everybody should drive a truck or an M1 tank—to heck with fuel efficiency—or at least we all deserve big Cadillacs.

Another example of efficiency is cogeneration, which is today referred to as combined heat. In the production of electricity, the low-grade (lower-temperature) energy can be used for other processes. In most cases, 60% of the heat from electricity generation by steam (coal, oil, gas, and even nuclear) is not used. In Europe, some electric power plants have heating districts associated with them.

As an example of efficiency, in 1975 the U.S. Congress passed laws for corporate average fuel efficiency (CAFE), fleet fuel economy for vehicles weighing less than 3,886 kg. Pickup trucks and large vans did not count in the CAFE. This law has saved the United States millions of dollars for imported oil. The problem is that sports utility vehicles (SUVs) were counted as light trucks, and their fuel consumption is around 5.5 km/L (12 miles/gallon [mpg]), so the overall fuel efficiency declined as SUVs gained market share. Even with the continued objections by the automobile industry, finally in 2007, the CAFE was increased to 15 km/L (34 mpg) by the year 2020. The European Union and Japan have fuel economy standards about twice those of the United States.

An interesting note: the big three U.S. automobile manufacturers have received over 2,000 million dollars in R&D from the government for the Partnership for New Generation of Vehicles [2]. The goal was a sedan for five people that would obtain 34 km/L (80 mpg). Later, the automotive manufacturers said there is no way to reach that goal. President G. W. Bush is promoting government incentives for fuel cells and the use of ethanol.

Amory Lovins, who was emphatically right about the soft energy path in response to the first energy crisis [3], is strongly advocating hybrid cars and light-weight cars. And guess what? Hybrid cars entered the market in 2000. Just think what large numbers of hybrid cars could do to alleviate the present energy dilemma of too much imported oil for the United States. Again, the question is: Where should the federal government place its incentives? It might be cheaper to subsidize higher-efficiency cars than to subsidize drilling for oil. What is the cost for oil if the costs for the Gulf War (Oil War I) and the Iraq War (Oil War II) are included?

In the past the Organization of Petroleum Exporting Countries (OPEC) wanted to keep the price of oil in the range where they made a lot of money, but not so high as to encourage conservation and efficiency. However, at some point the demand for oil across the world will be higher than can be supplied. At the point where world oil production starts to decline, we will have even higher prices.

2.5 EXPONENTIAL GROWTH

Our energy dilemma can be analyzed in terms of fundamental principles. A corollary of the first law of thermodynamics is: it is a physical impossibility to have continued exponential growth of any product or exponential consumption of any resource in a finite system.

The present rate of consumption and the size of the system give a tendency for people to perceive the resource as either infinite or finite. The total energy output of the sun and the amount of mass in the solar system are infinite sources at our present rates of energy and material use, even though the solar system is finite. Even just the amount of solar energy received by the earth is a very large resource. The energy dilemma is defined within the context of the system, and our present energy dilemma is due to the finite amount of fossil fuels on the earth.

An easy way to understand exponential growth (Figure 2.1) is to use the example of money. Suppose Sheri receives a beginning salary of \$1/year with the stipulation that the salary is doubled every year, a 100% growth rate. It is easy to calculate the salary by year (Table 2.1). After 30 years, her salary is \$1,000 million per year. Notice that for any year, the amount needed for the next year is equal to the total sum for all the previous years plus 1.

Suppose a small growth rate is used, the doubling time ($T2$) can be estimated by

$$T2 = 69/R \tag{2.7}$$

where R = % growth per unit time, generally years. Doubling times for some different yearly rates are given in Table 2.2.

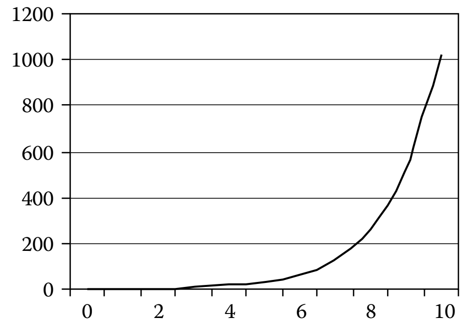

FIGURE 2.1 Exponential growth with a growth rate of 100% per year.

TABLE 2.1
Salary at Growth Rate of 100% Per Year

Year	Salary, $	Amount = 2^t	Cumulative, $
0	1	2^0	1
1	2	2^1	3
2	4	2^2	7
3	8	2^3	15
4	16	2^4	31
5	32	2^5	63
6	64	2^6	127
7	128	2^7	255
8	256	2^8	511
t		2^t	$2^{t+1} - 1$
30	$1 * 10^9$	2^{30}	$2^{31} - 1$

TABLE 2.2
Doubling Times for Different Rates of Growth

Growth, %/year	Doubling Time, years
1	69
2	35
3	23
4	17
5	14
6	12
7	10
8	9
9	8
10	7
15	5

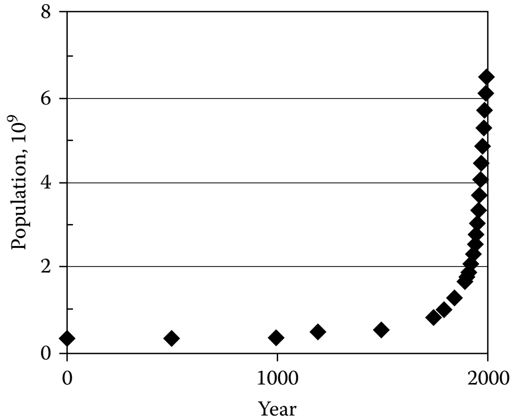

FIGURE 2.2 World population, year 0 to 2005.

There are numerous historical examples of growth: population, 2–3%/year; gasoline consumption, 3%/year; world production of oil, 5–7%/year; electrical consumption, 7%/year. Notice that if we plotted the value per year for smaller rates of growth, the curve would be the same as Figure 2.1, only the time scale along the bottom would be different (Figure 2.2). The projection of the growth of population in the future (Figure 2.3) assumes the growth rate will decrease to 0.5% in 2050. The United Nations projects a leveling off at $9 * 10^9$ to $11 * 10^9$ people by the year 2200.

However, even with smaller rates of growth, the final result is still the same. When consumption grows exponentially, enormous resources do not last very long. Order of magnitude calculations make the analysis quite clear.

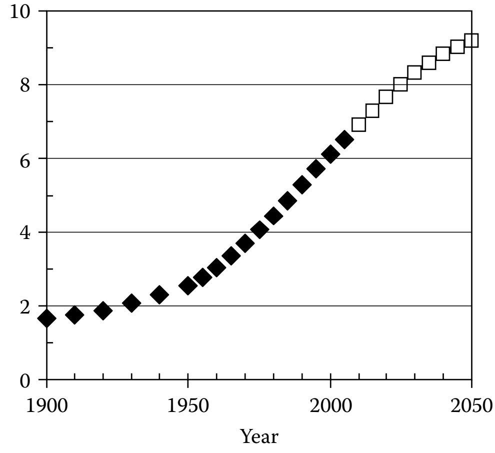

FIGURE 2.3 World population, 1900 to 2050, with United Nations projections for 2010 to 2050, under median variant.

2.6 USE OF FOSSIL FUELS

The night sky of the earth taken by satellite [4] illustrates the tremendous amount of energy consumed by humans. In the United States, 6% of the world's population consumes around 25% of the world's energy resources and 50% of the mineral resources. It is physically impossible to continue to consume fossil fuels with exponential growth rates.

2.6.1 Oil and Natural Gas

The magnitude of the problem can be seen by the cost of imported oil in the United States. In 1973, when consumption was 5.8 Gbbl/year and approximately 40% was imported, the cost was around $100,000,000,000 ($100 * 10^9) per year for oil at $40/bbl (if the cost is adjusted for inflation it would be higher, over $90/bbl in 2008 dollars). Even though consumption of imported oil was reduced in the 1980s, the cost for imported energy was still quite expensive. In the 1990s oil consumption and imports in the United States increased again. As of 2007, world oil production/consumption was around 31 Gbbl/year, and the United States oil consumption was over 7 Gbbl/year, with over half of that imported at $60 and even higher per barrel. Therefore, the cost for imported oil was over $200 * 10^9 per year. Notice that crude oil production and oil supply/consumption are different, as oil supply includes crude oil, natural gas, plant liquids, and other liquids.

The important concept is that crude estimates of resources give fairly good answers as to when production for finite resources will peak. Also, predictions on the future use of the resource can be made from past production, as production and consumption of a finite resource will probably be similar to the bell curve. Hubbert began his analysis of the U.S. oil production [5] in the early 1950s when he was with Shell Research. In 1956, Hubbert predicted that the U.S. oil production would peak mid-1970s, and he was very close, as the actual peak occurred in 1970. The prediction (logistic curve) of U.S. oil production in Figure 2.4 used actual oil production through 2006, and the prediction was calculated in a spreadsheet using the method of Deffeyes [6, chap. 7]. Notice that data include production from Alaskan oil fields and also show that imports are continuing to increase as the U.S. consumption has increased and production has decreased.

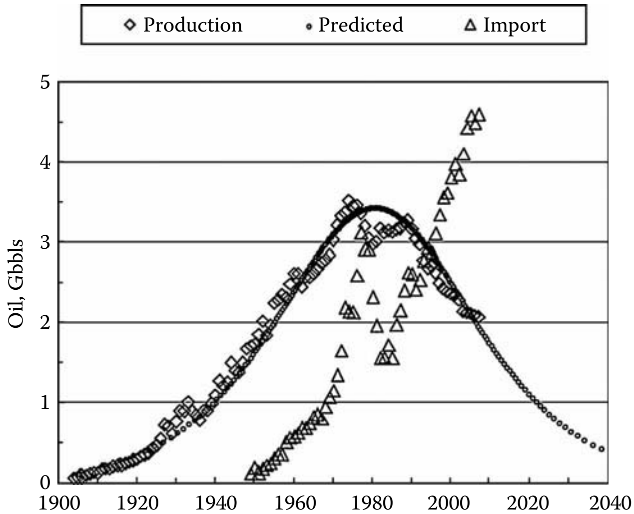

FIGURE 2.4 U.S. crude oil production, net imports, and production prediction using logistic curve.

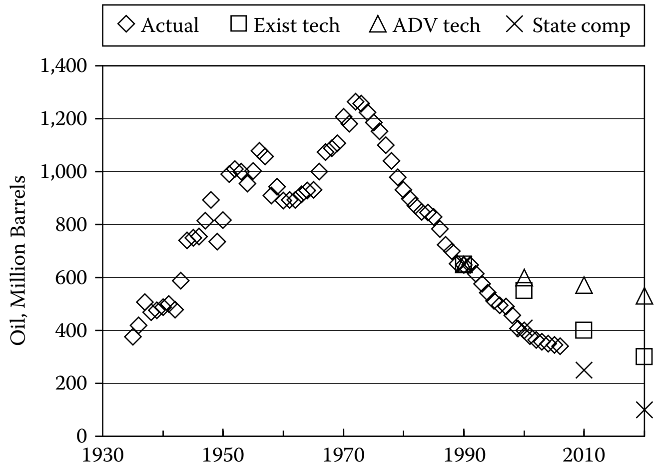

FIGURE 2.5 Texas crude oil production and predictions for the future. (Production data obtained from Texas Railroad Commission.)

Even if a larger resource base is assumed, with exponential growth the larger resource is used up at about the same time. Also, as the resource is used, it becomes more difficult to obtain the resource, i.e., it takes more energy, which also means more money, to obtain the resource. The amount of oil and natural gas discovered per foot of hole drilled decreases exponentially. The same type of analysis and predictions can be made for natural gas, coal, and nuclear ore.

The bell curve, also called the normal or Gaussian curve, will not be exact for predicting future production, as advanced technology will allow us to recover more of the fossil fuels and extend the time the resource is available. However, the end result is still the same. The actual production for oil (Figure 2.5) and natural gas (Figure 2.6) in Texas [7] corroborates the above

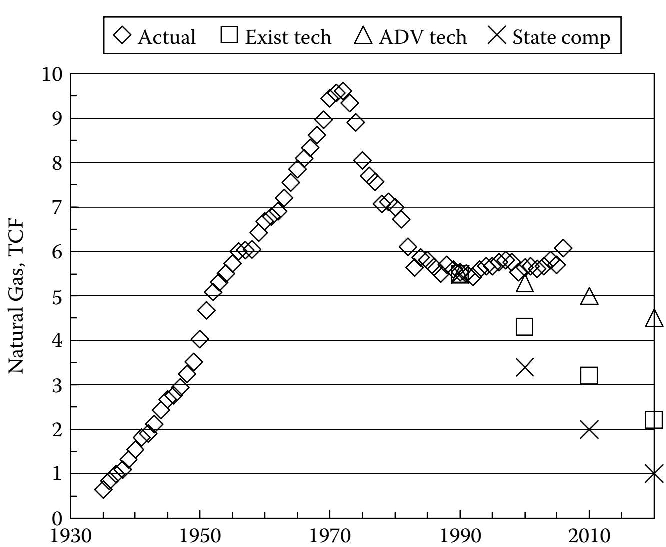

FIGURE 2.6 Texas natural gas production and predictions for the future. (Production data obtained from Texas Railroad Commission.)

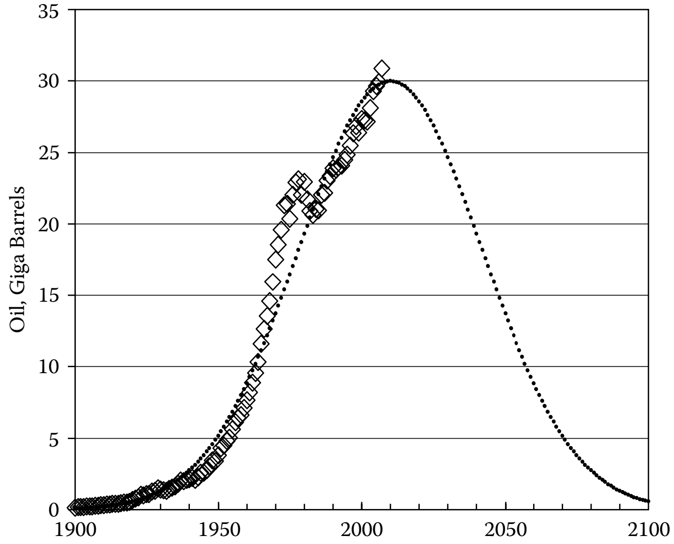

FIGURE 2.7 World oil production per year and production prediction (peak in 2010) using bell curve.

analysis. Notice the difference between predictions made in 1992 and the actual oil and natural gas production in Texas since that date. The predictions were based on existing and advanced technology for oil at $20–25/bbl and the state comptroller based its prediction on the continuation of past production (bell curve). The prediction for natural gas was based on $3/(thousand cubic feet). Oil production in Texas followed the low prediction curve, while natural gas production leveled off, primarily due to more drilling and also advanced technology. Many more wells were drilled for natural gas than for oil from 1990 through 2007. Even though Texas is the major producer in the United States for oil and natural gas, in the years 1994–1995 Texas became a net importer of energy.

World oil production [8] will follow the same pattern as oil production in the United States. Notice that the bell curve predicts world oil production (Figure 2.7) will peak around 2010. There are a number of websites on peak oil. The oil poster (www.oilposter.org) is very well done, and it also shows the world oil peak at 2010. Future production is stretched out because it includes heavy oil, deep-water oil, polar oil, and natural gas liquids, all of which will be more expensive. The reaction to the oil crises of 1973 and 1980 was increased efficiency, which shows as a dip in production. However, as developing countries demand more energy, the demand and production will in general be approximated by the bell curve. In the past the U.S. Energy Information Administration (EIA) predicted cheap energy ($20/bbl) for 2030, and even in 2006 they were predicting future oil at $45/bbl for 2030 for the reference case. Their long-term predictions (even the high case) are probably low, as prices in 2008 were already above $100/bbl. For EIA predictions, check the forecast and analysis section, www.eia.doe.gov/oiaf/forecasting.html.

2.6.2 Coal

Each fossil fuel industry touts the use of its product. The World Coal Institute is promoting the sustainable development of coal and conversion of coal to liquid fuels. In 2004 coal provided 26% of the primary energy for the world and 43% of global electricity. Production of coal has increased by 47% in the last 25 years, with production of 114 quads in 2004. In China 80% of the electricity is provided by coal, and coal also provides a major portion of heating and cooking.

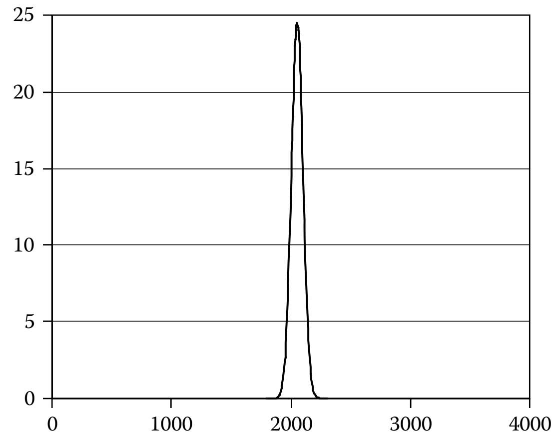

FIGURE 2.8 Fossil fuel exploration and use in human history from year 0 to 4000. Compare this graph with Figure 2.7.

The World Coal Institute estimates that U.S. coal reserves will last 200 years. Does that 200 years include increased production of coal, as coal producers want to increase their share of the energy market? Of course use of coal produces pollution and carbon dioxide emissions. For more information, go to the U.S. Energy Information Administration, or for the industry viewpoint, www.wci-coal.com.

In the long term, the use of fossil fuels could be called the fickle finger of fate (Figure 2.8). The earth is close to the midpoint of the 400-year age of fossil fuels as the major energy source. Also, global climatic change due to consumption of fossil fuels will have a major impact on civilization.

2.7 NUCLEAR

The first commercial plant was built in 1957, and as of 2008 [9] there were 443 nuclear power plants in the world, with an installed capacity of 365 GW (production, 2,659 TWH; 2006 data) and 104 plants in the United States (installed capacity, 106 GW; production, 788 TWH). They provide around 15% of global electricity, with the largest percentage being France at 78%. The United States has not built any new nuclear plants in a number of years, and the percent of the U.S. electricity has declined from 23 to 20% as new electric plants are primarily fired by natural gas (Table 2.3). The U.S. nuclear plants

TABLE 2.3
Percent by Fuel Type for Electric Generation in the United States, 2005

Type	%
Coal	50
Nuclear	19
Natural gas	19
Oil	2
Renewables[a]	10

Source: Data from EIA.
[a] Most renewable is hydro, although wind has been increasing.

have around a 90% capacity factor, which is a large improvement from a 66% capacity factor in 1990. Nuclear power has had a large amount of funding for R&D in the United States and continues to receive substantial federal funding. Again, go to the Energy Information Agency for more information.

2.8 MATHEMATICS OF EXPONENTIAL GROWTH

Values of future consumption, r, can be calculated from the present rate, r_0, and the fractional growth per time period, k:

$$r = r_0 e^{kt} \tag{2.8}$$

where e is the base of the natural log and t is the time.

EXAMPLE 2.5

Present consumption is 100 units/year and growth rate is 7% per year.

$$r_0 = 100 \text{ units/year},\ k = 0.07\text{/year}$$

Suppose $t = 100$ years.

$$r = 100\ e^{0.07*100} = 100\ e^{7} = 100 * 1{,}097 = 1 * 10^{5} \text{ per year}$$

The consumption per year after 100 years is 1,000 times larger than the present rate of consumption. *Note*: Exponents never have any units associated with them.

2.8.1 Doubling Time

The doubling time, $T2$ in years, for any growth rate can be calculated from Equation 2.8:

$$r = 2\ r_0,\quad 2r_0 = r_0 e^{kT2} \text{ or } 2 = e^{kT2}$$

Take the natural log ln of both sides of the equation:

$$\ln 2 = k * T2,\quad T2 = 0.69/k$$

If right-side values are multiplied by 100, $T2 = 69/R$, which is Equation 2.7, where R is the percentage growth rate per year.

2.8.2 Resource Consumption

The total sum of the resource consumed from any initial time to any time, T, can be estimated by summing up the consumption per year. This can be done by using a spreadsheet on personal computers or calculated. If r is known as a function of time, then the total consumption can be found by integration. For exponential growth, the total consumption is given by

$$C = \int r\,dt = \int_0^T r_0 e^{kt}\ dt$$

$$C = \frac{r_0}{k}(e^{kT} - 1) \tag{2.9}$$

TABLE 2.4
Estimated Resources or Reserves, 2007

Resource	Amount
U.S. crude oil	$42 * 10^9$ barrels
U.S. oil	$80 * 10^9$ barrels
U.S. natural gas	$630 * 10^{12}$ ft^3
U.S. coal	$243 * 10^9$ metric tons
U.S. uranium oxide	$1 * 10^5$ metric tons @ $66/kg
www.eia.doe.gov/cneaf/nuclear/page/reserves/ures.html	$4 * 10^5$ metric tons @ $110/kg
World crude oil (conventional)	$1.1 * 10^{12}$ barrels
World oil; includes heavy, sands, shale, deep sea, polar oil	$2.1 * 10^{12}$ barrels
World natural gas	$6200 * 10^{12}$ ft^3
World coal	$907 * 10^9$ metric tons
World uranium oxide	$2 * 10^6$ metric tons @ $80/kg
www.euronuclear.org/info/encyclopedia/u/uranium-reserves.htm	$5 * 10^6$ metric tons @ $130/kg

2.9 LIFETIME OF A FINITE RESOURCE

If the magnitude of the resource is known, or can be estimated, then the end time, T_E, when that resource is used up, can be calculated for different growth rates. The size of resource, S, is put in Equation 2.9, and the resulting equation is solved for T_E:

$$S = \frac{r_0}{k}(e^{kT_E} - 1)$$

$$T_E = \frac{1}{k}\ln\left(k\frac{S}{r_0} + 1\right) \tag{2.10}$$

If the demand is small enough or is reduced exponentially or reduced at the depletion rate, a resource can essentially last a very long time. However, with increased growth, T_E can be calculated for different resources (Table 2.4), and the time before the resource is used up is generally short. Remember, these are only estimates of resources, and other estimates will be higher or lower.

EXAMPLE 2.6

How long will conventional world oil last if consumption grows at 3%/year?

$$r_0 = 30 * 10^9 \text{ barrels/year}, S = 1{,}100 * 10^9 \text{ barrels}, k = 0.03$$

Place values in Equation 2.10:

$$T_E = \frac{1}{0.03}\ln\left(0.03\frac{1100*10^9}{30*10^9} + 1\right) = 33\ \ln(2.1) = 33 * 0.74 = 24 \text{ years}$$

If you do not use the equation, a spreadsheet is very useful for calculations, as you can play with different scenarios of growth and size of the resource.

Year	Consumption	Cumulative
0	3.00E + 10	
1	3.09E + 10	3.09E + 10
2	3.18E + 10	6.27E + 10
3	3.28E + 10	9.55E + 10
…	…	…
23	5.92E + 10	1.00E + 12
24	6.10E + 10	1.06E + 12
25	6.28E + 10	**1.13E + 12**
26	6.47E + 10	1.19E + 12
27	6.66E + 10	1.26E + 12

So at around 25 years all the conventional oil is gone. In the real world there is not the abrupt drop-off, as supply cannot meet demand. However, the example reinforces a previous statement: Exponential growth means large resources do not last very long.

According to the energy companies, the continued growth in energy use in the United States is to be fueled by our largest fossil fuel resource, coal, and nuclear energy. How long can coal last if we continue to increase production to offset decline in production of oil and to reduce the need for importation of oil? The preceding analysis will allow you to make order of magnitude estimates. Also, increased or even current production rates of fossil fuels may have major environmental effects, as global warming has become an international political issue.

2.10 SUMMARY

Continued exponential growth is a physical impossibility in a finite (closed) system. Previous calculations made about the future are just estimations, and possible solutions to our energy dilemma are:

1. Reduce demand of fossil fuels to depletion rate.
2. Use renewable energy at sustainable rate and begin a steady-state society.
3. Redefine the size of the system; colonize the planets and space. The problem is, this will not solve the energy dilemma on earth. From our present viewpoint, the resources of the solar system are infinite and our galaxy contains over $100 * 10^9$ stars.

Because the earth is finite, there is a limit for population, amount of fresh water, fossil fuels, and minerals [10], and even a limit on the amount of food production and catch of fish from the sea. Therefore, a change to a sustainable society, which depends primarily on renewable energy, becomes imperative within this century. For the world, we will have to do the following in the transition period (2007–2020) in order of priority:

1. Implement conservation and energy efficiency. Since the first energy crisis, this has been the most cost-effective mode of operation. It is much cheaper to save a barrel of oil than to discover new oil or import oil.
2. Increase the use of renewable energy.
3. Reduce dependence on oil and natural gas during the transition period.
4. Use coal (clean, means taking care of the carbon dioxide); however, it has to include all social costs (externalities).
5. Implement incentives and penalties that are in line with items 1 and 2.

Efficiency can be improved in all major sectors: residential, commercial, industrial, transportation, and electrical. The most gains can be accomplished in the transportation, residential, and commercial

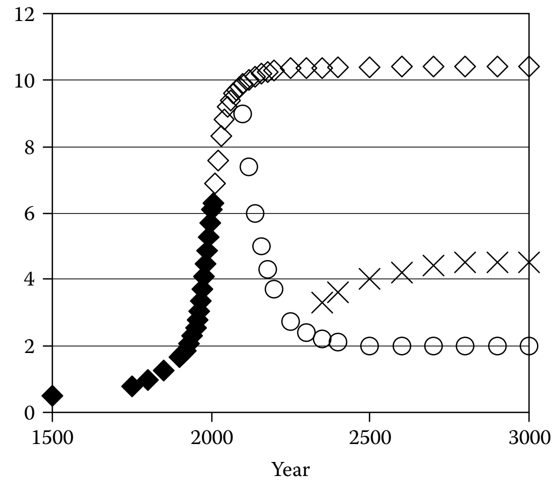

FIGURE 2.9 Possible future paths for the population of earth.

sectors. National, state, and even local building codes will improve energy efficiency in buildings. Finally, there are a number of things that you as an individual can do in conservation and energy efficiency. In addition, be an advocate for conservation, efficiency, renewable energy, and the environment.

Possible futures for human society are conservation and efficiency, transition to sustainable energy, and a steady state with no growth, catastrophe, or catastrophe with some revival (Figure 2.9). As overpopulation and overconsumption are affecting the earth, an uncontrolled experiment, the most probable future for population is catastrophe or catastrophe with some revival.

LINKS

Energy Information Administration, U.S. Department of Energy, www.eia.doe.gov. The EIA site contains a lot of information on U.S. and international energy resources and production. Reports and data files can be downloaded, as well as PDFs and spreadsheets.

International Energy Agency, www.eia.org. Oil and gas production in Texas are regulated by the Texas Railroad Commission, www.rrc.state.tx.us.

Peak Oil, www.peakoil.com.

United Nations, www.un.org/esa/population/unpop.htm. Information and projections on population.

U.S. Census, www.census.gov. Information on world population.

Worldmapper, www.worldmapper.org. Shows morphed countries of the world where size depends on topical data such as population, oil exports, oil imports, and others.

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R. L. George, "Mining for Oil," 84.

QUESTIONS/ACTIVITIES

1. Go to the U.S. Census site and look at the population clock in the upper right. What is the population of the United States? The world?
2. List three ways you are going to save energy this year.
3. Go to the Energy Information Administration (international) website. Use latest year available. What is the world oil production? What is the world coal production?
4. Would you rather stick your finger in a cup of hot coffee (T = 80°C) or be hit by a high-speed proton, which has a temperature of 1,000,000°C? Justify your answer.

5. Touch or place your hand near a 100 W incandescent lightbulb and a 20–40 W fluorescent lightbulb. Qualitatively describe the amount of light output and heat output for the two bulbs.

ORDER OF MAGNITUDE ESTIMATES

In terms of energy consumption, production, supply, and demand, estimates are needed and an order of magnitude calculation will suffice. By order of magnitude, we mean an answer (one or at most two significant digits) to a power of 10.

EXAMPLE

How many seconds in a year? With a calculator it is easy.

365 days * 24 h/day * 60 min/h * 60 s/h = 31,536,000 s, an answer to five significant digits

When you round to one significant digit, this becomes $3 * 10^7$ s. For two significant digits, the answer is $3.2 * 10^7$ s.

Order of magnitude estimate: Round all input to one number with a power of 10, then multiply the numbers and add the powers of 10. So without a calculator, the above becomes:

$$4 * 10^2 * 2 * 10^1 * 6 * 10^1 * 6 * 10^1 = 4 * 2 * 6 * 6 * 10^5 = 288 * 10^5 = 3 * 10^2 * 10^5 = 3 * 10^7$$

If you have trouble with powers of ten, please consult the instructor.

PROBLEMS

OM means order of magnitude problem.

1. A snowball, mass = 0.5 kg, is thrown at 10 m/s. How much kinetic energy does it possess? What happens to that energy after you are hit with that snowball?
2. OM: The Chamber of Commerce and the Board of Development are always promoting their city as the place for new industry. If a city has a population of 100,000 and a growth rate of 10% per year, what is the population after five doubling times? How many years is that?
3. What is the doubling time if the growth rate is 0.5%? The world population in 2008 was around $6.7 * 10^9$.
4. OM: If world population is $7 * 10^9$, estimate how many years before the population reaches $28 * 10^9$.
5. OM: How many people will there be on the earth by the year 2100? Assume present rate of growth of world population.
6. OM: If the growth rate of population could be reduced to 0.5% per year, how many years would it take to reach $24 * 10^9$ people?
7. OM: The population of the world is predicted to reach $11 * 10^9$. Mexico City is one of the largest cities in the world at $2 * 10^7$ people. How many new cities the size of Mexico City will have to be built to accommodate this increase in population?
8. OM: The most economical size of nuclear power plants is around 1,000 MW. How many nuclear power plants would have to be built in the United States over the next 50 years to meet the U.S. long-term historical growth of 7% per year in demand for electricity?
9. OM: Assume electricity demand increases by 10% per year over the next 30 years for the world. To meet all that increased demand, how many 1,000 MW nuclear plants would have to be installed by the end of 30 years? What is the total cost for those nuclear plants at $5,000/kW?

10. OM: If electricity demand increases by 50% over the next 30 years for China, how many 300 MW coal plants would have to be installed by the end of 30 years? What is the total cost for those coal plants at $2,000/kW?
11. OM: For problem 10, how many metric tons of coal would be needed for that thirtieth year? Assume plants operate at 90% capacity and 40% efficiency.
12. What is the efficiency at a nuclear power plant if the incoming steam is at 700°C and the outgoing steam is at 320°C? Remember, you have to use Kelvin.
13. The Hawaii Natural Energy Institute tested a 100 kW ocean thermal energy conversion (OTEC) system. The surface temperature is 30°C, and at a depth of 1 km the temperature is 10°C. Calculate the maximum theoretical efficiency of an OTEC engine. Remember, you have to use Kelvin.
14. For a binary-cycle, geothermal power plant the incoming temperature is 110°C and the outgoing temperature is 71°C. Calculate the maximum theoretical efficiency of that steam turbine.
15. OM: Use the coal reserves of the United States. At today's rate of consumption, how long would they last for the United States?
16. OM: Assume a growth rate of coal consumption for the United States of 10% per year, because they are going to also use coal for liquid fuels. How long will the U.S. coal last?
17. OM: Assume a growth rate of coal consumption for China of 15% per year. How long will the China coal last?
18. For your home, estimate the power installed for lighting. Then estimate the energy used for lighting for 1 year.
19. Estimate the energy saved if you converted your home lighting from incandescent to compact fluorescent lights. Fluorescent lights are more efficient, more light per watt.
20. What is the maximum power (electrical) used by your residence (assume all your appliances, lights, etc. are on at the same time)?
21. OM: World oil production will peak during 2008 to 2015. Estimated reserves are $2 * 10^{12}$ bbl. How long will that last at the present rate of consumption?
22. OM: Same as previous problem, but assume a demand increase of 2.5% per year. How long will the oil last?
23. OM: Calculate how long world coal reserves will last if world demand increases at a rate of 5% per year.
24. OM: The United States now has 200 million cars, which consume 10 million barrels of gasoline per day. Suppose the Chinese government goal is the same ratio of people to cars within 30 years. How many cars will they have and how many barrels of oil will they be consuming per year?

A nuclear power plant uses around $3 * 10^4$ kg of uranium oxide to generate 1 TWH of electricity.

25. OM: How long will U.S. uranium last for the present installed nuclear power plants?
26. OM: Same as problem 25, except assume a 2%/year growth in nuclear power plants.
27. OM: How long will world uranium last for the present world nuclear power plants?
28. OM: Same as problem 27, except assume a 4%/year growth in nuclear power plants.

3 Wind Characteristics

3.1 GLOBAL CIRCULATION

The motion of the atmosphere can vary in distance and time from the very small to the very large (Table 3.1). There is an interaction between each of these scales and the flow of air is complex. The global circulation encloses eddies, which enclose smaller eddies, which enclose smaller eddies, until finally the microscale is reached.

The two main factors in global circulation are the solar radiation and the rotation of the earth and the atmosphere. The seasonal variation is due to the tilt of the earth's axis to the plane of the earth's movement around the sun. Since the solar radiation is greater per unit area when the sun is directly overhead, there is a transport of heat from the regions near the equator toward the poles. Because the earth is rotating on its axis and there is conservation of angular momentum, the wind will be shifted as it moves along a longitudinal direction. The three-cell model explains the predominant surface winds (Figure 3.1). Those regions in the trade winds are generally good locations for the utilization of wind power; however, there are exceptions, as Jamaica is not nearly as windy as Hawaii.

Superimposed on this circulation is the migration of cyclones and anticyclones across the mid-latitudes, which disrupt the general flow. Also, the jet streams, the fast core of the central westerlies at the upper levels, influence the surface winds.

Local winds are due to local pressure differences and are influenced by the topography, friction of the surface due to mountains, valleys, etc. The diurnal (24 h) variation is due to temperature differences between day and night. The temperature differences between the land and sea also cause breezes; however, they do not penetrate very far inland (Figure 3.2).

3.2 EXTRACTABLE LIMITS OF WIND POWER

Solar energy drives the wind, which is then dissipated due to turbulence and friction at the earth's surface. The earth's atmosphere can be considered a giant duct, and if energy is taken out at one location, it is not available elsewhere. Therefore, it is important to distinguish between the kinetic energy in the wind and the rate and limits of the extraction of that energy, the power in the wind, and the maximum power extractable.

A comparison can be made on the basis of the kinetic energy of the winds per unit area of the earth's surface. Of the solar input, only 2% is converted into wind power, and 35% of that is dissipated within 1 km of the earth's surface. This is the wind power available for conversion to other forms of energy.

The amount extracted would be limited by the criteria of not changing the climate; however, the uncertainties are very large in determining such criterion. Man would be substituting wind turbines for naturally occurring frictional features such as trees, mountains, etc. Gustavson [1] assumed the extractable limit as 10% of the available wind power within 1 km of the surface. When these values are applied to the contiguous forty-eight states of the United States, the limit would be 2×10^{12} W (2 TW), or 62 quads/year. A similar analysis can be made for the world. Therefore, wind energy represents a very large energy source.

On a global scale, wind can be compared to other renewable sources (Table 3.2). In locations with high wind speeds, wind power is comparable to, or better than, the amount of solar power. The wind energy available represents approximately twenty times the rate of global energy consumption.

TABLE 3.1
Time and Space Scale for Atmospheric Motion

Name	Time	Length	Example
General circulation	Weeks to years	1,000 to 40,000 km	Trade winds, Jet stream
Synoptic scale	Days to weeks	100 to 5,000 km	Cyclones, Hurricanes, Typhoons
Mesoscale	Minutes to days	1 to 100 km	Thunderstorms, Land–sea breezes, Tornadoes
Microscale	Seconds to minutes	<1 km	Turbulence

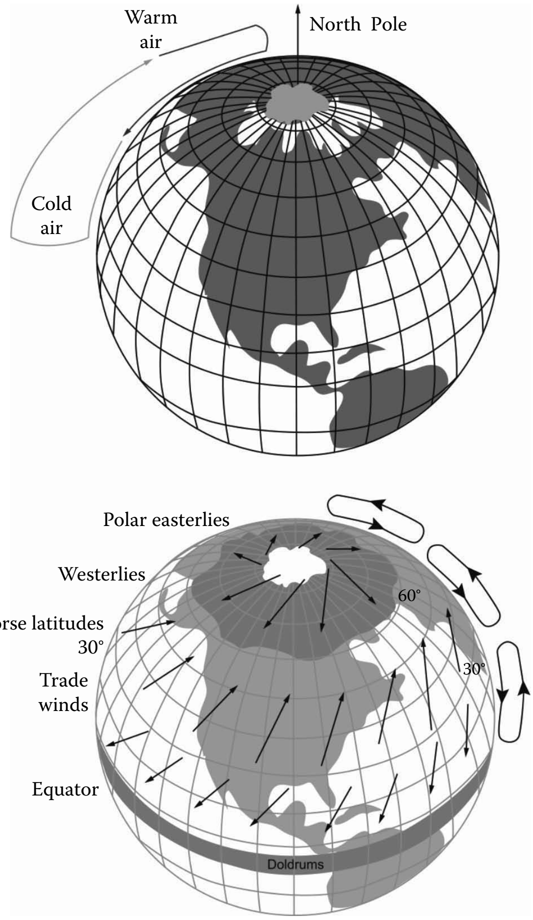

FIGURE 3.1 General atmospheric circulation, northern hemisphere.

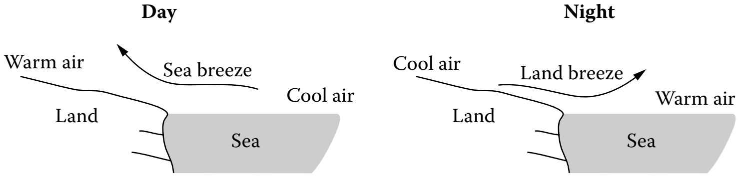

FIGURE 3.2 Sea breeze, day, and land breeze, night.

TABLE 3.2
Summary of Global Values for Renewable Sources

		Extractable	
	Power, W	Power, W	Energy, quads/year
Solar	$1.8*10^{17}$		
Wind	$3.6*10^{15}$	$1.3*10^{14}$	3,900
Hydro	$9.0*10^{12}$	$2.9*10^{12}$	86
Geothermal	$2.7*10^{13}$	$1.3*10^{11}$	4
Tides	$3.0*10^{12}$	$6.0*10^{11}$	1.9

3.3 POWER IN THE WIND

The moving molecules of air have kinetic energy, so locally the amount of air molecules moving across some area during some time period determines the power (Figure 3.3). This area is not the surface area of the earth, which was referred to in the estimation of extractable power and energy, but the area perpendicular to the wind flow. The mass, m, in the volume of the cylinder that will pass across the area, A, in time, t, can be determined from the density of the air, ρ, and the volume of the cylinder, V. The power is the kinetic energy (KE) of the air molecules divided by the time:

$$\begin{aligned} P &= KE/t = 0.5 \text{ m } \text{v}^2/\text{t} \\ \rho &= m/V \\ V &= \text{area} * \text{length} = A * L \\ m &= \rho * V = \rho * A * L \end{aligned} \tag{3.1}$$

Substitute this value of mass into Equation 3.1. Only those molecules with a velocity, $v = L/t$, will cross the area in time, t, and those further to the left will not, so the power is given by

$$P = 0.5\ \rho\, A\, L\, v^2/t = 0.5\ \rho\, A\, L/t\ v^2 = 0.5\ \rho\, A\ v\ v^2 = 0.5\ \rho\, A v^3$$

The power/area, referred to as wind power potential or wind power density, is

$$P/A = 0.5\ \rho\ v^3 \tag{3.2}$$

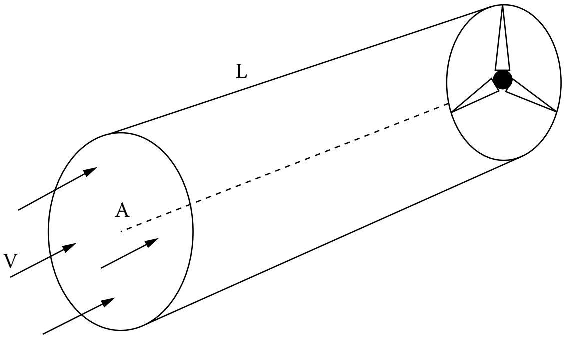

FIGURE 3.3 Flow of wind through a cylinder of area A.

TABLE 3.3
Estimated Wind Power Per Area, Perpendicular to the Wind

Wind Speed, m/s	Power, kW/m²
0	0
5	0.06
10	0.50
15	1.68
20	4.00
25	7.81
30	13.50

From Equation 3.2 the power/area in the wind can be calculated for different wind speeds (Table 3.3). However, not all the power in the wind can be extracted, as the maximum theoretical efficiency for wind turbines is 59%.

Note that if the wind speed is doubled, the power is increased 8 times, and the power at 25 m/s is 125 times the power at 5 m/s. Because there is so much power and energy in the wind at high speeds, there is usually some damage to structures and trees during severe storms and major damage due to tornadoes and class 3 and above hurricanes. This is also the reason wind turbines do not extract all the available energy at high wind speeds. All wind turbines have some means of control, or they would be destroyed in high winds.

EXAMPLE 3.1

A wind turbine with a radius of 2 m, area = 12.6 m^2, would have approximately 100 kW of wind power across that area due to a 25 m/s wind speed.

A first estimation of wind power potential (power/area) can be calculated using the annual mean wind speed, which can be estimated from the mean hourly speeds or other measurements of wind speed. However, use of average or mean wind speeds will underestimate the wind power because of the cubic relationship. For example, Culebra, Puerto Rico; Tiana Beach, New York; and San Gorgonio, California, each has an annual average wind speed of 6.3 m/s, but their annual average power potential is 220, 285, and 365 W/m^2, respectively [2]. For a better estimate of the wind power potential for any extended time period, you would need to know the frequency distribution of the wind speeds; the amount of time for each wind speed value, or a wind speed histogram; and the number of observations within each wind speed range.

EXAMPLE 3.2

Suppose the wind blows at 5 m/s for 1 h and 15 m/s for another hour. During the 2 h period, the average wind speed is (5 + 15)/2 = 10 m/s. Power/area calculated from the average wind speed is 500 watts/m^2. However, the power/area for the first hour is 62.5, and for the second hour the power/area is 1687.5, and the average for the 2 h is 875 W/m^2, which is 375 W/m^2 larger than the value calculated by using the average wind speed.

Wind power also depends on the air density:

$$\rho = 1.2929\ \frac{\mathrm{Pr}\ -\ \mathrm{VP}}{760}\frac{273}{T},\ \frac{\mathrm{kg}}{\mathrm{m}^3} \tag{3.3}$$

where Pr = atmospheric pressure, mm of Hg; VP = vapor pressure, mm of Hg; and T = temperature, Kelvin.

The vapor pressure term is a small correction, around 1%, and can be neglected. High temperatures and low pressures reduce the density of air, which will reduce the power per area. A major factor for change in density is the change in pressure with elevation. A 1,000 m increase in elevation will reduce the pressure by 10%, and thus reduce the power by 10%. If only elevation is known, air density can be estimated by

$$\rho = 1.226 - (1.194*10^{-4})z \tag{3.4}$$

The standard density for comparing output of wind turbines is 1.226 kg/m^3, which corresponds to a temperature of 15°C and an air pressure of sea level. For example, the average density for Amarillo, Texas, is around 1.1 kg/m^3. When this value is compared to standard pressure, sea level, and 15°C (288K), there would be 10% less power at Amarillo for the same wind speeds. With the measurement of wind speed, pressure, and temperature, wind power potential can be calculated from Equation 3.2.

The energy per area for a time period of the same wind speed is

$$\frac{E}{A} = \frac{P}{A}t \text{ kWh/m}^2 \tag{3.5}$$

3.4 WIND SHEAR

Wind shear is the change in wind speed or direction over some distance (Figure 3.4). There can even be a vertical wind shear (Figure 3.5). The change in wind speed with height, a horizontal wind shear, is an important factor in estimating wind turbine energy production. The change in wind speed with height has been measured for different atmospheric conditions [3, chap. 4].

The general methods of estimating wind speeds at higher heights from known wind speed at lower heights are power law, logarithm with surface roughness, and logarithm with surface roughness that has zero wind velocity at ground level. The power law for wind shear is

$$v = v_0 \left(\frac{H}{H_0}\right)^{\alpha} \tag{3.6}$$

where v_0 = measured wind speed, H_0 = height of known wind speed v_0, and H = height.

The wind shear exponent α is around 1/7 (0.14) for a stable atmosphere (decrease in temperature with height); however, it will vary, depending on terrain and atmospheric conditions. From Equation 3.6 the change in wind speed with height can be estimated (Figure 3.6). Notice that for $\alpha = 0.14$, the wind power at 50 m is double the value at 10 m, a convenient way to estimate power, so many wind maps give wind speed and power classes for 10 and 50 m heights. However, for wind farms, wind power potential is determined for heights from 50 m to hub heights.

The wind shear exponent values in continental areas will be closer to 0.20 for heights of 10–40 m and above, with large differences from low values during the day to high values at night.

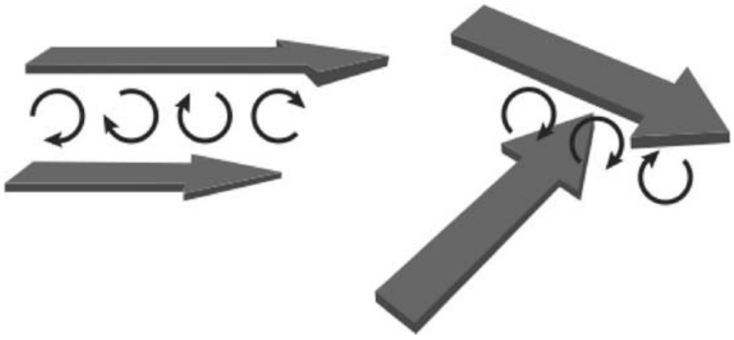

FIGURE 3.4 Left: Wind shear caused by a difference in wind speed with height. Right: Wind shear caused by a difference in wind direction.

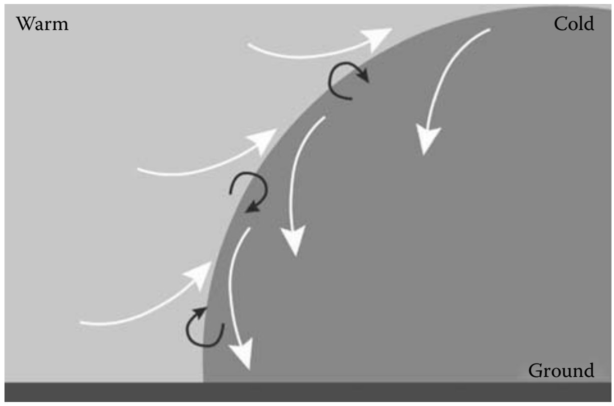

FIGURE 3.5 Example of vertical wind shear.

Measurements taken at heights of 10, 20, and 50 m for the northwest Texas region [3] for 12 h periods (6–18 h, day–night) showed a large difference between 10–20 m and 50 m levels. Data for sixteen sites in Texas and one site in New Mexico show the same results, a change in diurnal wind speed pattern at around 40 m [4]. Wind speeds were sampled at 1 Hz and averaging time was 1 h. The data were averaged by hour over a month, and then those were averaged over a year to obtain an annual average day (Figure 3.7). This same pattern is noted for data taken at heights above 50 m (Figure 3.8). The wind speed is still increasing with height, so the issue for wind farms is the trade-off between increased output with wind turbine height and increased cost for taller towers. These results clearly show that wind speed data need to be taken at least at a height of 40 m or higher to find the shift in pattern between day and night wind speeds. Once there are data at 10 m and 40–50 m, the wind shear can be used to predict wind speeds at higher levels. The higher night wind speeds means there is more power; however, those hours are also when there is less demand, so if the wind farm is selling at the market price, that energy may be worth less.

The wind shear exponent changes from low values during the day to high values at night over a 2 h period (Figure 3.9). Time of day data were averaged over each month. So the low values occur for more hours in the summer. There are locations where there is little wind shear, primarily mountain passes (Figure 3.10). In this case taller towers for wind turbines would not be needed.

The world standard height is 10 m for meteorology measurements for weather; however, using 10 m data and the 0.14 wind shear exponent to estimate wind power potential for 50 m for many

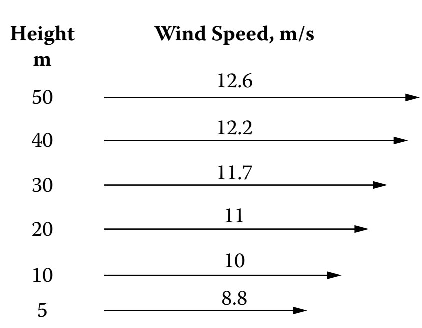

FIGURE 3.6 Wind shear, change in wind speed with height. Calculations are for given wind speed of 10 m/s at 10 m, α = 1/7.

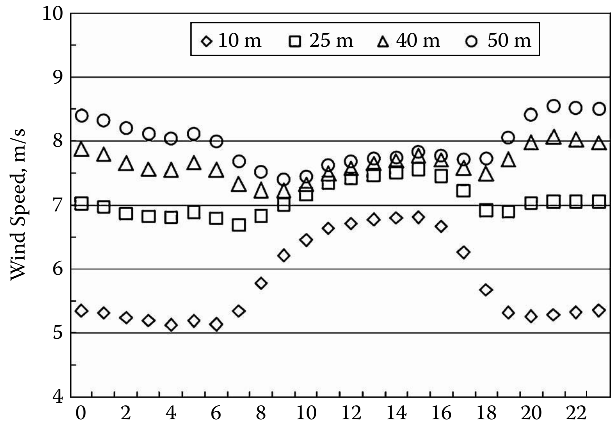

FIGURE 3.7 Annual average wind speed by time of day at 10, 25, 40, and 50 m heights, Dalhart, Texas, April 1996–2000.

locations will vastly underestimate the wind power potential for wind farms. The other formulas for estimating wind speed with height are

$$v = v \frac{\ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H_0}{z_0}\right)} \tag{3.7}$$

$$v = v \frac{\ln\left(1 + \frac{H}{z_0}\right)}{\ln\left(1 + \frac{H_0}{z_0}\right)} \tag{3.8}$$

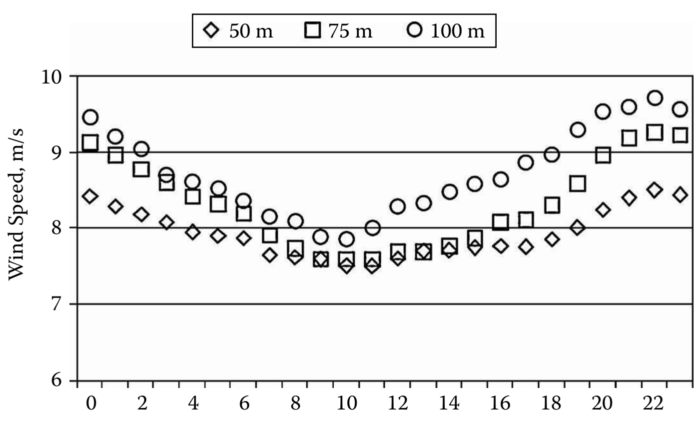

FIGURE 3.8 Annual average wind speed by time of day at 50, 75, and 100 m heights, Washburn, Texas, September 2003–2006.

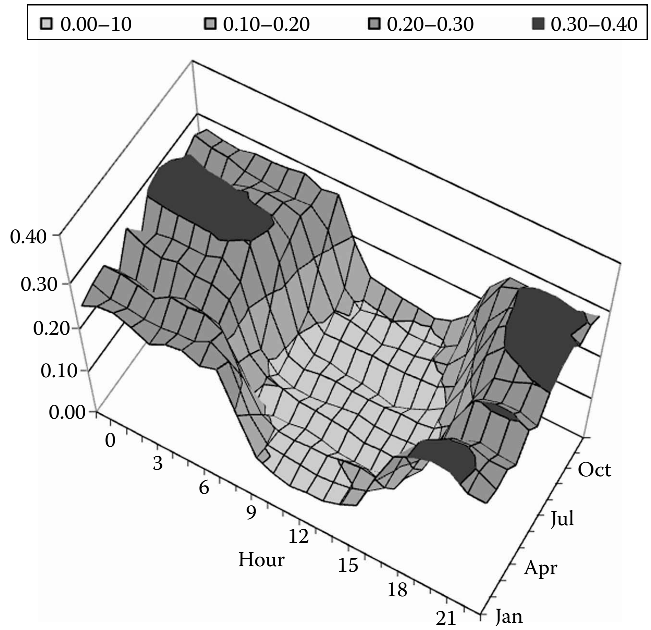

FIGURE 3.9 Wind shear exponent between 10 and 50 m for average month by time of day, Dalhart, Texas, April 1996–2000.

where z_0 is the roughness parameter. Equation 3.8 allows a zero wind speed at the surface. The roughness parameter ranges from 0.01–0.03 m for flat open terrain with short grass to larger than 1 m for rough terrain (Table 3.4).

EXAMPLE 3.3

A met tower is located close to the edge of town. If the wind speed is 8 m/s at 10 m height, what is the wind speed at 50 m? Use Equation 3.8 and select $z_0 = 1.2$.

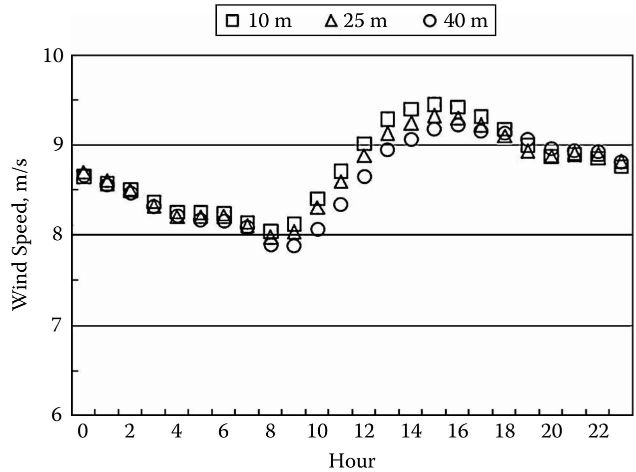

FIGURE 3.10 Annual average wind speed by time of day at 10, 25, and 40 m height, Guadalupe Pass, Texas, 1995–1999.

TABLE 3.4
Typical Values of the Roughness Parameter, z_0

Terrain Description	z_0, m
Snow, flat ground	0.0001
Calm open sea	0.0001
Blown sea	0.001
Snow, cultivated farmland	0.002
Grass	0.02–0.05
Crops	0.05
Farmland and grassy plains	0.002–0.3
Few trees	0.06
Many trees, hedges, few buildings	0.3
Forest and woodlands	0.4–1.2
Cities and large towns	1.2
Centers of cities with tall buildings	3.0

$$v = 8\,\frac{\ln\left(\frac{50}{1.2}\right)}{\ln\left(\frac{10}{1.2}\right)} = 8\,\frac{\ln(41.7)}{\ln(8.3)} = 8\,\frac{3.7}{2.1} = 14.1 \text{ m/s}$$

This compares to 10 m/s using the power law with a shear exponent = 0.14

3.5 WIND DIRECTION

Changes in wind direction are due to the general circulation of atmosphere, again on an annual basis (seasonal) to the mesoscale (4–5 days). The seasonal changes of prevailing wind direction could be as little as 30° in trade wind regions to as high as 180° in temperate regions. In the plains of the United States, the predominant directions of the winds are from the south to southwest in the spring and summer, and from the north in the winter. Traditionally, wind direction changes are illustrated by a graph, which indicates percent of winds from that direction, or a rose diagram (Figure 3.11).

There can also be change in wind direction on a diurnal basis. However, a wind shear of change in wind direction with height is generally nonexistent or small, except for very short time periods as weather fronts move through. Wind direction data (hour average wind speeds) from sixteen stations in Texas and one in New Mexico [5] did not find any significant wind shear of change in direction. Even on Padre Island, Texas, the land–sea breeze was not significant. Pivot tables were used to check on the relation between wind speed, wind direction, and time of day for the above seventeen met stations, plus two tall-tower met stations.

3.6 WIND POWER POTENTIAL

The most comprehensive, long-term source of information on wind speeds, pressure, and temperature is data collected at National Weather Stations. Other sources in the United States on record at the National Climatic Center, Asheville, North Carolina, are from Federal Aviation Administration stations, U.S. air bases, Coast Guard, etc. In the early 1960s anemometers at National Weather Stations were changed from their previous locations (20–30 m heights) on airport control towers, hangers, etc., to towers (around 6 m height) close to the runways and at least 1 km from buildings.

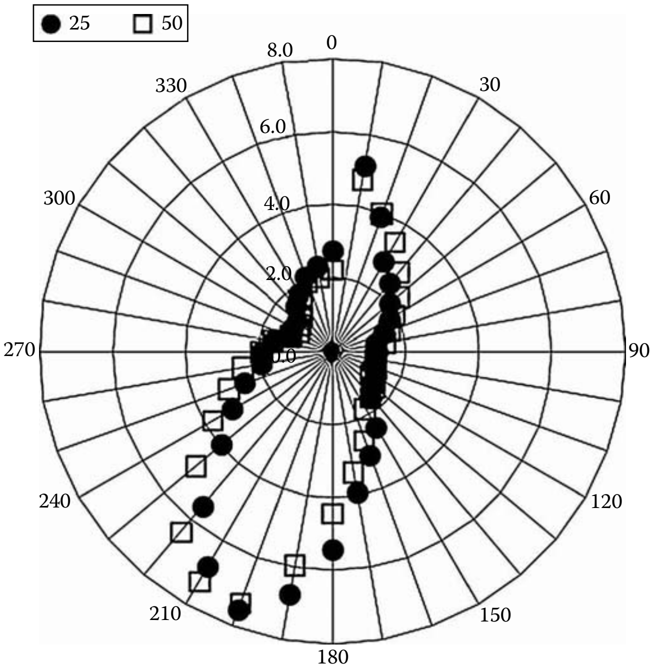

FIGURE 3.11 Annual average wind direction at 25 and 50 m height, 10° sectors, Dalhart, Texas, April 1996–2000.

Previously wind speed data at U.S. National Weather Service (NWS) stations were recorded on a strip chart and the observer estimated a wind speed over 1 to 2 min each hour. Wind speed data along with pressure, temperature, and other climatological data were put on magnetic tape for every hour. The National Weather Service converted to automated surface observation systems as of 1993–1994. Wind speed and direction are sampled at 1 Hz, averaged over 5 s, and rounded. Then a 2 min running average is calculated from the twenty-four 5 s samples. Data on CD-ROMs, data downloaded to a computer through the Internet, and data sheets of monthly summaries can be purchased (http://lwf.ncdc.noaa.gov/oa/ncdc.html).

If the wind speeds are known, then the average wind power or average wind energy per unit area can be estimated for any convenient time period, usually months, seasons, or year. When more than 1 year of data are available, then the year data or month data are averaged to obtain annual values by year or month. The wind power per area is referred to as the wind power potential or wind power density:

$$\frac{P_{avg}}{A} = \frac{\sum_{j=1}^{N} \frac{P_j}{A}}{N} = \frac{\sum_{j=1}^{N} \frac{0.5\rho_j v_j^3 A}{A}}{N} = \frac{\sum_{j=1}^{N} 0.5\rho_j v_j^3}{N} \tag{3.9}$$

where N is the number of observations.

Average values of temperature and pressure can be used to calculate an average density, and then the average power/area can be calculated for the available wind speed data. The result will be fairly accurate since the pressure and temperature will not vary over the month or year nearly as much as the wind speeds.

$$\frac{P_{avg}}{A} = \frac{0.5\,\rho_{avg}}{N} \sum_{j=1}^{N} v_j^3 \tag{3.10}$$

If the observations of wind speeds are compiled into a histogram, then the number of observations, n_j, in each wind speed bin could be changed to a frequency or probability by dividing the number of observations in a bin by the total number of observations:

$$N = \sum_{j=1}^{c} n_j, \quad f_j = \frac{n_j}{N}, \text{ and } \sum_{j=1}^{c} f_j = 1 \tag{3.11}$$

where c is the number of classes or bins. If the wind speed units are changed or if the wind speed is changed due to height, then the resulting histogram or frequency distribution should be normalized to contain the same number of observations.

Of course, for a large number of observations, a computer program or a spreadsheet would alleviate a lot of drudgery. Notice that the average wind speed (same as mean wind speed) is just the summation of the probability times the wind speed for each class in a frequency distribution:

$$v_a = \sum_{j=1}^{c} f_j v_j \tag{3.12}$$

The average power/area can be calculated from a selected wind speed histogram or wind speed frequency distribution by

$$\frac{P_{\text{avg}}}{A} = \frac{0.5\,\rho_{\text{avg}}}{N} \sum_{j=1}^{c} n_j v_j^3 = 0.5\,\rho_{\text{avg}} \sum_{j=1}^{c} f_j v_j^3 \tag{3.13}$$

Note the wind power potential is calculated from the sum. In one sense the individual power/area values are in energy/time for each class (bin). So if the energy in each bin is calculated and summed, then the average wind power potential can also be calculated from this total energy divided by the number of hours.

3.7 TURBULENCE

The wind will vary by location and time and be influenced by terrain, vegetation, and obstacles. Besides the mean wind speed, the variability of a set of data is represented by the standard deviation. For more detail, see Rohatgi and Nelson [9, Chapters 9 and 10]. The standard deviation for a set of wind speed data is

$$\sigma = \left[\frac{1}{1-N} \sum_{j=1}^{N} (v_j - \bar{v})^2 \right]^{0.5} \tag{3.14}$$

where $\bar{v}$ is the mean wind speed. Because N – 1 is close to N for a large sample, for data loggers and spreadsheets the standard deviation is calculated from

$$\sigma^2 = \frac{\sum_{j=1}^{N} v_j^2}{N} - \bar{v}, \quad \bar{v} = \frac{\sum_{j=1}^{N} v_j}{N}$$

In general, there are two different calculations, the standard deviation of the average values and the standard deviation of a set of data. If the average 1 h wind speeds are placed in 1 m/s bins for a month or a year, then a standard deviation can be calculated for each bin. This is different than the standard deviation of the 1 Hz data, which are averaged over 10 min or 1 h.

Turbulence intensity is usually calculated for short time periods, minutes to an hour, and is the mean wind speed divided by the standard deviation:

$$I = \frac{\bar{v}}{\sigma} \tag{3.15}$$

3.8 WIND SPEED HISTOGRAMS

A wind speed histogram shows the number of hours (or whatever time period is used) the wind blew at each wind speed class (Table 3.5). Wind speeds were sampled at 1 Hz and averaged for 1 h, and year wind speed histograms for 1996–1999 were averaged to obtain a representative annual value. An average density of 1.1 kg/m^3 was used to calculate the average wind power potential. The average wind speed was 8.2 m/s, and the average wind power potential was 467 W/m^2 for a height of 50 m. The plots of the wind speed histogram and energy histogram (Figure 3.12) show the relationship between the two. There is little energy in low wind speeds because of the low wind speed, and little energy at high wind speeds because of the small amount of time of high wind speeds.

TABLE 3.5
Annual Average: Wind Speed Histogram, Frequency and Calculation of Mean Wind Speed and Wind Power Potential at 50 m for White Deer, Texas, 1996–1999

Bin Class	Wind Speed, m/s	Hours	Frequency	$f_j v_j$	$f_j v_j^3$	Duration %	*k*Wh/m^2
1	0.5	54	0.01	0.00	0.0	100	0
2	1.5	146	0.02	0.03	0.1	99	0
3	2.5	353	0.04	0.10	0.6	98	3
4	3.5	487	0.06	0.19	2.4	94	11
5	4.5	617	0.07	0.32	6.4	88	31
6	5.5	747	0.09	0.47	14.2	81	68
7	6.5	844	0.10	0.63	26.4	73	127
8	7.5	950	0.11	0.81	45.7	63	220
9	8.5	949	0.11	0.92	66.5	52	320
10	9.5	940	0.11	1.02	92.0	41	443
11	10.5	801	0.09	0.96	105.9	31	510
12	11.5	702	0.08	0.92	122.0	21	588
13	12.5	486	0.06	0.69	108.4	13	522
14	13.5	302	0.03	0.47	84.8	8	409
15	14.5	175	0.02	0.29	60.9	4	293
16	15.5	85	0.01	0.15	35.9	2	173
17	16.5	52	0.01	0.10	26.9	1	130
18	17.5	32	0.00	0.06	19.6	1	94
19	18.5	22	0.00	0.05	15.7	0	76
20	19.5	12	0.00	0.03	10.5	0	51
21	20.5	4	0.00	0.01	3.6	0	17
	Sum	8,760	1	**8.2**	849		4,088
			Power/area		**467**		

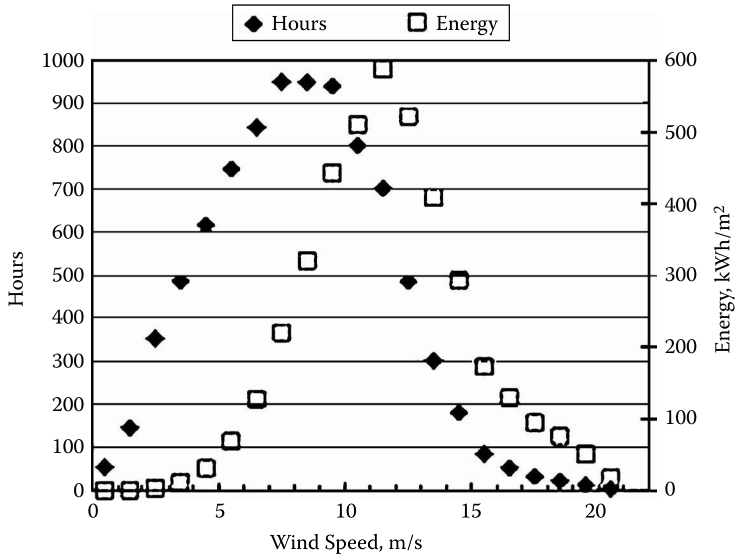

FIGURE 3.12 Annual average, comparison of wind speed and energy histograms at 50 m for White Deer, Texas, 1996–1999.

3.9 DURATION CURVE

Wind data can also be represented by a speed-duration curve (Figure 3.13), which is a plot of cumulative frequency starting at the largest wind speed (subtract 100 from percent frequencies of cumulative frequencies if starting at the lowest wind speed). The percent duration is usually converted (multiplying by 8,760) to number of hours in a year. From wind speed–duration curves, estimates of the time the wind speed is above a given value can be obtained. The data in Table 3.5 and the curve in Figure 3.12 show, for example, that a wind of 3 m/s or greater blows 95% of the time, or 8,300 hours in a year for that location.

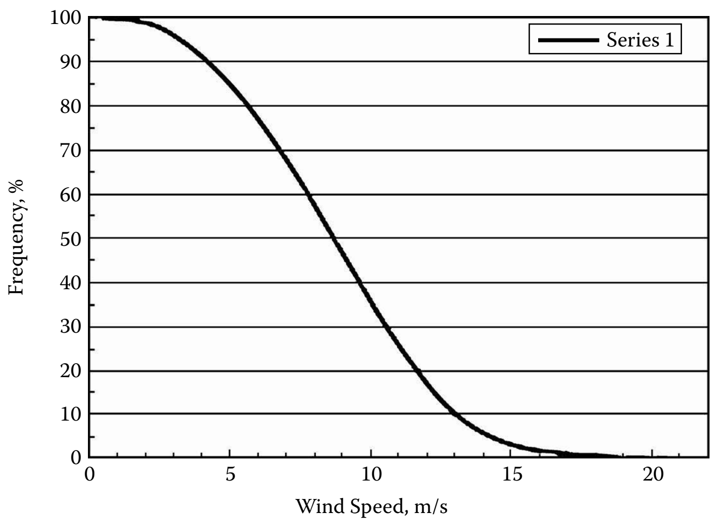

FIGURE 3.13 Wind speed–duration curve at 50 m height for White Deer, Texas, 1996–1999.

In general, whatever the wind speed is at any point in time, over the next hour the behavior ought to be similar. This is called persistence: $v(t + t_0) \sim v(t_0)$, where t is variable. However, a histogram does not give a time sequence of data, nor does a wind speed–duration curve tell the length of calm periods. As more wind turbines are installed, wind farm operators and utilities will be interested in predicting wind speeds, average variation by season and time of day, duration of low wind speeds, and values for the next 1 to 36 h.

3.10 VARIATIONS IN WIND POWER POTENTIAL

Since the motion of the atmosphere varies on a scale from seconds to years, wind power and wind energy will also vary on the same time scale. The annual average wind power (6 m height) for Amarillo, Texas, was 220 watts/m^2 for the period 1962–1977 [6]; however, the variation from one year to the next can be quite large. A minimum of 2 years of data are needed to obtain an estimate for the annual wind power potential, and 5 years of data are needed to obtain a mean value within 6% of the long-term mean. Most people assume that if you have 2–3 years of data, then that will suffice, along with longer-term regional data for comparison, to determine the wind power potential. The annual wind power potential (Figure 3.14) for White Deer and Dalhart, Texas, shows the correlation between sites, which are 140 km apart in the same region. Data were sampled at 1 Hz and averaged over 1 h. Therefore, for a region where long-term base data are available for comparison, 1–2 years of data would suffice for determining the wind power potential at a specific location.

The seasonal variation for most of the United States is high wind speeds in the spring, with low wind speeds in the summer (Figure 3.15). Notice the standard deviations at 10 and 50 m are comparable, and the average value for both is 0.6 m/s. Also, the standard deviation of the wind speed by month is close to the same as the standard deviation of wind speeds for an individual month (744 data points). The most notable exception to general seasonal variation is the mountain passes in California between the coast and inland deserts. The windy season corresponds to heating of the deserts in the summer, where the hot air rises and is replaced with cooler air flowing in from the ocean.

There are also variations with the movement of synoptic weather patterns, which is represented by a 4- to 5-day variation. The diurnal (daily) variation is due to heating during the day. These frequency representations (Figure 3.16) are common to many locations [7]. The peak at 0.01 cycle/h corresponds to a period of 100 h, which is the 4- to 5-day variation, and the peak near 0.1 cycle/h corresponds to the diurnal variation.

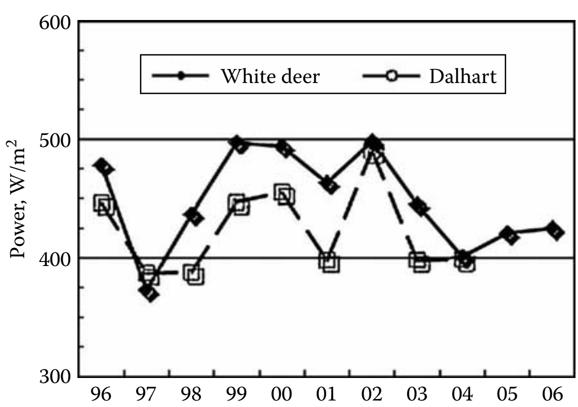

FIGURE 3.14 Annual variation of wind power potential at 50 m for White Deer and Dalhart, Texas.

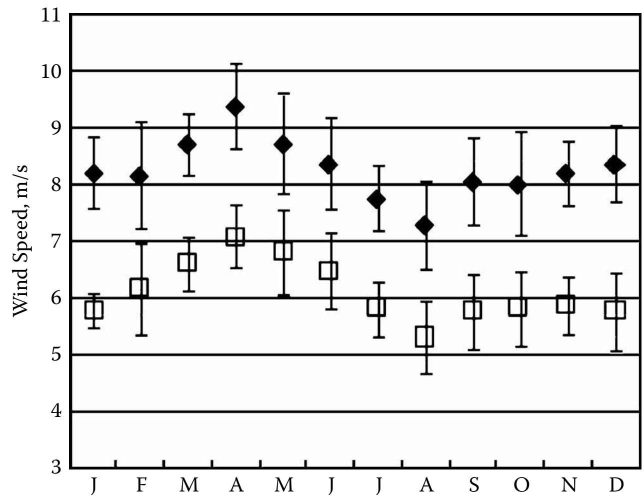

FIGURE 3.15 Annual wind speed and standard deviation by month at 50 m for White Deer, Texas, 1996–2006.

During the investigation of power storage for a wind/diesel system, an appropriate wind speed power spectrum became a significant issue [8]. A power spectrum was developed from 13 years of hourly average data, 1 year of 5 min average data, and particularly gusty days, and 1 s data, all at 10 m height. The general shape is similar to the Van der Hoven spectrum; however, few of his peaks were found in the power spectrum at the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS), Bushland, Texas. While higher average wind speeds tend to suggest higher amplitudes in the high-frequency end of the spectrum, this is not always true. Similar results were found for a power spectrum from 3 years of 15 min average data (sample rate, 1 Hz) at a 50 m height near Dalhart, Texas (Alternative Energy Institute met site). For wind speed data around the 40 m height, there would not be a diurnal peak in the continental areas of the United States. The Van der Hoven spectrum is not really useful for the wind turbine industry.

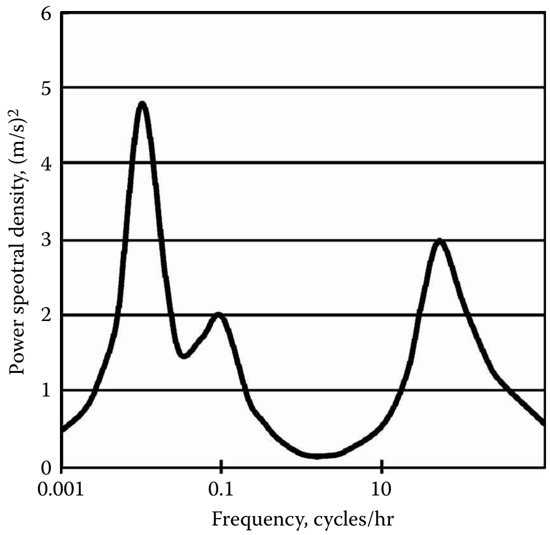

FIGURE 3.16 Example of power spectrum for wind speed. (From I. Van der Hoven [7]. With permission.)

3.11 WIND SPEED DISTRIBUTIONS

If data are not available, then the wind speeds can be predicted from one or two parameters. A number of different distributions have been tried, but only two are in general use, Rayleigh and Weibull distributions. These distributions give poor estimates of power for low mean wind speed situations. At higher wind speeds, both give adequate estimates for many locations; however, for those regions with steady winds, such as the trade winds, the Weibull distribution is better. The Rayleigh distribution is simpler because it depends only on the mean wind speed.

The Rayleigh distribution is

$$F(v) = \Delta v \frac{\pi}{2} \frac{v}{v_a^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{v_a}\right)^2\right] \tag{3.16}$$

where $F(v)$ = frequency of occurrence associated with each wind speed, v, which is at the center of Δv; Δv = width of class or bin; and v_a = average wind speed (same as mean wind speed)

The wind speed histogram for 1 year can be calculated from 8,760 * $F(v)$.

The Rayleigh frequency is calculated for two different values, $v = 3$ m/s and $v = 9$ m/s, with $v_a = 8$ m/s and $\Delta v = 2$ m/s:

$$F(3) = 2\frac{p}{2}\frac{3}{8^2}\exp\left[-\frac{p}{4}\left(\frac{3}{8}\right)^2\right] = 0.147\ e^{-0.11} = 0.132$$

$$F(9) = 2\frac{p}{2}\frac{9}{8^2}\exp\left[-\frac{p}{4}\left(\frac{9}{8}\right)^2\right] = 0.44\ \mathrm{e}^{-0.994} = 0.164$$

Note: As a check, the sum of the frequencies (probabilities) should be close to 1. If not, you have made a mistake. Also, the curve will be smoother for smaller bin widths; however, 1 m/s will suffice. For large bin widths, the wind speed histogram might have to be renormalized by bin value * 8,760/(sum of observations).

The Weibull distribution is characterized by two parameters, the shape parameter, k (dimensionless), and the scale parameter, c (m/s). The Rayleigh distribution is a special case of the Weibull distribution where $k = 2$. For regions of the trade winds where the winds are fairly steady, the shape factor may be as high as 4 to 5. For most sites in Europe and the United States, k varies between 1.8 and 2.4.

$$F(v) = \Delta v \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{3.17}$$

In many parts of the world the wind speed data are sparse. If only the average wind speed by day or month is known, then the average values and deviation of the average values are used to estimate the two parameters. Rohatgi and Nelson [9, chap. 9] give details on estimating the Weibull parameters by three methods: a plot of c and k from log-log paper, analysis of standard deviations, and analysis of the energy pattern factor.

A higher k value means wind speeds are peaked around the average wind speed (Figure 3.17). The values in the graph were calculated for a mean wind speed of 6 m/s for the Rayleigh distribution and $c = 6$ m/s and $k = 3$ for the Weibull distribution, and both used a bin width of 1 m/s.

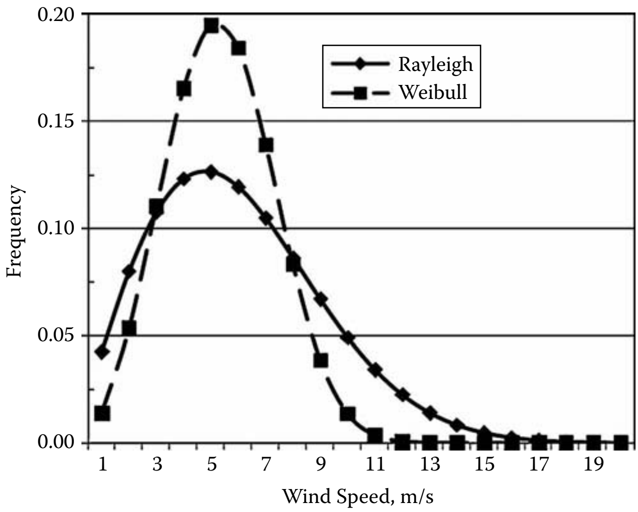

FIGURE 3.17 Example wind speed frequency calculated using Rayleigh distribution and Weibull distribution.

The energy pattern factor is not much used; however, it is an estimate of the variability of the wind speed. It is the relation between the mean of the cubes of each data point divided by the cube of the mean for a series of data (see Example 3.2 for a series of two points). The energy pattern factor is always greater than 1, and in the Southern High Plains, it varied from 1.6 to 3.4.

3.12 GENERAL COMMENTS

Previous studies of the behavior of the wind were done by meteorologists who were mainly interested in weather and, for research, turbulence and momentum transfer. Since 1975, numerous studies have been funded on wind characteristics as they pertain to wind energy potential and the effects on wind turbines. In the United States this research was primarily through the Battelle Pacific Northwest Laboratories (PNL), and it was then transferred to the National Wind Technology Center (NWTC), National Renewable Energy Laboratory (NREL). A list of publications on wind characteristics is available from NREL. States and universities have also funded projects for estimating the wind energy potential. After using the national atlas, contact your state energy office or the American Wind Energy Association in the United States.

National labs in many of the countries in the European Union did the same thing, with one of the prominent labs being Riso, Denmark. To obtain information in other countries, the procedures are the same: contact national entities, universities, institutes, and state, national, and international wind energy associations.

LINKS

National Climatic Center, http://lwf.ncdc.noaa.gov/oa/ncdc.html. Wind speed data.
National Wind Technology Center, NREL, http://www.nrel.gov/wind/about_wind.html.

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QUESTIONS/ACTIVITIES

1. What is the wind power class for your home? In the United States go to the NREL site on wind data or go to your state map, http://rredc.nrel.gov/wind/pubs/atlas/. In other countries try to find wind data values close to your home.
2. Note day and time. Go outside and estimate the wind speed. Now go to the information channel on your TV and write down that wind speed. If you are far off, what could be the reason? Going out on a calm day does not count.

PROBLEMS

Use spreadsheet if applicable and available.

1. Calculate the power, in kilowatts, across the following areas for wind speeds of 5, 15, and 25 m/s. Use diameters of 5, 10, 50, and 100 m for the area. Air density = 1.0 kg/m^3.
2. Solar power potential is around 1 kW/m^2. What wind speed gives the same power potential?
3. Calculate the factor for the increase in wind speed if the original wind speed was taken at a height of 10 m. New heights are at 20 and 50 m. Use the power law with an exponent $\alpha = 0.14$.
4. Calculate the factor for the increase in wind speed if the original wind speed was taken at a height of 10 m. New heights are at 50 and 100 m. Use the power law with an exponent $\alpha = 0.20$.
5. Calculate the factor for the increase in wind speed if the original wind speed was taken at a height of 50 m. New heights are at 80 and 100 m. Use the power law with an exponent $\alpha = 0.20$.
6. Houston Intercontinental Airport is surrounded by trees (20 m tall). Calculate the factor for increase in wind speed from 10 to 100 m. Use the ln relationship and an estimated z_0 from Table 3.4.
7. What is the air density difference between sea level and a height of 3,000 m?
8. In the Great Plains there is a wide temperature difference between summer (100°F) and winter (–20°F). What is the difference in air density? Assume you are at the same elevation; average pressure is the same.
   For problems with wind speed distributions, remember the wind speed has to be the number in the middle of the bin. If you use a bin width of 1 m/s, then the numbers have to be 0.5, 1.5, etc. In general, bin widths of 1 m/s are more than adequate. Smaller bin widths mean more calculations.

9. Calculate the wind speed distribution using the Rayleigh distribution for an average wind speed of 8 m/s. Use 1 m/s bin widths.
10. Calculate the wind speed distribution for a Weibull distribution for $c = 8$ m/s and $k = 1.7$. Use 1 m/s bin widths.
11. Calculate the wind speed distribution for a Weibull distribution for $c = 8$ m/s and $k = 3$.
12. From Figure 3.13, what is the percent of the time the wind is 5 m/s or larger?
13. From Figure 3.13, what is the percent of the time the wind is 12 m/s or larger?
14. From a 10 min period, the mean wind speed is 8 m/s and the standard deviation is 1.5 m/s. What is the turbulence intensity?
15. At the Delaware Mountains wind farm, very high winds with gusts over 60 m/s were recorded. An average value for 15 min was 40 m/s with a standard deviation of 8 m/s. What was the turbulence intensity?

Use the following table to calculate answers for problems 16–21. The most convenient way is to use a spreadsheet.

Bin *j*	**Speed** m/s	**No. Obs.**
1	1	20
2	3	30
3	5	50
4	7	100
5	9	180
6	11	150
7	13	120
8	15	80
9	17	40
10	19	10

16. Calculate the frequency for each class (bin). Remember, sum of $f_j = 1$.
17. Calculate the power/area for $j = 5$ bin and $j = 10$ bin.
18. Calculate the average (mean) wind speed.
19. Calculate the wind power potential (power/area).
20. From the mean wind speed of problem 18, calculate the power/area. How will that value compare (smaller, same, larger) to value in problem 19. Justify your answer.
21. From the answer to problem 18, use the mean wind speed and calculate a Rayleigh distribution for an average wind speed = 10.2 m/s. Use $\Delta v = 1$ m/s.

4 Wind Resource

There are two aspects of wind resource assessment: (1) determination of the general wind power potential and (2) determination of wind power potential and predicted energy production for wind farms. Wind resource assessment for wind farms will be covered in the chapter on siting.

The general wind power potential was determined from the wind speed data available, and then wind maps were developed. In general, the wind speed data that were available were at heights of 6 to 20 m; however, some anemometers were on top of buildings or control towers at airports, which influences the accuracy of the data. In many parts of the world the amount of wind speed data was limited to daily or even monthly averages. Wind classes were developed for 10 m height, because that was the standard for world meteorological data, and then the wind power potential at 50 m was double that at 10 m due to the assumption that the wind shear exponent was 1/7 for all locations.

A world wind map was prepared by Pacific Northwest Laboratory using wind data compiled in 1980 [1]. The assessment was made by critically analyzing all available wind data and previous assessments in order to estimate the broad-scale distribution of wind power potential. Much of the data were used cautiously because of the lack of information on anemometer height and exposure. Global pressure and wind patterns, upper air wind data, and boundary layer meteorology were also used to obtain a consistent estimate of the wind energy resource. Where an actual wind speed frequency distribution was available, that was used, or a Weibull distribution was used, to estimate the wind power potential. If only mean wind speeds were available, a Rayleigh distribution was used.

Most of the general results were known; for example, there are strong trade winds, northeast in the northern hemisphere and southeast in the southern hemisphere. At mid-latitudes (about 40–60°) the flow is westerly, and strong westerlies circle the world all year round in the southern hemisphere, which results in very strong winds at the tip of South America, southwest coast of South Africa, southern coast of Australia, Island of Tasmania, and New Zealand. The flow of the westerlies in the northern hemisphere is broken up by the large land masses. The region off the northern coast of South America also shows high wind speeds. The wind around the poles is predominantly easterly. The world wind map is available online [2] showing wind class at 50 m height for typical open, well-exposed sites. This is a very broad map and should be viewed with caution in estimating wind power potential. Country, state, and regional maps, formulated from better data and with much higher resolution, are now available for many parts of the world.

Note: If you are searching the Internet for world winds, links referring to NASA World Wind are for open-source Windows software to view satellite images of the earth and do not have anything to do with world wind maps or estimations of world wind power potential.

Archer and Jacobson [3] quantified the world's wind speeds, which are an indication of wind power potential, at 80 m height for the year 2000. A least square extrapolation technique was used to estimate wind speeds at 80 m from observed wind speeds at 10 m and a network of sounding stations. Globally, ~13% of the stations have class 3 (mean wind speeds ≥ 6.9 m/s) and above winds at 80 m, regions that are suitable for wind farms. This is a conservative estimate; for example, India does not show any winds above class 2, and it has a number of wind farms. Wind maps are presented for Europe, North America, Australia and New Zealand, Asia, and Africa. In general, the maps show the same regions of high winds as the previous world wind map. The major difference is that each met station is classified by a dot indicating the wind class. Again, these maps should be used with caution, as mean wind speeds are just an indicator of wind power potential, and mean wind speeds are only for 1 year; however, it was considered representative of the 5-year period 1998–2002.

Wind Atlases of the World [4] shows another wind map for the world, which includes values of mean wind speeds at 10 m height for the period 1976–1995. Again, the global westerlies in the southern hemisphere are prominent.

A project for renewable energy resource assessment, REmapping the World, will provide information for potential users, from individuals to governments. The interactive map provides global wind data at heights of 20, 50, and 80 m, with a 15 km resolution for a single year. It estimates that 40% of the world's land mass has wind speeds of 6 m/s or more. The global wind map can be viewed at firstlook.3tiergroup.com.

As more data have been collected specifically for wind power potential for nations, states, and regions, digital wind maps are available with better resolution than the older maps, and the values are more accurate, as data above 10 m have become available. However, the data collected by private wind farm developers are not available to the public, so data at 20–50 m heights are still being collected to provide regional data bases. Anemometer loan programs are available for private individuals in some states in the United States, and after some period of time, the data generally become public.

Computer tools for modeling the wind resource have been developed by a number of groups: NWTC NREL, RISO in Denmark (WAsP), other government labs, and private industry. Information from AWS True Wind about the Northwest Wind Mapping Project describes the process.

> The advanced MesoMap™ mesoscale modeling system simulates complex meteorological phenomena not adequately represented in standard wind flow models. It models sea breezes, offshore winds, mountain/valley winds, low-level nighttime jets, temperature inversions, surface roughness effects, flow separations in steep terrain, and channeling through mountain passes. This model utilizes historical upper air and surface meteorological data, thereby providing a consistent long-term, three-dimensional wind resource record. This record can later be used as a substitute for long-term surface wind measurements in the correlate-measure-predict (CMP) method, which adjusts short-term site measurements to the long-term climatological norm. The modeling results can help identify where limited wind measurement resources should be applied. Based on prior model validations, the expected range of discrepancy between measured and predicted winds in complex terrain is 3 to 7%.

Now remember what a 5% error in wind speed does to the error in wind power. Therefore, siting for wind farms is still important, and on-site data are imperative for financing a project.

4.1 UNITED STATES

A number of wind power and wind energy maps have been prepared for the United States; however, the earlier maps did not take into account the height differences of the anemometers. As part of the overall evaluation of wind energy, two major contracts were awarded to General Electric and Lockheed in 1975. Their estimates of the wind energy potential for a height of 50 m indicated that most of the United States has a fairly large potential. The problem is that most of these values were estimated from data taken at a height of 6 to 10 m, with the value at 50 m being double that at 10 m.

Pacific Northwest Laboratory oversaw a comprehensive assessment of the wind energy potential. The Wind Energy Resource Atlas covers the United States and its territories [5]. Wind power potential by year and season were also estimated for each state and region. The wind power classes (Table 4.1) were estimated for a grid of 20 min longitude by 15 min latitude (27 by 25 km, 16 by 15 miles). This atlas and the wind maps were updated in 1985 [6]. The different wind power maps are similar in gross features. Regions of better wind power are in the Great Plains, along the coasts, Hawaii, and selected sites, such as ridges, mesas, and mountain passes.

TABLE 4.1
Classes of Wind Power Potential at 10 and 50 m Levels

	10 m		50 m	
Class	Power W/m²	Speed m/s	Power W/m²	Speed m/s
1	0	0	0	0
	100	4.4	200	5.6
2	100	4.4	200	5.6
	150	5.1	300	6.4
3	150	5.1	300	6.4
	200	5.6	400	7.0
4	200	5.6	400	7.0
	250	6.0	500	7.5
5	300	6.4	600	8.0
	400	7.0	800	8.8
6	400	7.0	800	8.8
	1,000	9.4	2,000	11.9
7	1,000	9.4	2,000	11.9

Note: Values at 50 m are based on 1/7 power law from data at 10 m. Wind speeds are the equivalent value based on a Rayleigh distribution to give that power.

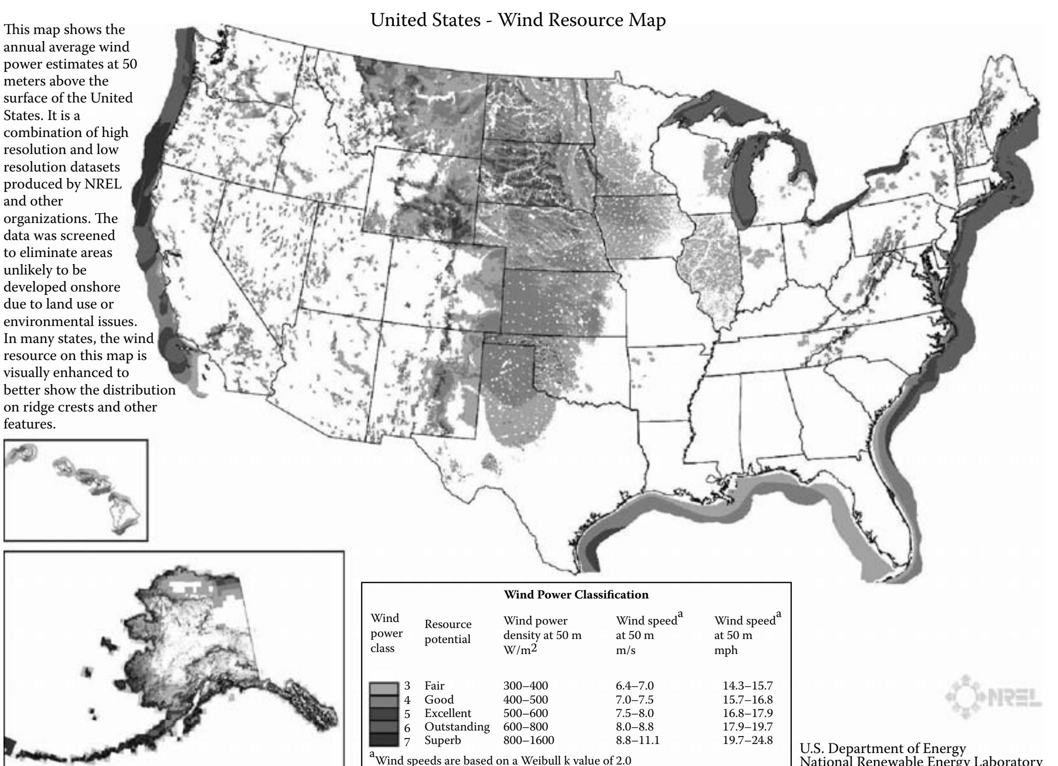


FIGURE 4.1 Wind power map for the United States. (Image from NREL. With permission.)

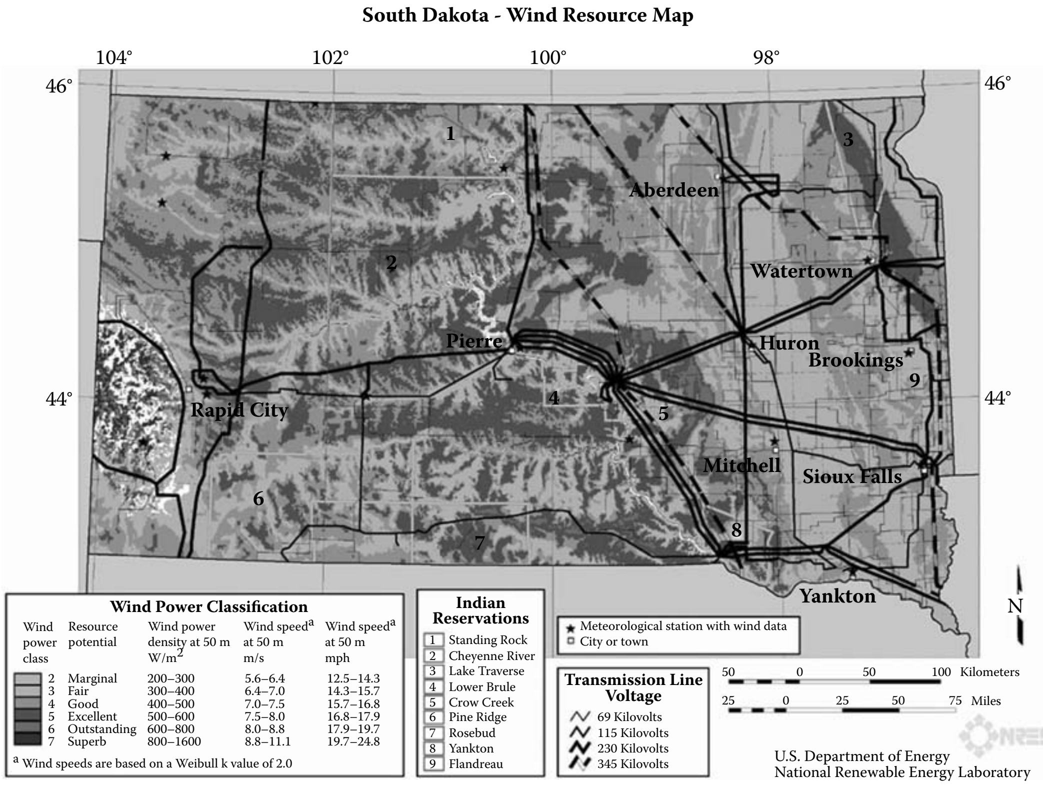


FIGURE 4.2 Wind power map for South Dakota using terrain enhancement. (Image from NREL. With permission.)

Now all of this information has been placed online and the maps are in a digital format (Figure 4.1). The National Wind Technology Center (NWTC), National Renewable Energy Laboratory (NREL), is updating the wind maps for states using terrain modeling, and maps have been completed for a number of states (Figure 4.2). The procedure uses actual data for verification. Information and data on wind resources are available at the NWTC [7], and digital wind maps for the United States are available from Wind Powering America [8].

New computer tools and technical analyses, which use satellite, weather balloon, and meteorological tower data, are being used to create better maps for assessing the wind power potential. Geographic Information Systems (GIS) provide wind maps with selected overlays, for example, transmission lines, roads, parks, and wildlife areas, etc., to assist in wind resource assessment. The higher resolution of these maps (1 km) provides better assessment for possible location of wind farms and has also shown higher-class winds in areas where none were thought to exist. The wind maps for the Northwest region [9] and Texas [10] have online interactive features to zoom in on local areas.

NWTC had a program of collecting data on tall towers, up to 100 m. The data from the thirteen tall towers in the Central Plains show that wind speeds and, of course, wind power potential continue to increase with height. Because wind speed increases with height, some regions with class 2 winds, which were presumed to have little potential for wind farms, have now become viable if they are close to large load centers. Three years of met data from the two tall tower sites in Texas and five years of met data from sixteen met sites in Texas and one met site in New Mexico are available to the public [11]. Some met data from the General Land Office, Texas, are also available.

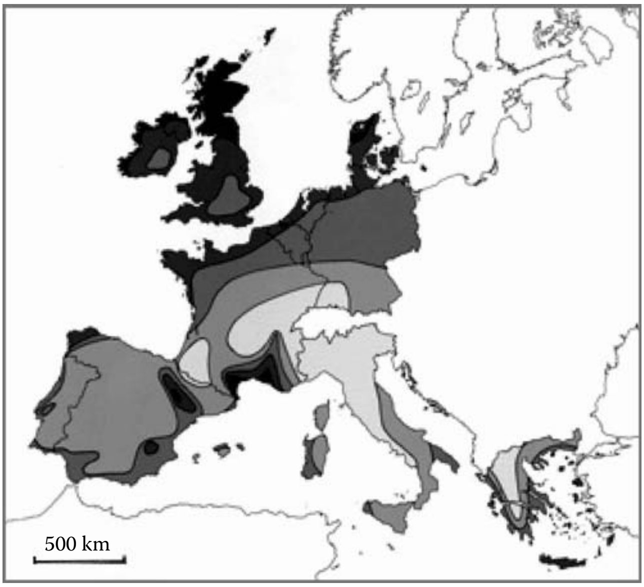


FIGURE 4.3 European wind resources at 50 m above ground level for five different topographic conditions. (From I. Troen and E. L. Petersen, *European Wind Atlas*, Riso National Laboratory, Denmark, 1989. With permission.)

4.2 EUROPEAN UNION

The Europeans have a concentrated effort on wind resource assessment beginning with the publication of the *European Wind Atlas* [12] in 1989. Part 1 provides an overall view of the wind resources. Part 2 provides information for determining the wind resource and the local siting of wind turbines. It provides descriptions and statistics for the 220 met stations in the countries of the European Community (EC) and includes methods for calculating the influence on the wind due to landscape features such as coastlines, forests, hills, and buildings. Part 3 explains the meteorological background and analysis for the *European Wind Atlas*, and includes the physical and statistical bases for the models. This wind map for the EC (Figure 4.3) shows high winds for northern United Kingdom and Denmark and across the northern coasts from Spain to Denmark. Also, wind maps are available for the thirteen countries. The wind power classes are somewhat different from those of the United States, and they also include different terrain (Table 4.2). Since then the EC has expanded and is now the European Union, and there are wind maps available for more countries.

TABLE 4.2
Wind Classes for Different Terrains, *European Wind Atlas*

	Shelter Terrain		Open Plain		Sea Coast		Open Sea		Hills and Ridges	
Class	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²
5	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1,800
4	5.0–6.0	150–250	6.5–7.5	300–500	7.0–8.5	400–700	8.0–9.0	600–800	10.0–11.5	1,200–1,800
3	4.5–5.0	100–150	5.5–6.5	200–300	6.0–7.0	250–400	7.0–8.0	400–600	8.5–10.0	700–1,200
2	3.5–4.5	50–100	4.5–5.5	100–200	5.0–6.0	150–250	5.5–7.0	200–400	7.0–8.5	400–700
1	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400

4.3 OTHER COUNTRIES

Wind power maps and isovent maps (contour lines of wind speed) are available for a number of countries and regions around the world (Table 4.3), as wind energy has become part of many national energy policies. For some of the countries the wind maps are private, and surely some countries that have wind maps are not listed, and more countries will have wind maps in the future. NREL is helping to develop wind maps worldwide, and as of 2008, twenty-three countries were listed [13]. Some of the maps are available through the Solar and Wind Energy Resource Assessment (SWERA) Program and the Asia Alternative Energy Program. SWERA provides online, high-quality renewable energy maps and other resource information at no cost to the user for countries and regions around the world. Renewable energy maps, atlases, and assessments can be downloaded [14].

Wind Atlases of the World contains links for over fifty countries [15], many of which contain wind data and wind statistics on disk. At present, the wind atlas methodology, WAsP, has been employed in around 105 countries and territories around the world.

A database of wind characteristics is compiled and maintained by the Technical University of Denmark and Riso National Laboratories, Denmark [16]. The database contains four categories of wind data: time series, wind resource measurements, structural wind turbine response measurements, and wind farm measurements. There are also links for wind maps.

TABLE 4.3
Countries That Have Maps of Wind Resource, 2008

North America	Europe	Asia
United States + protectorates	Belgium	Russia
Canada	Denmark	Afghanistan
Mexico	France	Armenia
El Salvador	Germany	Azerbaijan
Guatemala	Greece	Kazahkstan
Honduras	Ireland	Saudi Arabia
Nicaragua	Italy	China
	Luxembourg	Hong Kong
Caribbean	Netherlands	India
Cuba	Portugal	Indonesia
Dominican Republic	Spain	Mongolia
	United Kingdom	Japan
South America		Philippines
Argentina	Austria	Sir Lanka and Maldives
Brazil	Croatia	
Chile	Czech Republic	
Colombia	Estonia	
Venezuela	Finland	**Southeast Asia**
	Hungary	Cambodia
Africa	Latvia	Laos
Algeria	Lithuania	Thailand
Egypt	Poland	Vietnam
Eritrea	Slovak Republic	
Ethopia	Slovenia	Australia
Ghana	Sweden	New Zealand
Tunisia	Turkey	
South Africa		

Examples of older maps are given in Rohatgi and Nelson [17, chaps. 5 and 6]. China and India have installed substantial capacity of wind turbines, which means that resource assessment preceded the installation.

More detailed assessments are available from measurements to provide a database for wind power by state, region, and nation, and to delineate possible locations for wind farms. Even micro siting for wind turbines within wind farms is important.

4.4 OCEAN WINDS

Ocean winds are and have been measured by ships and instruments on buoys. Now complete coverage of the oceans is available using reflected microwaves from satellites [18, 19]. A physically based algorithm calculates ocean wind speed and direction at 10 m from surface roughness measurements. Water vapor, cloud water, and rain rate are also calculated. This algorithm is a product of 15 years of refinements and improvements. Data are the orbital daily observations mapped to a 0.25° grid, and then averages are calculated for 3 days, a week, and a month. Images of the data can be viewed on websites for the world, by region, or selected area.

At the Remote Sensing Systems website images can be viewed in the browse/download section. For SSM/I and TMI satellites the wind speed images do not include direction and have a maximum value of 12 m/s. Dynamic Data Imaging lets you select region, dates, and zoom factor, and also gives statistics.

The QSCAT satellite images include direction and higher wind speeds (Figures 4.4 and 4.5). There is no dynamic imaging, but world is divided into regions. Ocean winds are not available within 25 km of the shore, as radar reflections off the bottom of the ocean skew the data.

Notice that ocean winds will indicate onshore winds for islands, coasts, and also some inland regions of higher winds. Two regions of average wind speeds of 10 m/s due to the northeast trade winds are in the Istmus of Teohuantepec, Mexico, and the Arenal region of Costa Rica, where winds are funneled by the land topography.

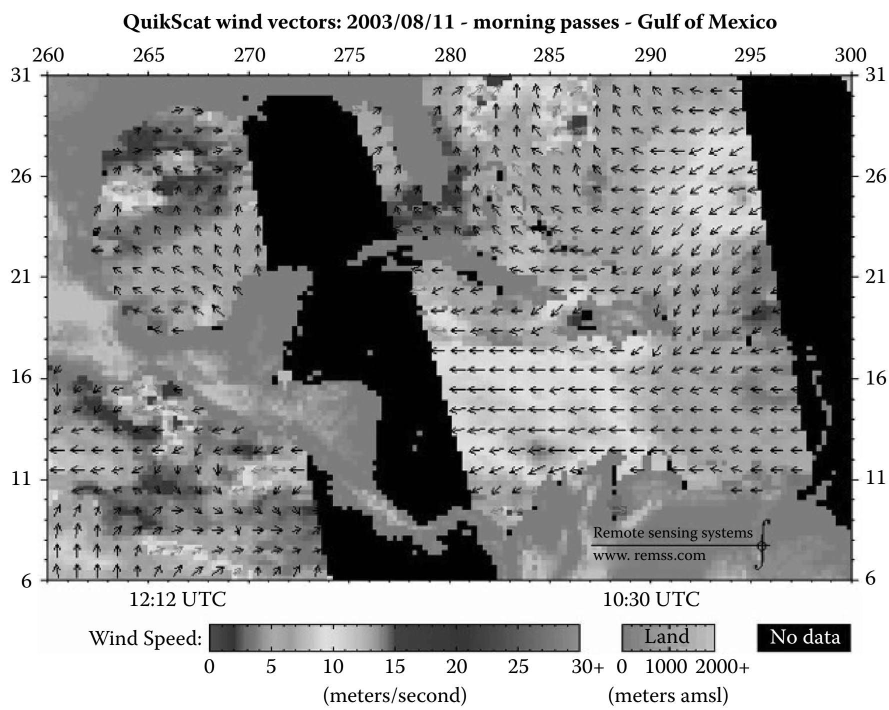


FIGURE 4.4 Example of daily satellite passes for Gulf of Mexico.

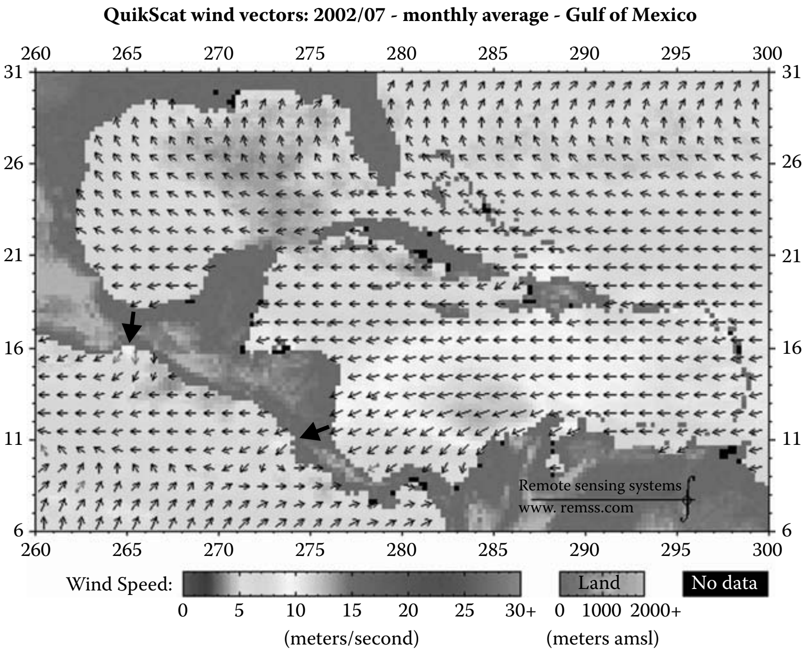


FIGURE 4.5 Average wind speeds for July 2002. Large arrows on land indicate excellent onshore wind regions, average wind speeds of 10 m/s.

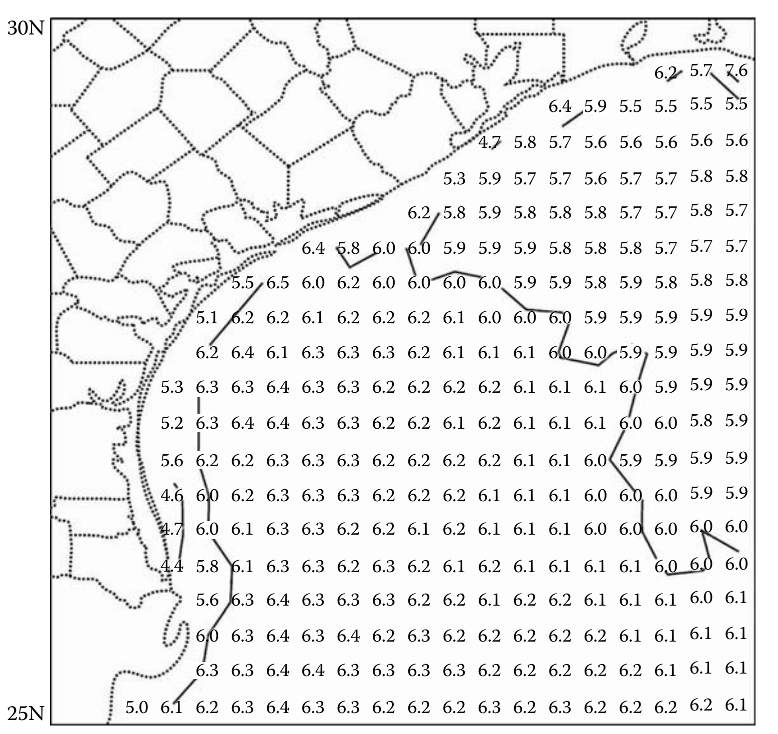


FIGURE 4.6 Average wind speeds, m/s, at 10 m height for 1988–1994 for Gulf of Mexico, Texas coast.

Over 1,000 MW have been installed in offshore wind farms in Europe, because in general wind speeds are higher and onshore land has a high value. The United States is considering offshore wind farms near Cape Cod, Massachusetts, and the Gulf Coast of Texas. Wind farm developers have expressed interest in offshore in the Great Lakes and on both coasts. A program for offshore wind resource assessment has began at NREL [20]. The maps will extend from coastal areas to 90 km offshore and have a horizontal resolution of 200 m. The final maps of wind speed and power will be for 50 m height, and the model data will be modified with data taken at sites on the coast and offshore.

4.4.1 Texas Gulf Coast

The ocean wind data were used to calculate wind speed and power (10 m height) for 0.25° pixels for a 5 by 5° area (longitude, 25–30 N, and latitude, 93–98 W) for the period of 1988–1994 [21]. The average wind speed is around 5 m/s, and further out in the Gulf of Mexico it is above 6 m/s (Figure 4.6). December and January are the high months, with June being the low wind month.

The National Renewable Energy Laboratory and the Texas State Energy Conservation Office have a cost share project to produce high-quality and validated offshore wind resource maps [22]. These data include the near-shore region not covered by the ocean wind data. Maps of mean annual wind speed at 10 to 300 m and mean annual wind power potential at 50 m are available. There are class 3 winds along the northern third of the Gulf Coast, then class 4 winds with a region of class 5 winds from Corpus Christi almost to the border with Mexico. NREL also plans to use the data to analyze the offshore wind shear plus other wind characteristics for offshore wind turbine design and performance. The state has control of the land for a distance of 16 km from the coast and is interested in leasing areas for wind farms.

4.4.2 World

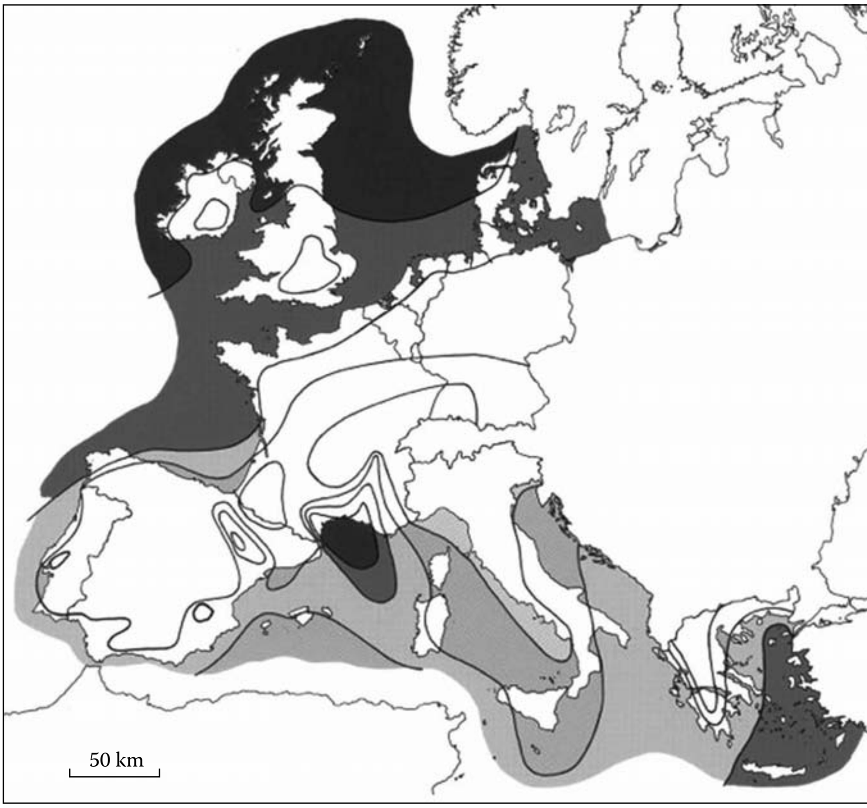
The *European Wind Atlas* also has offshore winds (Figure 4.7). The Predicting Offshore Wind Energy Resources project [23] aimed to assess the offshore wind power potential in European Union waters, taking into account coastal effects and highlighting those sea areas where hazardous wind or wave conditions exist. These estimates can then be used to pinpoint areas, which are favorable for siting a wind farm. More detailed monitoring can then be undertaken to improve the initial wind power estimates at selected sites.

4.5 INSTRUMENTATION

An anemometer is a device for measuring airflow. There are a number of measuring devices for wind speed: pitot tube, cup, vane, propeller, hot wire, hot film, sonic, and laser Doppler anemometers. The common devices are the cup and propeller anemometers, since they are cheaper. However, their response times to changes in wind speed are slower. Wind turbines also have a response time to changes in wind speed, so cup anemometers are adequate for determining the wind energy potential. Sonic and hot wire anemometers have the advantage of no moving parts and no response time in contrast to mechanical sensors. However, their higher cost has kept them from much penetration into the wind resource assessment market.

An anemometer can be obtained to measure the amount of wind that has passed, a wind run. From the wind run, the average wind speed can be calculated for the time period. An anemometer can also be obtained to measure the fastest mile, the maximum wind speed.

Previously, meters and strip charts, which give analog outputs, were used. However, analyzing strip chart data becomes quite tedious, and the time resolution is fairly coarse unless the paper feed rate is large. Today the major difference is the availability of microprocessors for sampling, storing, and even analyzing data in real time. Also, personal computers alleviate most of the problems in analyzing large amounts of data.



Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
	>8.0	>600	>8.5	>700	>9.0	>800	>10.0	>1100	>11.0	>1500
	7.0–8.0	350–600	7.5–8.5	450–700	8.0–9.0	600–800	8.5–10.0	650–1100	9.5–11.0	900–1500
	6.0–7.0	250–300	6.5–7.5	300–450	7.0–8.0	400–600	7.5–8.5	450–650	8.0–9.5	600–900
	4.5–6.0	100–250	5.0–6.5	150–300	5.5–7.0	200–400	6.0–7.5	250–450	6.5–8.0	300–600
	<4.5	<100	<5.0	<150	<5.5	<200	<6.0	<250	<6.5	<300

FIGURE 4.7 European offshore wind resources at five heights for open sea. (From I. Troen and E. L. Petersen, *European Wind Atlas*, Riso National Laboratory, Denmark, 1989. With permission.)

Digital instruments or analog inputs, which are digitized, typically have sample rates of 0.1 to 1 Hz (Hertz = number/second). Values can be stored in a histogram of wind speeds, or wind speed and other selected variables can be stored for selected averaging time periods, along with standard deviations. Events such as maximums and time of occurrence can also be recorded and stored. Micro data loggers were designed specifically for wind potential measurements and record time sequence data (averaging time is selectable) on chips. The chips can store data from a number of channels, and the data loggers can even be queried by telephone (cell or direct), radio link, or satellite, so data are transmitted directly to the base computer. Now Internet connection is available. More detailed information on instrumentation and measurement can be found in Rohatgi and Nelson [17]. Also see the *Wind Resource Assessment Handbook* [24] for detailed information on wind measurement, instrumentation, and quality assurance.

The advantages of sonic detection and ranging (SODAR) and light detection and ranging (LIDAR) are that the instrumentation is at ground level and no tower is needed, and wind speeds can be measured to 500 m (SODAR) and even out to several kilometers (LIDAR). The disadvantage is the cost; however, the cost for met towers over 60 m is substantial and the cost for a met tower of 150 m, a height to the top of the rotor for large turbines, is quite expensive. A short-term study [25] compared the relative accuracy of high-resolution pulsed Doppler LIDAR with a mid-range Doppler SODAR and direct measurements from a 116 m met tower that had four levels of sonic anemometers. The primary objective was to characterize the turbulent structures associated with the Great Plains low-level nocturnal jet. The actual measuring volumes associated with each of the three measurement systems vary by several orders of magnitude, and that contributed to the observed levels of uncertainty. The mean differences were around 0.14 m/s.

There are three general types of instrumentation for wind measurements: (1) instruments used by national meteorological services, (2) instruments designed specifically for determining the wind resource, and (3) instruments for high sampling rates in determining gusts, turbulence, and inflow winds for measuring power curves, stress, fatigue, etc., for wind turbines.

The data collection by meteorological services is the most comprehensive and long term; however, in much of the world, the data are almost worthless for determining wind power potential. The reasons are the following: few stations; most locations are in cities and airports, which are generally less windy areas; sensors are mounted on buildings and control towers; the quantity of data actually recorded is small (one data point per day, or sometimes monthly averages); and lack of calibration after installation. As an example of the problem of using meteorological data, the annual mean wind speed for Brownsville, Texas, is 5.4 m/s, compared to 2.8 m/s for Matamoros, Mexico, which is just across the Rio Grande River.

There are several types of instruments at varying costs for measuring wind speed: handheld anemometers, $400; data loggers, $1,500; and data loggers with cell phones, $3,000. Companies sell instruments that sample at rates of 0.1 to 1 Hz and with the output displayed on analog devices (meters and recorders) or digital devices (stored on tape or chips). Instruments will record and analyze time sequence data, as not only wind speeds and direction can be stored for selected time intervals, but the power can be calculated and selected events such as maximums, gusts, and time of occurrence are also available. Companies that sell instrumentation specifically for wind measurements also sell digital readers and provide software for analyzing the data. Pole towers are available specifically for wind measurements from 10 m, $500, to 60 m (with gin pole), $10,000. Guyed lattice towers can be obtained for higher heights. Pole towers of 50 and 60 m are normally used for the following reasons: tower can be raised and lowered with gin pole, tall enough to obtain the higher nighttime wind speeds, and tower is below height (61 m, 200 ft) for required lights per U.S. Federal Aviation Administration.

In many countries, mechanical anemometers were the norm; however, they require more maintenance and more frequent calibration. The power from the cup anemometers drove the strip chart recorder or a counter. Because of the small number of data points, the Weibull distribution was widely used to estimate wind power potential. As an example of the problem, wind run data were collected three times a day from an anemometer at less than 2 m height at a national meteorological station in Jujuy, Argentina (Figure 4.8), to determine daily average wind speed. Due to height and of course blockage of trees and buildings, the wind power potential would be vastly underestimated.

Data from Mexicali Airport, Mexico [26], provide an example of a trend in wind speed data over time (Figure 4.9). The number of observations, 1 h values, was fairly consistent from 1973 to 1999, when the airport was operating. The downward trend indicates degradation in the anemometer (not maintained or recalibrated) or less exposure due to increased vegetation or other obstructions. The wind power changes from 170 W/m^2 at the beginning to 25 W/m^2 at the end, a factor of 7.

4.5.1 Cup and Propeller Anemometers

A widely used anemometer for wind resource measurements has a circular magnet (four poles) in the cup housing, and then one or two coils for pickup of the signal (Figure 4.10), which approximates

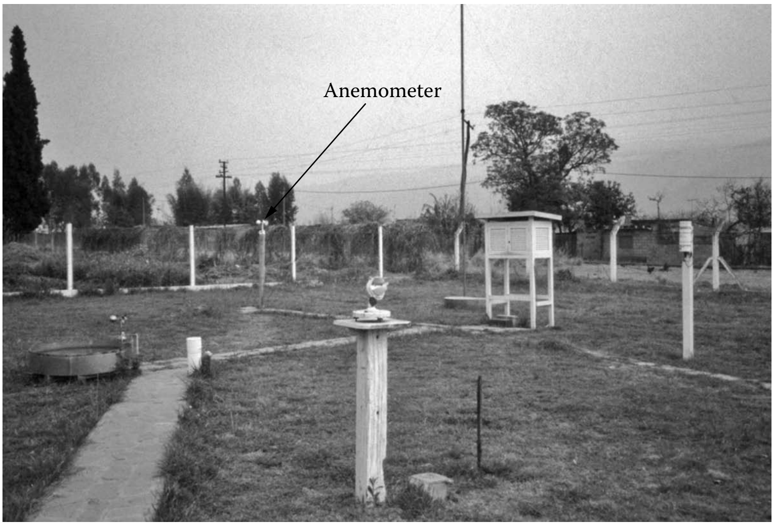


FIGURE 4.8 Meteorological station in Jujuy, Argentina.

a sine wave. The transducer counts zero crossings (sampling time is generally 1 Hz), so wind speed is related to number of counts. The advantage is that signals can be transmitted 150 m without loss of accuracy (none of the problems of attenuation and amplification needed with analog signals). An estimate of the accuracy of cup anemometers in wind tunnels is reported to be ±2% [27].

Another type of cup anemometer has a disk containing up to 120 slots and a photocell. The periodic passage of slots produces pulses in each revolution of the cup. This gives a better resolution, so the sampling rate can be increased to 5 Hz.

The propeller anemometers (Figure 4.11) have faster response and behave linearly in changing wind speeds. The wind speed is measured by measuring the voltage output of a DC generator. The propeller is kept facing the wind by a tail vane, which also works as a direction indicator. The accuracy normally is about 2% for wind speed and direction. The propeller is usually made of

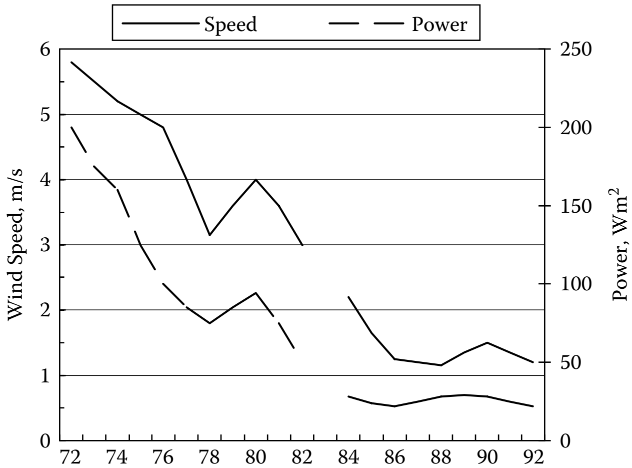


FIGURE 4.9 Wind speed data for Mexicali Airport, Mexico.

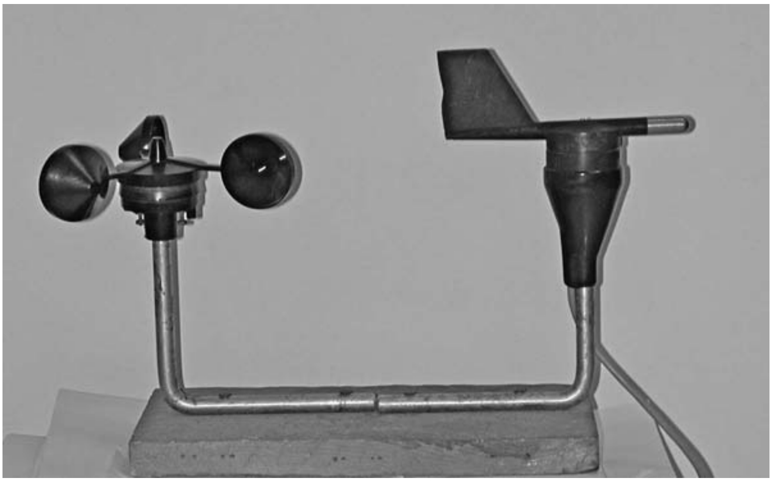


FIGURE 4.10 Maximum cup anemometer and wind vane. Anemometer is about 15 cm across.

polystyrene foam or polypropylene. However, for turbulent winds, the values may be misleading in determining power curves for wind turbines. A propeller anemometer is better suited to measure the three components of wind velocity, because it responds primarily to wind parallel to its axis. An array of three units in mutually perpendicular directions measures the three components of wind.

4.5.2 Wind Direction

The wind direction is measured by a wind vane, which is counterbalanced by a weight fixed on the other end of a rod. However, in the case of propeller anemometers, the vane is a part of the

FIGURE 4.11 Propeller anemometers for measuring in three directions. (Photo by R. M. Young. With permission.)

propeller's axis. The vane requires a minimum force to initiate movement. The threshold wind speed for this force, usually, is of the order of 1 m/s. Normally the motion of the vane is damped to prevent rapid changes of directions. Wind vanes generally produce signals either by contact closures or by potentiometers. The accuracy obtained from potentiometers is higher than that obtained from contact closures, but the latter are less expensive.

4.5.3 Instrument Characteristics

Sensors, transducers, and signal conditioners measure and transform signals for recording. Resolution is the smallest unit of a variable that is detectable by a sensor. Recorders may limit the resolution. Reliability is a measure of an instrument's ability to produce useful data over a period of time. The best indicator of reliability is the past performance of similar instruments.

Accuracy and precision are two separate measures of system performance that are often treated ambiguously. Accuracy refers to the mean difference between the output of a sensor and the true value of the measured variable. Precision refers to the dispersion about the mean. For example, an instrument may produce the same measured value every time but produce a value that is off by 50%. That system has a high precision but low accuracy.

The accuracy, however, may be a function of time, or dependent on maintenance. Anemometers are calibrated in wind tunnels, where the airflow is steady. Another calibration of performance, scale and offset, of anemometers for wind resources assessment uses the controlled velocity method (boom mounted on truck). Generally, calibrated anemometers produce a signal that is accurate to within 0.5 to 2% of the true wind speed. Under normal use in the atmosphere, good anemometers should be accurate to around 2 to 4%.

The distance constant is the length of fluid flow past a sensor required to cause it to respond to 63.2% of a step change in speed. A step change is change from one value to another value, similar in shape to stair step. The larger and heavier cup anemometers usually have distance constants of 3 to 5 m. For light-weight and smaller cup anemometers, such as those used for turbulence, the distance constant is typically about 1 m. The time constant is the period that is required for the sensor to respond to 63.2% of a step change in input signal.

The damping ratio is a constant that describes the performance of a wind vane in response to a step change in wind direction. The damping ratio is dimensionless and is generally between 0.3 and 0.7.

The sample rate is the frequency (Hz) at which the signal is sampled. This may include the time for recording the data. Since a large amount of data requires large storage, wind speeds are averaged over a longer time period, and these are the values stored, along with standard deviations. Typical values for wind power analysis are sample rates of 1 Hz and averaging time of 10 min. Previously, 1 h averaging times were used for many resource assessment projects.

4.5.4 Measurement

Anemometers mounted on towers should be mounted away from a lattice tower a distance of two to three tower diameters to reduce the effect of the tower on the airflow. For solid towers, they should be mounted six tower diameters away. Met towers have to be located away from the influence of obstacles: trees, buildings, etc.

The time and money spent for measuring the wind resource depends on whether it is for a wind farm or a small wind turbine. The difference between finding class 3 and class 4 and above wind sites will easily determine the economic viability for wind farms. Individuals who install small wind turbines tend to overestimate the wind resource before their turbine is installed, and then bemoan the lack of wind afterwards.

Instrumentation for measuring turbulence and the wind inflow for wind turbine response uses multiple anemometers and a higher sampling rate. A system for characterizing turbulence [28]

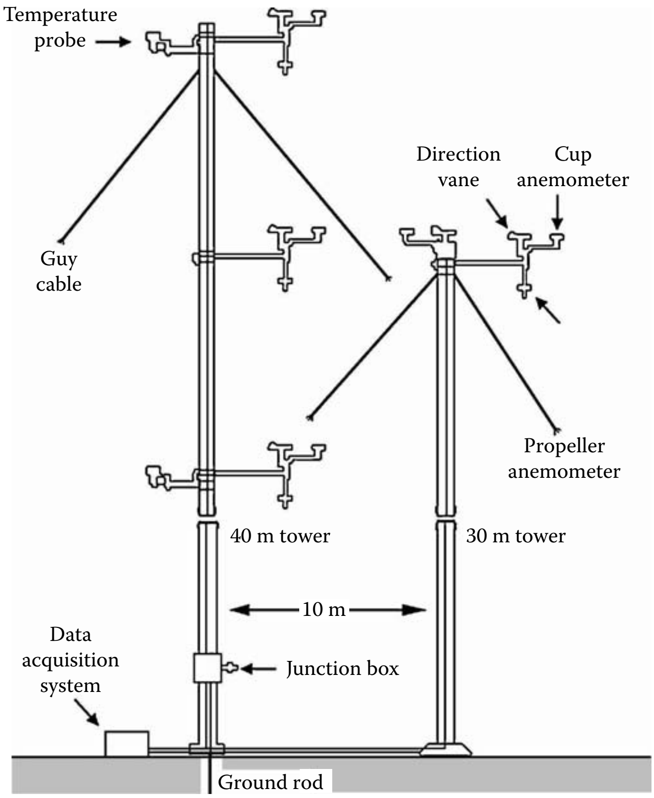


FIGURE 4.12 System for measuring turbulence.

developed and tested by Pacific Northwest Laboratory consisted of two towers and nine anemometers (Figure 4.12), data sampled at 5 Hz. The propeller vane anemometers for horizontal measurements were replaced by cup anemometers due to problems of maintenance and errors in measurement of wind speed.

4.5.5 Vegetation Indicators

Vegetation can indicate regions of high wind speed where there are no measurements available. Deformation or flagging of trees [17, p. 96] is the most common indicator (Figure 4.13). In some cases the flagging of trees is a more reliable indicator of the wind resource than the data available. For example, the Arenal region of Costa Rica has high winds, which have now been measured (average for twelve stations) at 11 m/s [29]. There is a meteorological station near Fortuna in the region, which was primarily for collecting data for hydrology. The mechanical anemometer height is less than 2 m, as they were interested in determining evaporation, and furthermore the station was located close to trees. Therefore, that wind speed data indicated no wind power potential. However, flagged trees in the area indicated high wind speeds.

The Griggs and Putnam Index [30] for flagging of coniferous trees (Figure 4.14) is related to the annual mean wind speed [31] by

$$\bar{u} = 0.96\ G + 2.6$$

FIGURE 4.13 Examples of flagging of trees: left, tree on plains, Canyon, Texas (6 m/s average wind speed at 10 m height); right, tree at South Point, Hawaii (10 m/s average wind speed at 10 m height).

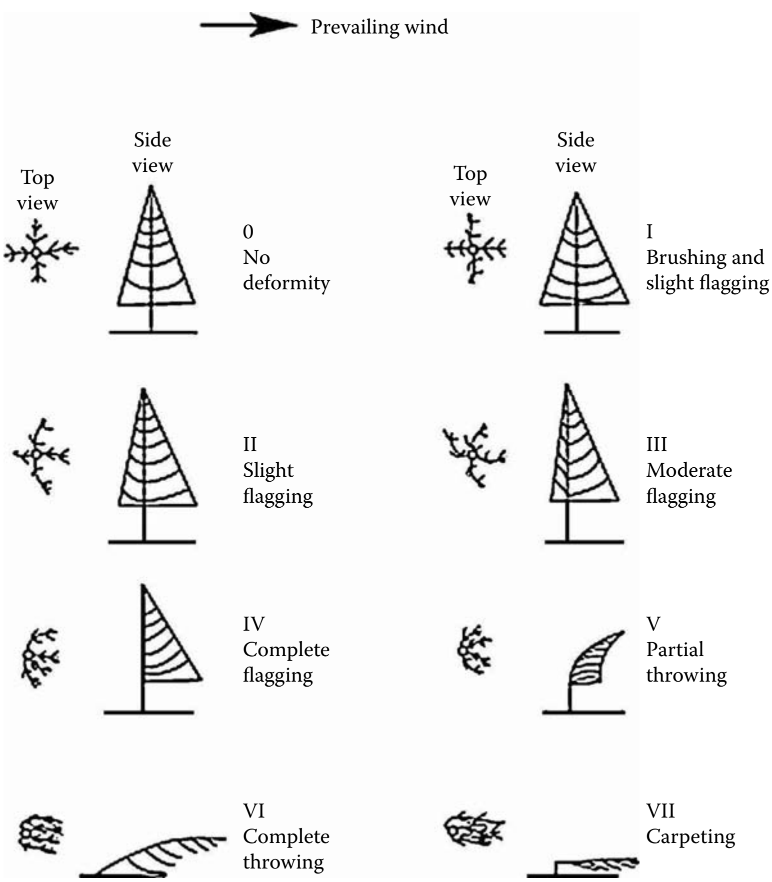


FIGURE 4.14 The Griggs-Putnam Index of tree deformation.

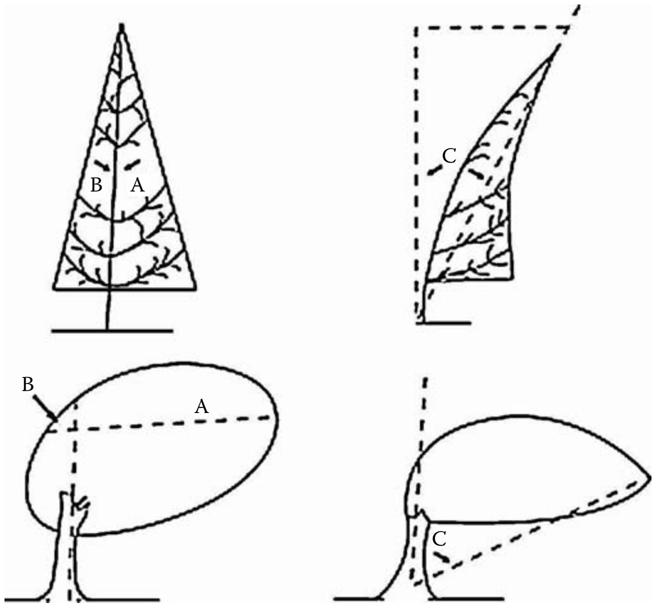


FIGURE 4.15 Estimation of wind speed by tree deformation.

An index for broad leave trees is the deformation ratio, D, which represents the amount of crown asymmetry and trunk deflection of trees caused by the wind (Figure 4.15):

$$D = A/B = C/45°$$

The relationship is used for both coniferous and hemispherical crowned trees. For coniferous trees, A is the angle formed by the crown edge and the trunk on the leeward side, B is the angle formed by the crown edge and the trunk, and C is the average angle of trunk deflection. For hemispherical crowned trees, A is the distance between the trunk and the crown perimeter on the leeward side, B is the distance between the trunk and the crown perimeter on the windward side, and C is the angle between the crown perimeter and the trunk on the leeward side. The ratio A/B assumes that $1 \leq A/B \leq 5$. As a result, the minimum value of D is 1, which corresponds to no crown asymmetry, or trunk deflection C. Since the maximum deflection is 90° for a tree growing along the ground, then the maximum deformation ratio is D = 7.

The relation of deformation ratio to the mean annual wind speed, $\bar{u}$, was estimated for Douglas fir or Ponderosa pine trees [31]. From regression analysis of the data,

$$\bar{u} = 0.95\ D + 2.3$$

Photographs can be used to determine the deformation ratio in lieu of direct examination. The deformation ratio and Griggs–Putnam Index give similar ranges of wind speeds.

The use of trees as an indicator of wind speed is subject to a number of practical limitations. Of greatest concern is the tree's exposure to the wind. The deformation should be viewed perpendicularly to the prevailing wind direction so that the full effects of flagging and throwing are taken into consideration. Hence, trees selected as indicators must be well exposed to the prevailing winds. Seldom do trees in a forest extend far enough above the canopy to be in an airstream undisturbed by the other trees. However, isolated trees or those in small, widely spaced groups should be favored as wind speed indicators. In case a comparison between several locations is to be made, trees should be of nearly the same height and species. Near the seashore, flagging may be the result of sea spray (salt) and not totally due to the wind.

4.6 DATA LOGGERS

Data loggers for wind resource measurements are now the norm. Data are stored on data chips, and either chips are retrieved or data loggers send information to a base personal computer. The BASE program monitors the phone lines, answers the call, and determines which site is calling and what is the status of the data card and call-in schedule (card unread, first call of six tries; card partially read, fourth call of six; etc.).

For time sequence data, the amount of data is large. For example, suppose you want to measure wind speeds, wind direction, pressure and temperature (1 Hz sampling rate), average values, and statistics stored every 10 min. That would be around 130 KB of data per month. A 60 min magnetic tape will store 180 KB; however, standard data chips now store 16 MB, which is around 2 years of data. You still need to retrieve the data at least once per month as a check on problems. With phones or satellite connection, data should be retrieved once per week.

The logistic problems have to be taken care of to ensure high data recovery and the quality of the data analyzed. Calibration and replacement of sensors must be part of a routine maintenance program. For example, anemometers should be replaced once per 6 months to 2 years, depending on the number of revolutions and the environment.

A quality assurance program for flagging suspect data is imperative. Data recovery should be around 95%. Sensors problems are due to failure, low/no values due to icing, lightning, and even vandalism. Data loggers and transmission problems can also lead to loss of data. Yearly failure rates are around 25% for sensors and 10% for data loggers. Rates could be higher for sites with very harsh conditions, for example, hail, lightning, dust or sandy areas, or extended periods of high winds.

Generally, there will be two anemometers and one wind vane per level with two or more levels. If one anemometer is down, there are still data from the second anemometer. If both are not operating, there is the possibility of estimating values based on data at another level and past wind shear values. So the 95% data recovery is feasible.

Wind farm developers want the average wind speed (10 min or 1 h) so they can predict energy production. Data analysis programs, which are fairly flexible, are available. As an example, the monthly average, minimums, and maximums for each sensor for the month plus selected graphs and tables are available.

EXAMPLE OF SUMMARY REPORTS AVAILABLE BY MONTH FROM AN ANALYSIS PROGRAM

Comparison of hourly wind speeds (two anemometers at same height or between different heights)
Frequency distributions (calculate wind power/area) (Figure 4.16)
Frequency distribution graph
Diurnal wind speed graph
Average turbulence intensity (upper level, use prevailing wind anemometer)
Wind rose graph
Average wind shear table (between two heights)
Average temperature graph

Data can be placed in spreadsheets for further analysis, as most data loggers allow export. Another benefit is that data analysis is not tied to a proprietary program, which sometimes even the manufacturer has trouble updating, especially if a subcontractor developed the software program.

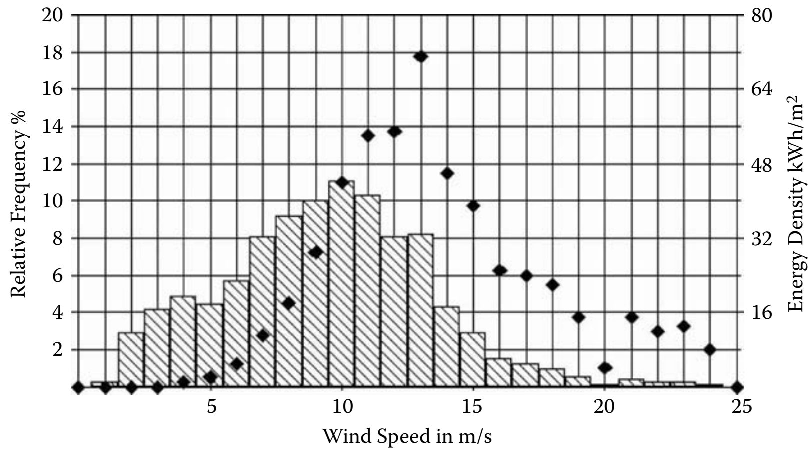


FIGURE 4.16 Example graph, frequency distribution plus energy, from analysis program, 50 m height, White Deer, Texas, April 1998.

4.7 WIND MEASUREMENT FOR SMALL WIND TURBINES

For a very small wind turbine of the order of 100 W to 3 kW, the expense of anemometers, data loggers, and the analysis is more than the price of the wind turbine. In one sense, the wind turbine is the anemometer, as the energy produced is the measurement. So you should depend on historical and regional data to determine feasibility of installing a small wind turbine. Two other indicators of feasibility are the past historical use of farm windmills in the area and a check with owners on performance of other small wind turbine installations in the region. For a wind turbine of 10 to 50 kW, the investment is fairly large, $35,000 to $135,000. Inexpensive digital weather stations are now available for $300 to $600, including the data logger, and the data logger can be plugged into a personal computer for analysis. These instruments are not suitable for collecting long-term data for wind resource assessment or for wind farms. If there are wind maps indicating sufficient winds, and if there are wind farms in the area, then there is no need to collect wind data before installing this size turbine. However, use caution when installing wind turbines inside cities, even in windy areas, as the winds will be less than those indicated on wind maps.

LINKS

MAPS

Canada, www.windatlas.ca/en/index.php.
Database of wind characteristics, www.winddata.com.
NREL, international, www.nrel.gov/wind/international_wind_resources.html.
NREL, United States, www.nrel.gov/wind/resource_assessment.html.
Wind Atlases of the World, www.windatlas.dk/.

OCEAN WINDS

College of Marine Studies, University of Delaware, www.ocean.udel.edu/windpower/. Annual and monthly values.
European, www.windatlas.dk/Europe/oceanmap.html.
Galathea 3, www.gathea3.emu.dk, http://galathea3.emu.dk/satelliteeye/projekter/wind/back_uk.html. Nine-month expedition, education.

Ocean surface winds, http://manati.orbit.nesdis.noaa.gov/doc/oceanwinds1.html.
Riso National Laboratory, Denmark, www.risoe.dk/business_relations/Products_Services/Software/VEA_windmaps.aspx. Offshore wind fields.
Wind Resource Assessment Handbook, www.nrel.gov/docs/legosti/fy97/22223.pdf. Excellent source.

The following sites have information and photos for data loggers, sensors, towers, etc. This list does not imply any endorsement.

www.campbellsci.com
www.ekopower.nl
www.nrgsystems.com
www.secondwind.com
www.wilmers.com
www.rohnproducts.com (towers)

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PROBLEMS

1. If there is a wind map for your nation, what is the wind speed or wind power potential near your location?
2. What is the average wind speed offshore in the ocean south of Cape Cod, Massachusetts? Use ocean wind data or Figure 4.1.
3. For South Dakota (Figure 4.2), make an educated guess of percent area with wind class 5 and above.
4. For the offshore wind map for Europe (Figure 4.7), what regions have the highest wind power potential?
5. What region of Nicaragua has the best wind power potential? Go to NREL, international wind maps.
6. What offshore location for Texas has the highest wind speeds at 10 m height? Use Figure 4.6 or map (reference 22).
7. Go to www.windmap.org. Stateline wind farm is located near the boundary of Oregon and Washington. The Columbia River forms the boundary as it comes out of Washington. Just east of where it crosses the border, the boundary is straight. The wind farm is located there, primarily in Oregon. Go to the Oregon wind map. What is the highest wind class for the project area? On a large map, zoom in once. Can you obtain a larger image by going to the interactive tool on the left navigation bar?
8. You have a tall tower, 13 cm in diameter. How far should the anemometer be placed away from the tower?
9. You are installing anemometers on an existing guyed lattice tower (three sides, each side is 1.5 m wide) for radio communication. How far should the anemometer be placed away from the tower?
10. You are installing anemometers on a stand-alone, lattice tower for radio communication. The tower has three sides, and each side is 4 m wide at 10 m height. Compare the recommended length with a practical length of the boom (mounting pipe or bracket).
11. Why were the propeller anemometers for horizontal wind measurements on the turbulent characterization tower (Figure 4.12) replaced with cup anemometers?
12. Are there any examples of vegetation indicators of wind in your region? What wind speed do they indicate?
13. With a laser system for measuring wind speed, you do not need a tower. What is the reason for not employing a laser system?
14. You want to measure the wind speeds and direction at three levels (10, 25, and 50 m) at six sites (dispersed across your state) for 2 years. Estimate the cost for equipment and people (installation, data collection, and data analysis). You may choose any type of data logger, tower, data retrieval, and analysis.

15. Contrast the amount of storage needed for data between the following: (a) 1 h average and standard deviation (sample rate, 1 Hz) of sixteen channels, 1 year of data, and (b) 1 min average and standard deviation (sample rate, 5 Hz) for sixteen channels, 1 year of data.
16. How many years should data be taken to establish a database to which shorter-term data for wind farms can be referenced? In other words, a database to be used for a wind map for a large region or state.
17. Estimate the cost for installation for a 50 m pole tower, guyed. For travel costs, estimate difficulty for getting to the site.
18. Estimate the cost for installation for a 50 m lattice tower, guyed (example, Rohn 25G or 45G); include travel. For travel costs, estimate difficulty for getting to the site. For installation of the lattice tower, are you going to use a crane or an attached gin pole?
19. Estimate the cost for installation for a 100 m lattice tower, guyed; include travel. For travel costs, estimate difficulty for getting to the site. For this lattice tower you are going to use a crane. Remember, you now have to have lights per FFA regulations, which means additional cost of power for remote locations.
20. Compare wind resource instrumentation (cost, sample rate, data storage, and data analysis) from two different companies.
21. Are there any shareware programs for wind resource analysis?

5 Wind Turbines

Wind turbines are classified according to the interaction of the blades with the wind (aerodynamics), orientation of the rotor axis with respect to the ground, and innovative or unusual types of machines. The aerodynamic interaction of the blades with the wind is by drag or lift, or a combination of the two.

5.1 DRAG DEVICE

In a drag device, the wind pushes against blade or sail (Figure 5.1), and drag devices are inherently limited in efficiency since the speed of the device or blades cannot be greater than the wind speed. For a drag wind turbine, the wind pushes on the blades, forcing the rotor to turn on its axis.

Examples of drag devices are cup anemometers, vanes, and paddles, which are shielded from the wind or change parallel to the wind on half the rotor cycle (Figure 5.2). Clams shells, which open on the downwind side and close on the upwind side, are another example of a drag device. There are no commercial drag wind turbines for producing electricity, since they are inefficient and require a lot of material for blades. However, drag devices are popular with inventors and homebuilders, as they are easy to construct (Figure 5.3). Invariably, the inventors become irate when they are told that the inefficient aerodynamics and large amount of material for blades for drag devices limits their commercialization.

5.2 LIFT DEVICE

Most lift devices use airfoils for blades similar to propellers or airplane wings; however, other concepts have been used. Using lift, the blades can move faster than the wind and are more efficient in terms of aerodynamics and amount of material needed for the blades. The *tip speed ratio* is the speed of the tip of the blade divided by the wind speed. At the point of maximum efficiency for a rotor, the tip speed ratio is around 7 for a lift device and 0.3 for a drag device. For a lift device the ratio of amount of power per material area is around 75, again emphasizing why wind turbines using lift are used to produce electricity. The optimum tip speed ratio also depends on the solidity of the rotor. *Solidity* is the ratio of blade area to rotor swept area.

So one blade rotating very fast can essentially extract as much energy from the wind as many blades rotating slowly (Figure 5.4). A wind turbine with one blade would save on material; however, a counter weight is needed for balance. Most modern wind turbines have two or three blades because of other considerations, and almost all large wind turbines in the commercial market have three blades. The MBB Monopteros and the FLAIR designs were single-bladed wind turbines built in Germany, and a one-bladed (5 kW) unit was built by Riva Calzoni, Italy. The Monopteros had full-span pitch control and the rotor was upwind. MBB and Riva Calzoni collaborated on a 20 kW one-bladed unit, and then Riva Calzoni built a 330 kW unit. Chalk [1] invented a rotor with a large number of blades based on the design of a bicycle wheel. There have been some modern wind turbines with four to six blades.

A Savonius rotor (Figure 5.5) is not strictly a drag device, but it has the same characteristic of large blade area to intercept area. This means more material and problems with the force of the

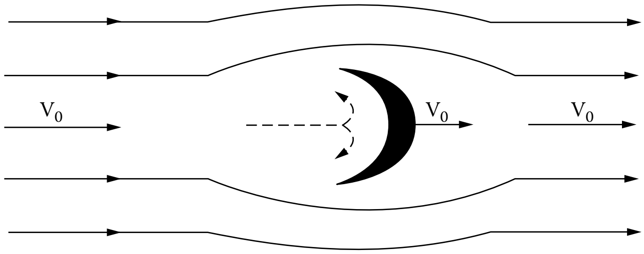


FIGURE 5.1 Drag device. An example is a sailboat moving downwind.

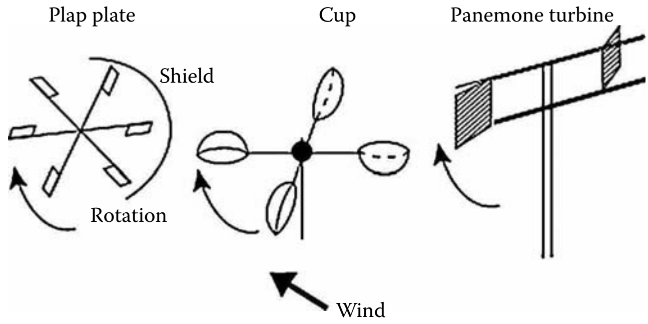


FIGURE 5.2 Diagrams of drag wind turbines.

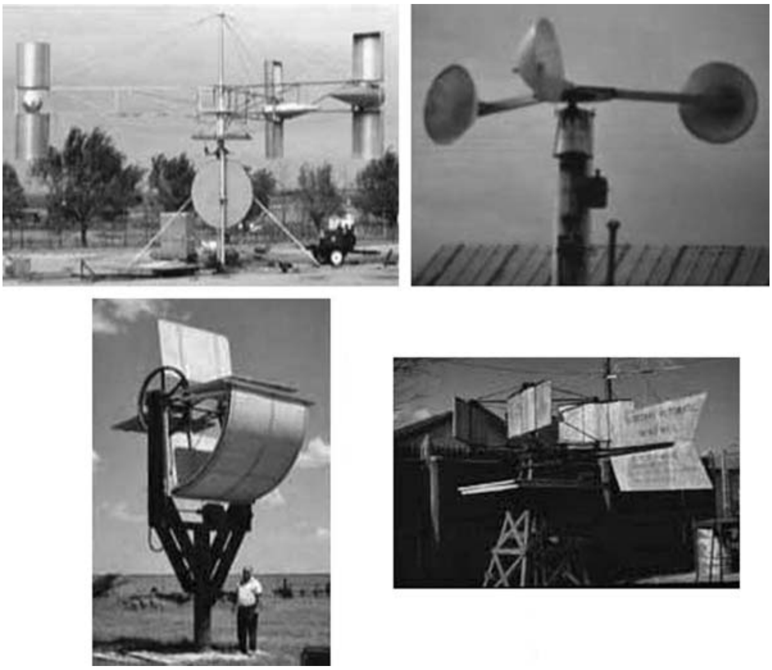


FIGURE 5.3 Examples of drag devices. Top left, clockwise: (1) Around 10 m diameter, with flywheel that was suppose to store energy and reduce variation in power; (2) cups, 1.2 m diameter, inventor predicted power output as 4 kW; (3) panemone device, blades move parallel to wind when moving upwind; (4) shielded plywood sheets, 1.2 by 2.5 m. Notice the large wheel for speed increase to the generator. Inventor predicted output as 4 kW.

FIGURE 5.4 Left: One-blade wind turbine, Monopteros, 475 kW, variable-pitch blade, upwind, near Hamburg, Germany. Right: Six-blade wind turbine, Mehrkam, 40 kW, fixed-pitch blades, downwind, United States.

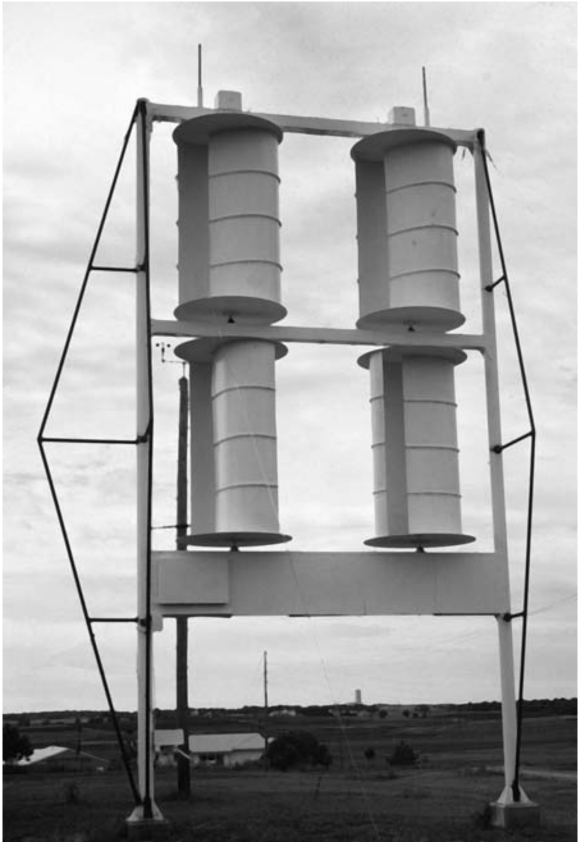


FIGURE 5.5 Savonius wind turbine (5 kW, each rotor is 3 m height by 1.75 m diameter) test at Kansas State University. (Photo by Gary Johnson. With permission.)

wind at high wind speeds, even if the rotor is not turning. An advantage of the Savonius wind turbine is the ease of construction.

5.3 ORIENTATION OF THE ROTOR AXIS

Wind turbines are further classified by the orientation of the axis of the rotor with respect to the ground: horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT; Figures 1.7 and 5.6). The rotors on HAWTs need to be kept perpendicular to the flow of the wind to capture the maximum energy. This rotation of the unit or rotor about the tower axis, *yaw*, is accomplished by a tail on upwind units (small wind turbines, up to 10 kW, although there have been tails on some 50 kW units), by *coning* on downwind units (Figure 5.7), or by a motor (electric or wind [fan tail rotor]) to drive the unit around the yaw axis. *Coning* is where the blades are at an angle from the plane of rotation.

VAWTs have the advantage of accepting the wind from any direction. However, the Darrieus wind turbine is not reliably self-starting, as the blades have to be moving faster than the wind to generate power. So the induction motor/generator or another motor is used for start-up to get the blades moving fast enough that they generate positive power. The giromill (Figure 5.8) may have articulated blades, which can change angle on the rotational cycle, so it can be self-starting. Another advantage of VAWTs is the speed increaser and generator can be at ground level. There are two disadvantages: the rotor is closer to the ground, and there is cyclic variation of power on every revolution of the rotor.

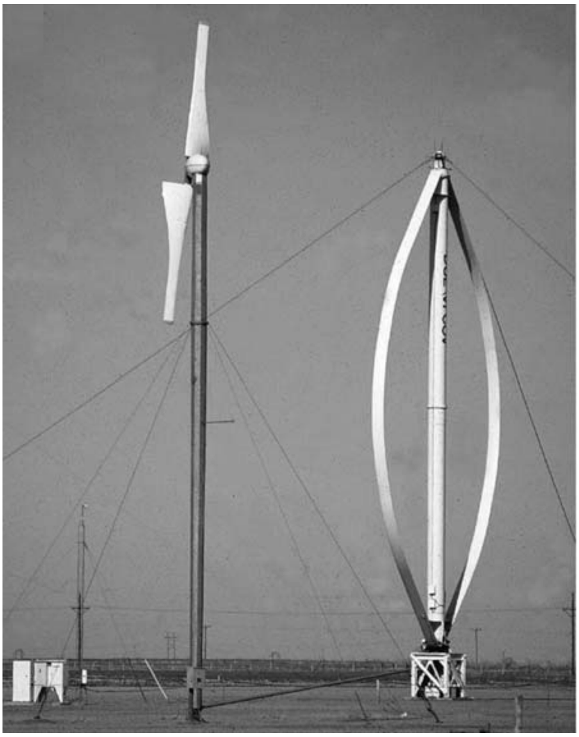


FIGURE 5.6 Horizontal-axis wind turbine, 10 m diameter, 25 kW, and vertical-axis wind turbine, Darrieus, 17 m diameter, 100 kW, USDA-ARS, Bushland, Texas.

FIGURE 5.7 Photo of downwind turbine (Enertech, 6.5 m diameter, 5 kW) and upwind turbine (Hummingbird, 6 m diameter, 5 kW) at AEI Wind Test Center, Canyon, Texas.

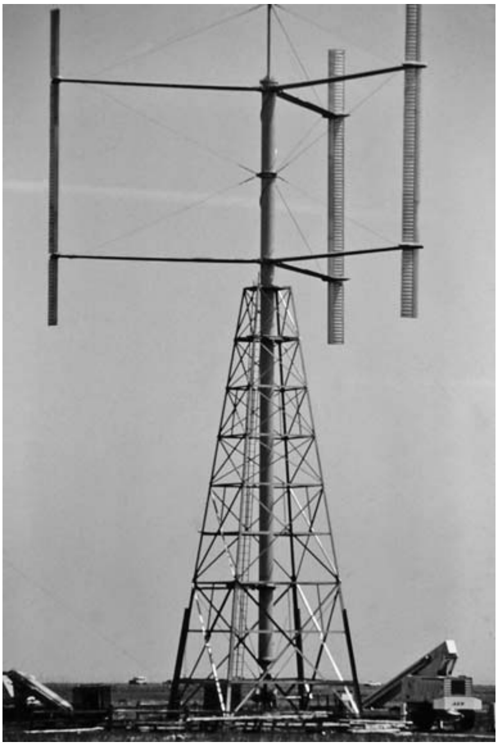


FIGURE 5.8 Giromill, rotor diameter = 18 m, height = 12.8 m, McDonnell Douglas, at National Wind Technology Center, NREL.

5.4 DESCRIPTION OF THE SYSTEM

The total system consists of the wind turbine and load. A typical wind turbine consists of the rotor (blades and hub), speed increaser (gearbox), conversion system, controls, and tower (Figure 5.9). The nacelle is the covering or enclosure. The output of the rotor, rotational kinetic energy, can be converted to electrical, mechanical, or thermal energy. Generally, it is electrical energy, so the conversion system is a generator.

Blade configuration may include a nonuniform platform (blade width and length), twist along the blade, and variable (blades can be rotated) or fixed pitch. The pitch is the angle of the chord at the tip of the blade to the plane of rotation. The *chord* is the line from the nose to the tail of the airfoil.

Components for a large unit mounted on a bedplate are shown in Figure 5.10. Most large wind turbines, which are pitch regulated, have full-span (blade) control, and in this case, electric motors are used to rotate, change the pitch of the blades. All blades must have the same pitch for all operational conditions.

For units connected to the utility grid, 50 or 60 Hz, the generators can be synchronous or induction connected directly to the grid, or a variable-frequency alternator or direct current generator connected indirectly to the grid through an inverter. Most direct current (DC) generators and permanent magnet alternators on small wind turbines do not have a speed increaser. One type of large wind turbine has no gearbox, which means it has very large generators. Some HAWTs use slip rings to transfer power and control signals from the top of the tower to ground level, while others have wire cords that have extra length for absorbing twist. After so much twist, it must be removed by yawing the turbine or by a manual disconnect. For large wind turbines, the transformer or a winch may be located in the nacelle. A total system is called a wind energy conversion system (WECS).

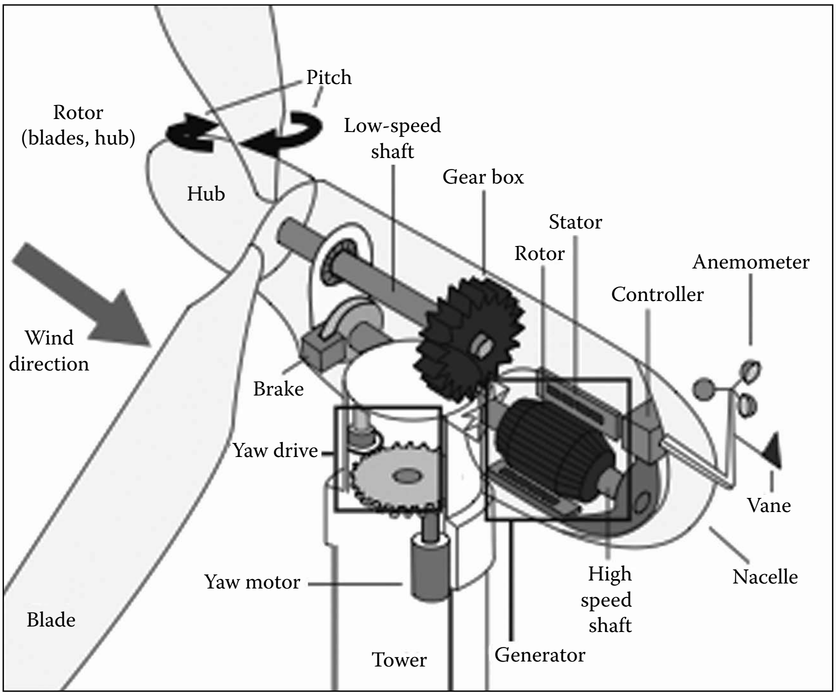


FIGURE 5.9 Schematic of major components for large wind turbine.

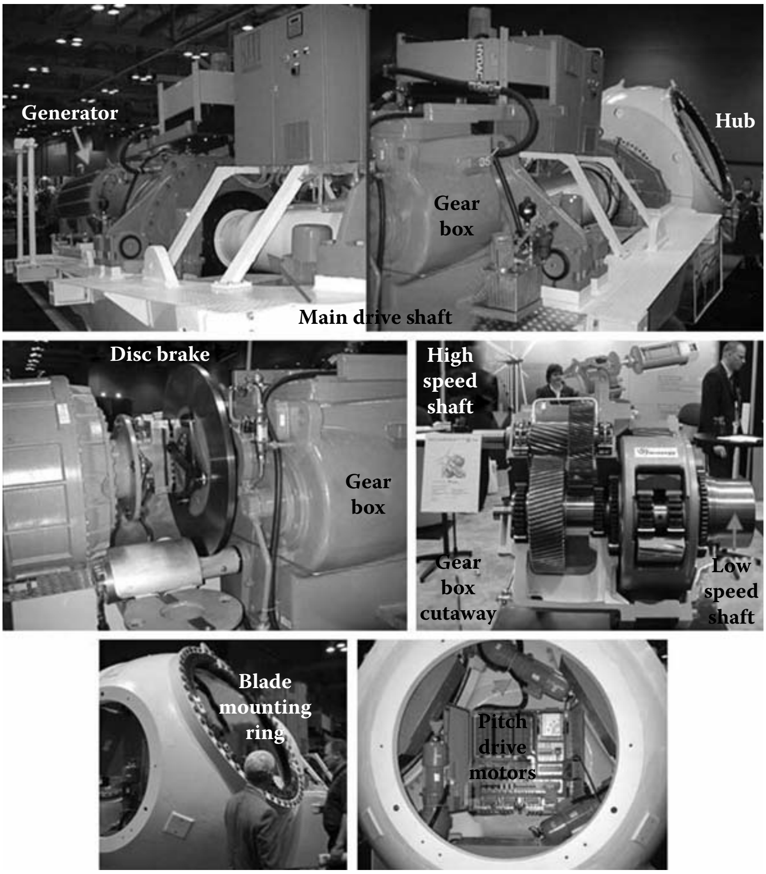


FIGURE 5.10 Photos of components, Suzlon, 64 m diameter, 1,000 kW, induction generator 4/6 pole. Bottom right: Cutaway of gearbox, Winergy.

5.5 AERODYNAMICS

The moving blades of the wind turbine convert part of the power in the wind to rotational power.

$$P = T * \omega \tag{5.1}$$

where T is the torque (N–m) and ω (rad/s) is the angular velocity. The same power can be transferred with a large T and small ω, or a small T and large ω. The torque–ω characteristics of the rotor should be matched to the torque-ω characteristics of the load.

Note: Θ is the angle, where units are degrees or radians. A radian is the angle where the arc of the circle equals the radius, so circumference = 360° = 2π radians, or 1 radian = 57.3°. Angular velocity, $\omega = \Delta\Theta/\Delta t$. Linear velocity of the tip of the blade is given by $v = \omega * r$, where r = radius of the blade. For the same angular velocity, the larger the radius, the faster the tip of the blade is moving. However, for the same tip speed ratio, an increased rotor size will result in slower rpm for the rotor. That is why small-diameter rotors have large revolutions per minute (rpm) and large-diameter rotors have small rpm.

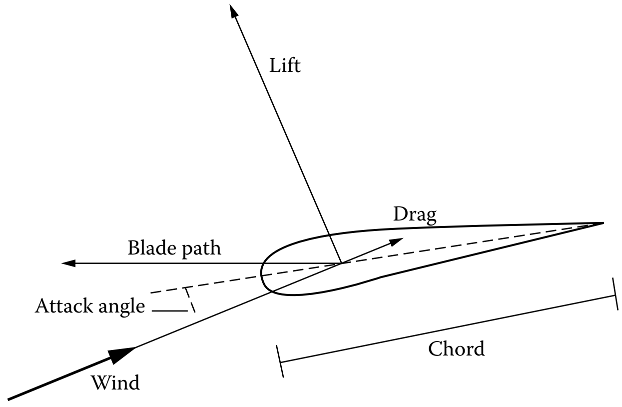


FIGURE 5.11 Forces on blade, lift and drag, due to airflow of relative wind.

The torque-rpm relationship also explains why drag devices are not used to produce electricity. Drag devices have larger torque; however, the small rpm means the amount of power is low. Too many inventors of drag devices equate torque with power.

From conservation of energy and momentum, the maximum theoretical efficiency for the capture of wind power and wind energy is 59%. Highest experimental efficiencies for wind energy conversion systems are around 50%, from wind to electricity.

Lift and drag forces are measured experimentally in a wind tunnel for airfoils as a function of the *attack angle*, the angle of the relative wind to the chord of the airfoil (Figure 5.11). Lift is perpendicular and drag is parallel to the relative wind. The horizontal component of the lift on the blades, which depends on the angle of attack, makes the rotor turn about the axis (Figure 5.12).

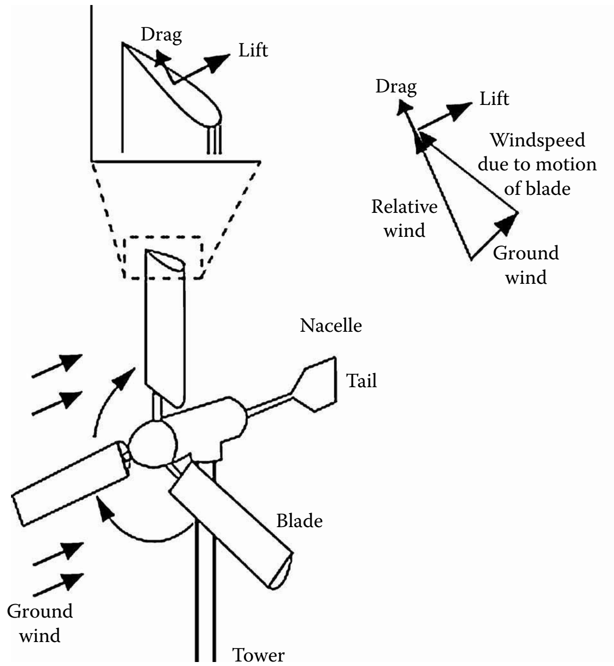


FIGURE 5.12 Wind produces forces on the blade. Relative wind (wind the blade sees) is the vector sum of the blade speed plus the ground wind. Rotor is perpendicular to ground wind.

The relative wind as seen by the blade is composed of two parts: the vector sum of the motion of the blade and the motion of the wind, which is the ground wind far away from the unit.

Maximum power output for any wind speed can be obtained by letting the revolutions per minute of the rotor for fixed-pitch operation increase as the wind speed increases, or by changing the pitch of the blades to obtain the correct attack angle for constant rpm operation. A fixed-pitch blade or constant-rpm rotor only reaches maximum power coefficient at a single wind speed. The *power coefficient* is the power output of the wind turbine divided by the power input (power in wind across the rotor area). Even though rotor efficiency decreases above the point of maximum power coefficient for fixed-pitch blades, power output of the wind turbine can remain high since power available is increasing as the cube of the wind speed.

Computer programs are available for estimating the aerodynamic performance of wind turbines, for both HAWT and VAWT. Inputs include airfoil lift and drag versus attack angle, radius, twist and pitch of the blade, and solidity. Wind speeds or tip speed ratios can be varied to obtain power, forces, moments, etc., for each blade section and for the total blade.

The theoretical values of torque versus rpm were calculated for a VAWT for constant values of wind speed (Figure 5.13). The design point was selected as a rated wind speed of 12.5 m/s, and the other parameters of number of blades, airfoil, etc., were selected for a low-solidity rotor. Each point on the curves is an operating point (power) along lines of constant wind speed. Wind turbines can be operated at constant tip speed ratio (line B, maximum power coefficient), constant rpm (line A), or constant torque (line C). As noted, the rpm is variable along line B, which is the operation of maximum power coefficient. However, at some point there is too much power in the wind, and the wind turbine is controlled to capture less power and, in most cases, in very high winds to shut down. Notice that the constant torque operation soon reaches very high values of rpm, so the wind speed range of operation is limited. For constant torque loads, high torque is necessary for start-up. Therefore, it is very difficult to connect a constant torque load to a wind turbine and obtain much efficiency. The other side of that is high-solidity rotors, like the farm windmill, have high starting torque at low winds and tip speed ratios around 1, which means they are too inefficient for generating electricity.

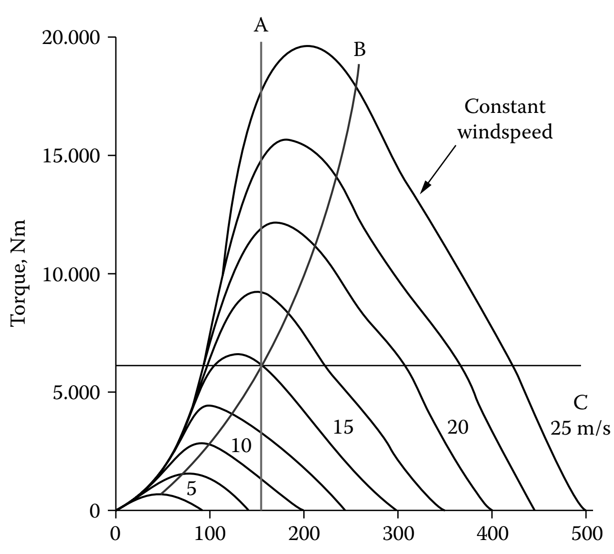


FIGURE 5.13 Theoretical curves of torque versus rpm for different wind speeds.

5.6 CONTROL

Because the power in the wind increases so rapidly, all wind turbines must have a way to dump power (not capture power) at high wind speeds. The methods of control are:

1. Change aerodynamic efficiency
   a. Variable pitch, feather or stall
   b. Operate at constant rpm
   c. Spoilers

2. Change intercept area
   a. Yaw rotor out of wind
   b. Change rotor geometry

3. Brake
   a. Mechanical, hydraulic
   b. Air brake
   c. Electrical (resistance, magnetic)

All of these methods have been used alone or in combination for control in high wind speeds and for loss of load control. There were two vertical-axis wind turbines where they actually changed the rotor geometry; one was a V shape that became flatter in high winds, and the other was a two-bladed giromill where the rotor geometry changed from an H shape to a <-> shape. A blade was designed where the length could be change as the outer part of the blade moved into the rest of the blade.

For control in high winds, most small wind turbines and farm windmills have a tail to yaw the wind turbine out of the wind, to *furl* the rotor. This operation is also called furling. There are some wind turbines where the rotor is rotated about the horizontal axis for the high wind speed control, rather than yawed about the vertical axis. The results are the same; the intercept area has been decreased.

A pitch control system is one method to control rpm, start up (need high torque), and overspeed. Blades are in the *feather* position (chord parallel to the wind) during shutdown, and when the brake is released, the feather position provides starting torque, and then the pitch is changed to the run position (pitch angle around 0°) as rpm increases. The blades are kept at the same pitch over a range of wind speeds, the run position. For high wind speeds and overspeed control, the blades are moved to the feather or *stall* position (blades perpendicular, negative pitch, to wind) to shut the unit down. The pitch can be changed to maintain a constant rpm for synchronous generators. For an induction generator, variable-speed generator, or alternator that operates over a range of rpm in the run position, over this range the tip speed ratio is constant, and the unit operates at higher efficiency.

For fixed-pitch blades, there are two possible operations, constant tip speed ratio (variable rpm), which is the maximum efficiency, and constant rpm. The blade has to have enough twist to produce torque for start-up, or the induction motor/generator starts the rotor at the cut-in wind speed. The constant rpm operation with induction generators means that the maximum efficiency is reached only at the design wind speed. Above rated power, the power output is controlled by the reduced aerodynamic efficiency, called stall control.

Part of the control system can be electronic, generally a microprocessor or microcomputer (Figure 5.14). In constant-rpm operation, such as an induction generator, the unit is connected to the utility line after the rpm is above the synchronous rpm of the generator. In reality, an induction generator is not strictly constant rpm, as there is a small change in rpm (slip) with power output. Doubly fed induction generators have a large rpm range, around 50%, and are

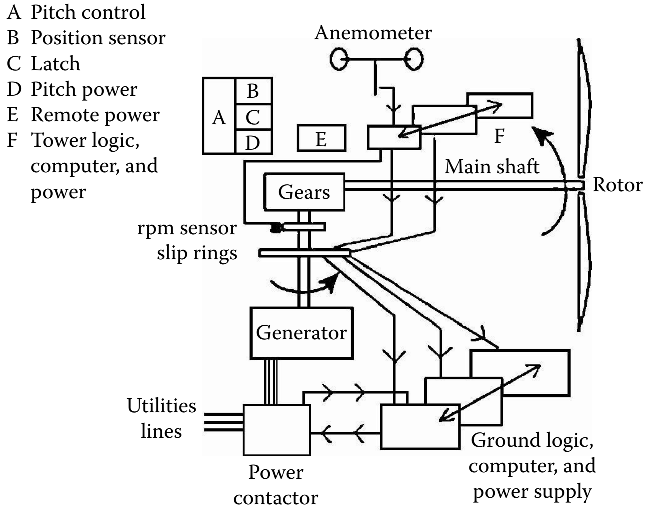


FIGURE 5.14 Block diagram for system with pitch control.

used because of the increased aerodynamic efficiency with blades in the run position for large wind turbines.

5.6.1 Normal Operation

A *power curve*, power versus wind speed, describes the normal operation of a wind turbine (Figure 5.15). Notice that difference in power output at low wind speed is due to difference in the electric efficiency of the generators. At the cut-in wind speed the unit starts to rotate or produce power, then reaches rated power (size of generator) at the rated wind speed and continues to produce

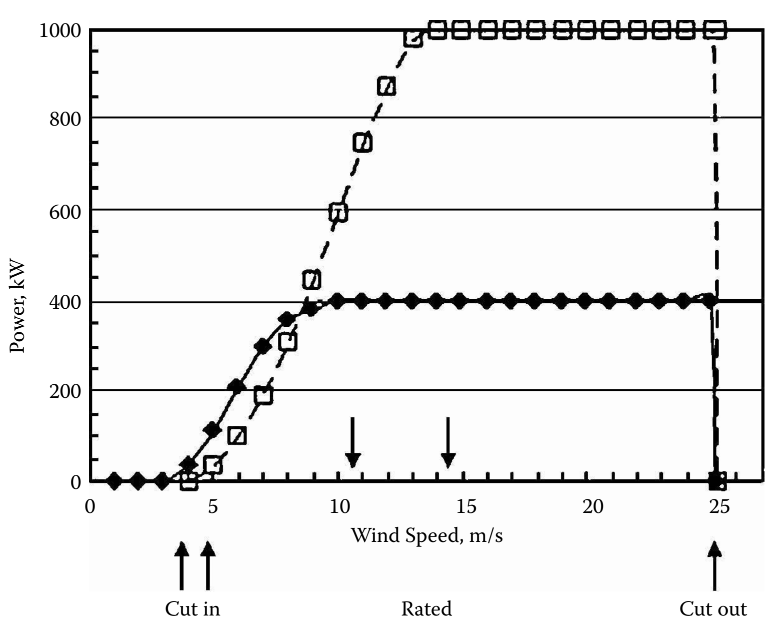


FIGURE 5.15 Power curves for a rotor with two different generator sizes.

that power until the unit shuts down at the cut-out wind speed. Some wind turbines with fixed-pitch blades and induction generators continue to operate at any wind speed. Above the rated wind speed the power output is constant or even decreases somewhat because of the decreasing aerodynamic efficiency with increasing wind speed.

The most important parameter in determining energy production is the rotor area, as energy production will increase as the square of the radius. A larger generator does not necessarily mean more energy production because the efficiency at low wind speeds will change with generator size. Some large wind turbines have two generators, one a smaller generator for lower wind speeds to increase overall efficiency. Although a larger generator is probably desirable in the best wind regimes, the optimum size for a given rotor radius for a given wind regime is still undetermined. Manufacturers are now offering different size generators (rated power) for the same rotor diameter, or the same size generator for different rotor diameters. Jay Carter, Sr. designed and built a wind turbine for both medium and good wind regimes, which is done by only changing the size of the induction generator (30 kW, six poles; 50 kW, four poles).

5.6.2 Faults

Wind turbines are shut down for faults such as loss of load, vibration, loss of phase, current or voltage anomalies, etc. Each of these safety features could save the unit, but the most important feature is a method of controlling the rotor when there is a loss of load (fault on the utility grid) during high winds (overspeed control). If the unit is not shut down within a few seconds, it will reach such high power levels that it cannot be shut down and will self-destruct. The large torque excursions and also the emergency application of mechanical brakes may damage the gearbox. Faults result in power spikes, large current, and voltage drops.

5.7 ENERGY PRODUCTION

Annual energy production is the most important factor for wind turbines. Of course, that is combined with economics to determine feasibility for installation of wind turbines and wind farms. Approximate annual energy can be estimated by the following methods:

1. Generator size (rated power)
2. Rotor area and wind map
3. Manufacturer's curve of energy versus annual wind speed

5.7.1 Generator Size

This method gives a rough approximation because wind turbines with the same size rotors can have different size generators:

$$\mathrm{AKWH} = \mathrm{CF} * \mathrm{GS} * 8{,}760 \tag{5.2}$$

where AKWH = annual energy production, kWh/year; CF = capacity factor; and 8,760 = number of hours in a year.

The effect of the wind regime and the rated power for the rated wind speed can be estimated by changing the capacity factor. The *capacity factor* is the average power divided by the rated power (generator size). The capacity factor is estimated from energy production over a selected time period, and in general, capacity factors are quoted on an annual basis, although some are calculated for a quarter of a year. Capacity factors can also be calculated for wind farms, and they should be close to the same values as capacity factors calculated for individual wind turbines. However, if the wind farm is composed of different wind turbines, it should be noted. For example, the Green Mountain Wind Farm at the Brazos near Fluvana, Texas, has 160 1 MW wind turbines; however, 100 have rotor diameters of 61.4 m and 60 have rotor diameters of 56 m. Therefore, the capacity factor will be larger for the units with the larger rotor. Notice that capacity factor is like an average efficiency. In general, the generator size method gives reasonable estimates if the rated power of the wind turbine is around 10–13 m/s. If the rated power is above that range, or for wind regimes below class 3, then the capacity factor should be reduced accordingly.

EXAMPLE 5.1

Wind turbine has the following specifications:
Rated power = 25 kW at 10 m/s
Rotor diameter = 10 m
Estimated capacity factor = 0.25

$$\text{AKWH} = 0.25 * 25 \text{ kW} * 8{,}760 \text{ h/year} = 55{,}000 \text{ kWh/year}$$

For a poor wind regime, AKWH would be closer to 30,000 kWh/year.

A capacity factor of 0.25 would suffice for a generator rated at a wind speed of 10 m/s and the wind turbine is in a medium wind regime. Wind farms are located in good to excellent wind regimes, and capacity factors should be 32–40%. There have been reported capacity factors up to 50% for a wind farm located in the Isthmus of Mexico.

5.7.2 Rotor Area and Wind Map

The amount of energy produced by a wind turbine primarily depends on the rotor area, also referred to as cross-sectional area, swept area, or intercept area. The swept area for different types of wind turbines can be calculated from the dimensions of the rotor (see Figure 1.7).

HAWT area = πr^2, where r = radius.
VAWT, where H = height and D = diameter of rotor:
  Giromill area = H * D
  Savonius area = H * D
  Darrieus area = 0.65 H * D

The annual average power/area can be obtained from a wind map, and then the energy produced by the rotor can be calculated from

$$\text{AKWH} = \text{CF} * \text{Ar} * \text{WM} * 8.76 \tag{5.3}$$

where Ar is the area of the rotor, m^2; WM = power/area from a wind map, W/m^2; and 8.76 gives the answer in kWh/year, the conversion W to kW.

Again, the capacity factor reflects the annual average efficiency of the wind turbine, around 0.20 to 0.35.

EXAMPLE 5.2

Use the wind turbine in Example 5.1, and from wind map:

$$\text{WM} = 200 \text{ W/m}^2$$

$$\text{Area} = \pi r^2 = 3.14 * 25 \text{ m}^2 = 78.5 \text{ m}^2$$

$$\text{AKWH} = 0.25 * 78.5 \text{ m}^2 * 200 \text{ W/m}^2 * 8.76 \text{ kWh/year} = 34{,}000 \text{ kWh/year}$$

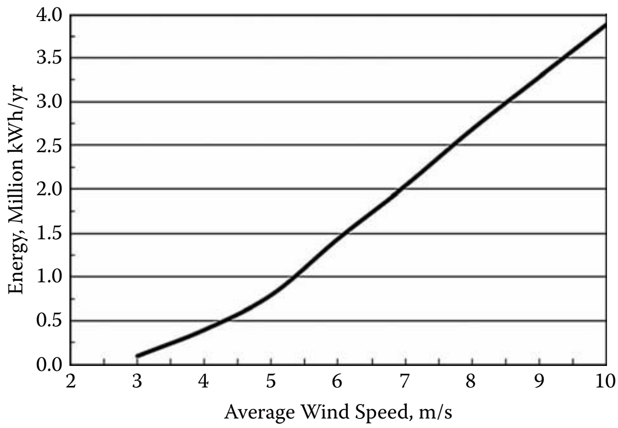


FIGURE 5.16 Estimated annual energy production based on annual average wind speed.

Notice the large difference in the answers for the two examples, which could be related to two factors: generator size is too large for rotor size, or the wind regime is low, that is, the wind map value is low. With this estimate of energy production, the wind map value should be selected or estimated for the hub height of the wind turbine, especially when estimating energy production for large wind turbines.

5.7.3 Manufacturer's Curve

Manufacturers assume a Rayleigh distribution for the wind speed at 1 m/s intervals and then calculate the annual energy production at standard density using the power curve for their wind turbine at a selected hub height. An example graph of the annual energy production versus average wind speed is given for a 1 MW wind turbine (Figure 5.16). Notice the average wind speed at your location should be somewhat close to the hub height. At 10 m height, the average wind speed was around 6 m/s for the High Plains of Texas (1,100 m elevation), and at 50 m height, the wind speed was 8.2 m/s. So, from the graph, a wind speed of 8.2 m/s means the turbine should produce around 2,800,000 kWh/year.

5.8 CALCULATED ANNUAL ENERGY

If the wind speed histogram or wind speed distribution is known from experimental data, then a good estimation of energy production can be calculated from the histogram and the power curve for the wind turbine. Manufacturers will supply power curves for their wind turbines, and most of the power curves are available online. For each interval (a bin width of 1 m/s is adequate), the number of hours at that wind speed is multiplied by the corresponding power to find the energy. These values are added together to find the energy production for the total number of hours (Table 5.1). This is the method that wind farm developers use to estimate the energy production. Wind speed histograms should reflect annual values, not the value for part of a year or even 1 year, which could be above or below the annual values. A 1-year histogram could be adjusted to annual values if long-term regional data are available. Two to 3 years of wind speed data, averaged to an annual histogram, will suffice.

Wind speed histograms and power curves have to be corrected to the same height and adjusted for air density due to location of the data compiled for the power curve. So when the density correction is made from 1.2 to 1.1 kg/m^3 for the Texas Panhandle and an availability of 98% is assumed, that reduces 3,061,000 kWh/year to 2,750,000 kWh/year.

TABLE 5.1
Calculated Annual Energy Production for 1 MW Wind Turbine in the Panhandle of Texas

Wind Speed m/s	Power kW	Bin Hours h	Energy kWh
1	0	119	0
2	0	378	0
3	0	594	0
4	0	760	171
5	34	868	29,538
6	103	914	94,060
7	193	904	174,281
8	308	847	260,760
9	446	756	337,167
10	595	647	384,658
11	748	531	396,855
12	874	419	366,502
13	976	319	311,379
14	1,000	234	233,943
15	1,000	166	165,690
16	1,000	113	113,369
17	1,000	75	74,983
18	1,000	48	47,964
19	1,000	30	29,684
≥20	1,000	40	39,540
25	0		0
		8,760	3,060,545

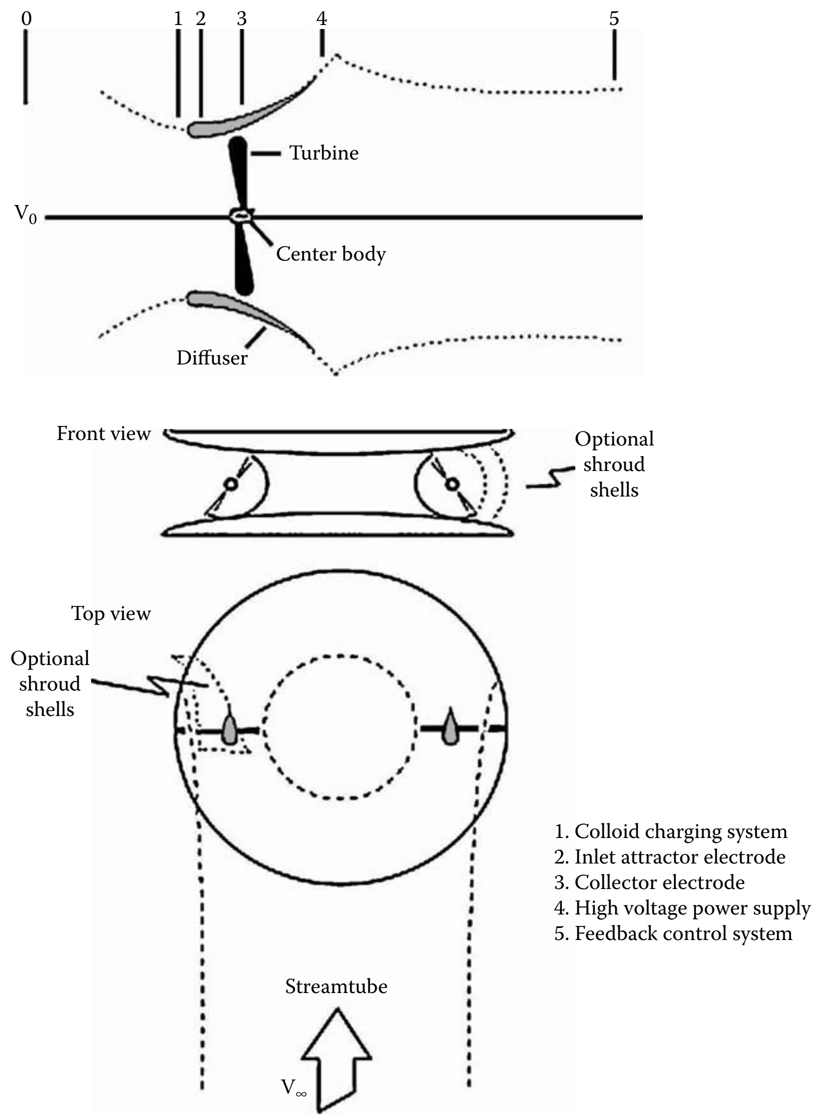
Availability is the time that the wind turbine is in operational mode, and it does not depend on whether the wind is blowing. Availability is related to reliability of the wind turbine, which is affected by both the quality of the turbine and operation and maintenance. Experimental values of availability of wind turbines in the field were poor for first production models; however, availabilities of 98% are now reported for later units, which have a good program of ongoing maintenance. Remember, a wind turbine does not have problems when the wind is not blowing. Therefore, preventive maintenance is imperative to maintain energy production.

Calculation of estimated energy production is simple using spreadsheets or by writing a program to do the calculation from a histogram and a power curve. The data would be in tabular form and can be graphed using spreadsheets or generic plot programs. Spreadsheets for calculation of energy production are available at the accompanying website for Renewable Energy and the Environment.

5.9 INNOVATIVE WIND SYSTEMS

Innovative or unusual wind systems (Figure 5.17) have to be evaluated in the same way as other wind turbines. The important categories are system performance, structural requirements, and quantity and characteristics of materials. Innovative ideas include the tornado type, tethered units to reach the high winds of the jet stream, tall tower to use rising air, tall tower and humid air, torsion flutter, electrofluid, diffuser augmented, the Magnus effect, and others. Many of these have been reported in *Popular Science* [2–4]. Most all innovative concepts remain at the feasibility or lab experiment stage. Not all innovative systems are recent inventions; for example, sail wings, wings on railroad cars, and the Magnus effect (Madaras concept was rotating cylinders on railroad cars) have been around for a long time.

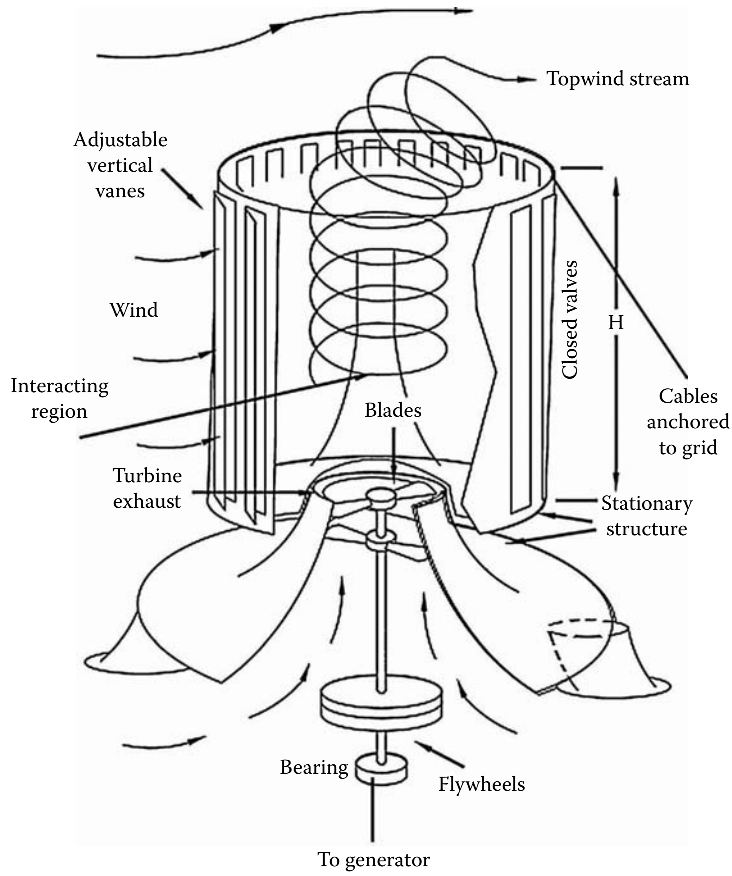
The West German government funded the construction of a 200 m tall tower in Spain [5]. A 240 m diameter greenhouse at the bottom provided the hot air to drive the air turbine, rated at 75 kW, which was located inside the tower. A private entrepreneur in California constructed a Magnus type wind turbine [6], 17 m in diameter, with purported rated capacity of 110 kW (Figure 5.18). The unit was later moved to the wind test site of Southern California Edison, which was located in San Gorgonio Pass. A small wind turbine has been built with spirals on the cylinders (Figure 5.19). A built-in motor spins the cylinders, which in the wind makes the rotor rotate due to the Magnus force on the cylinders. The unit is 11.5 m diameter and rated power is 12 kW.



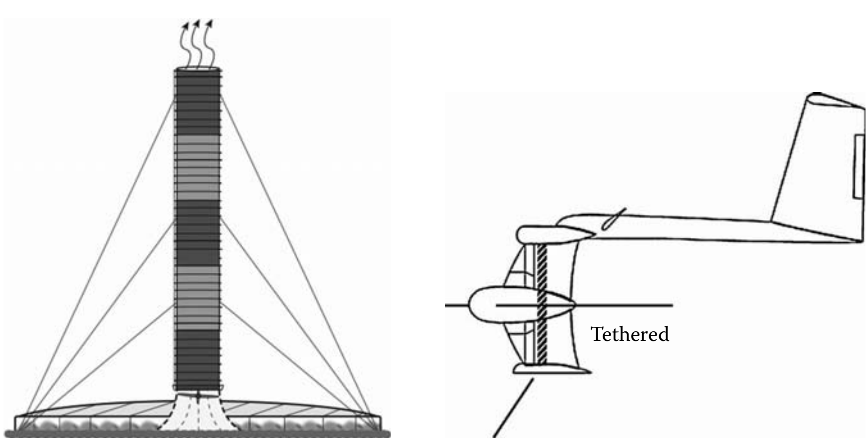
Torodial acceleration rotor platform

(a)

FIGURE 5.17 Examples of innovative wind turbines.



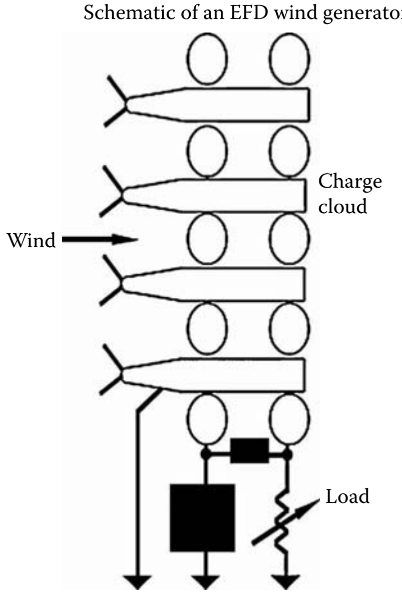
(b)



Tower with greenhouse at bottom

(c)

FIGURE 5.17 *(Continued)*



(d)

FIGURE 5.17 *(Continued)*

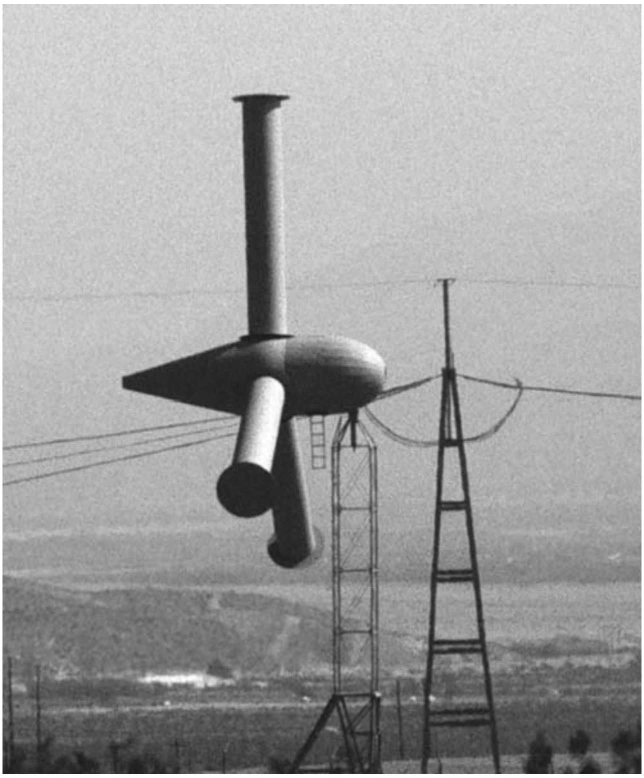


FIGURE 5.18 Magnus effect wind turbine at Southern California Edison test site.

FIGURE 5.19 Spiral Magnus wind turbine (11.5 m diameter, 12 kW). Model shows spiral (helix fins) on cylinders. (Photos: Left, MECARO, Japan; right, Charlie Dou. With permission.)

The most different concept is the electrofluid unit, which has no moving mechanical parts. The wind carries the moving charge to generate electricity for a load. A somewhat similar device consists of a balloon covered with a thin conductive layer. Static electricity generated by wind friction would be conducted through a cable to the surface [7]. Oscillations of piezoelectric polymers driven by the wind would also make a unique type of wind turbine. One idea was to place such devices along highways to use the turbulent wind generated by passing trucks and cars.

The Solar Energy Research Institute (SERI), later renamed NREL, was the lead agency in innovative concepts (Table 5.2), and reports on the projects funded by SERI are available in conference

TABLE 5.2
Solar Energy Research Institute, Innovative Wind Program

Project	Contract
Innovative wind turbines (VAWT)	West Virginia University
Tornado type wind energy system	Grumman Aerospace
Diffuser-augmented wind turbine	Grumman Aerospace
Wind/electric power–charged aerosol	Marks Polarized
Electrofluid dynamic wind generator	University of Dayton
Energy from humid air	South Dakota School, M&T
Madras rotor power plant, phase I	University of Dayton
Vortex augmenters	Polytechnic Institute, New York
Yawing wind turbine, blade cyclic pitch	Washington University, St. Louis
Oscillating vane	United Technologies
Dynamic inducer	AeroViroment

proceedings [8–10]. The U.S. Department of Energy (DOE) discontinued funding for this program after a few years.

Winglets or tips (dynamic inducer) on the ends of the blades [11], which reduce the drag due to the tip vortex, were tested by Aerovironment and the University of Delft, the Netherlands. The results were inconclusive due to the variability of the wind speeds. In some cases, energy production could be improved, but the cost of the winglets could be offset by increasing the radius of the blades. Where the wind speed variability is not a major factor, winglets can reduce drag and increase lift, like on some airplanes.

A simple sail wing consisting of a pipe spar, and a trailing cable was designed and built by Sweeney [12]. The advantages are light weight and ease of repair. The patent rights were purchased by Grumman, who built a couple of prototypes but never put the unit into production. WECS Tech installed a number of sail wing units on a wind farm in Texas and others on wind farms in California. The operating history was very poor, as high winds destroyed the sails and most units were destroyed within a short time. The same sail wing design was used on a prototype project by the Instituto de Investigación Electricas in Mexico.

The idea of a confined vortex, a tornado, was invented by T. J. Yen. DOE funded theoretical and model studies of this concept. Another concept was to use unconfined vortices produced along the edges of a delta wing and then place two rotors at those locations. Again, DOE funded model studies. Existing structures could be modified or new buildings would incorporate features to increase the wind speed, which then would be captured by a WECS. Since wind speed increases with height, if rotors could be placed in low-altitude jets by use of tethered balloons or airfoils, a large amount of energy could be obtained from small-size rotors.

Other ideas are lift translators with horizontal or vertical axis, which is similar to the idea of railroad cars with wings, except cables hold the sails or airfoils and the wind turbine resembles a moving clothes line. Both concepts need wind from a predominant direction, as large units cannot be oriented. A number of foundations were constructed, and a few lift translators were built during the early 1980s in California; however, they were never really operational.

An idea for reducing weight was to use cables for tension, as proven in suspension bridges, to support long cage-containing blades. An oscillating vane or airfoil could extract energy from the wind, but the intercept area is fairly small for the amount of material.

There have numerous designs and a number of wind turbines have been built with different combinations and unusual blade shapes. A few examples are Darrieus or giromill wind turbines with Savonius rotors on the inner shaft for start-up torque, wind turbines with double rotors (some rotors close together, some farther apart), multiple rotors on a single shaft (either vertical or horizontal), double-bladed giromills, and blades with nontraditional shapes (curved like a helix) on horizontal or vertical axes. A wind system with three stacked Darrieus units (4 kW each) was built at a newspaper office in Florida. Other units have enclosures to increase the wind speed or are designed to be incorporated into tall buildings.

The Noah wind turbine had two rotors (Figure 5.20), which were close to one another, each with five blades, and the wind rotors were counterrotating, with one connected to the stator and the other to the rotor of a generator, so a gearbox was not needed. The wind turbine had a unique overspeed control, which consisted of a counterweight that tilted the rotor assembly to the horizontal position, which then had to be reset manually. Another system has multiple rotors on a coaxial shaft [13], where the line of the rotors is kept at an angle to the wind to improve influx of the wind to the downwind rotors. Units with two to seven rotors have been built (two and three blades) with rated power from 2 kW (diameter, 2.4 m; two rotors, 3.7 m apart) to 4 kW. One unit even has 13 two-bladed rotors, each with a diameter of 0.5 m, and rated at 400 W.

Lagerway built a unit with two conventional wind turbines (25 kW each) mounted on a horizontal cross-beam at the top of the tower. Then another was built that resembled a tree, as it had two more levels, for a total of six wind turbines.

FIGURE 5.20 Wind turbine with double rotor.

5.10 APPLICATIONS

The kinetic energy of the wind can be transformed into mechanical, electrical, and thermal energy. Historically, the transformation was mechanical where the end use was grinding grain, powering ships, and pumping water [14, 15].

The applications can be divided into wind-assist and stand-alone systems. In the wind-assist system the wind turbine works in parallel with another source of energy to provide power. The advantages of such systems are power is available on demand, generally there is no storage, and there is better matching between the power sources and the load. Stand-alone systems will provide power only when the wind is blowing and the power output is variable, unless a storage system is connected to the wind turbine. Wind-diesel is an application where the wind turbine is primarily a fuel saver, which is a wind-assist system. Another application, which is now emerging, is a hybrid system for villages and telecommunications.

5.10.1 Electrical Energy

Most wind turbines are designed to provide electrical energy. In a wind-assist system, wind turbines are connected to the utility line either directly through induction generators and synchronous generators or indirectly where variable-frequency alternators and DC generators are connected through inverters. The utility line and generating capacity of the power station act as the storage system. For stand-alone systems, battery storage is the most common option.

The U.S. Department of Agriculture (USDA), Bushland, Texas, and the Alternative Energy Institute (AEI), West Texas A&M University, are evaluating stand-alone, electric-to-electric systems for pumping water [16]. The wind turbine generator is connected directly to an induction motor or a submersible pump, which is run at variable rpm. The advantages of such a system are higher efficiency and higher volumes of water, enough for village water supply and low-volume irrigation. Such systems are now commercially available.

5.10.2 Mechanical Energy

The major use for windmills has been the pumping of water. The farm windmill is well designed to pump small volumes of water at low wind speeds. Since the farm windmill has a large number of blades (vanes), it will start under a load because it has a large torque. However, the large number of blades means it takes a lot of material, and the unit is inefficient at high wind speeds. Power ratings are around 0.5 kW for a 5 m diameter rotor.

The Brace Research Institute combined a modern three-bladed wind turbine, a transmission from a truck, and a conventional centrifugal pump on a prototype project to pump irrigation water on the Island of Barbados [17, 18]. The rotor was not self-starting, and the blades of fiberglass were expensive. A person had to manually shift the transmission to match the load of the pump to the output of the wind turbine at different wind speeds.

In 1976, AEI and USDA studied the feasibility of using wind turbines for pumping irrigation water with positive displacement pumps and airlift pumps. There are problems in matching the power output of the wind turbine with the power needed by the irrigation pump. Calculated maximum efficiencies were very low, on the order of 10%, for both types of pumps.

The airlift pump has the advantages of no moving parts in the well, and the wind turbine does not have to be located at the well. Airlift pumps were in use at the turn of the century for pumping water from mines, but were replaced by other types. Two companies in the United States have manufactured a wind-powered airlift pump to compete with the farm windmill; however, only Airlift Technologies has units for sale today. For maximum efficiency, the submergence, depth of pump below the water level, should be equal to the lift. Wells with little water at large depths present a problem for airlift pumps. Also, there is the problem of load matching between the wind turbine and the air compressor, a constant torque device, and the inherent inefficiencies.

A wind turbine can be connected mechanically to another power source, a wind-assist system for pumping water. The other power source could be an electrical motor or an internal combustion engine. Both systems have been tested.

5.10.3 Thermal Energy

Thermal energy can be obtained directly by churning water or some fluid with viscosity. The load matching between the wind turbine and the churn is very good. A prototype system for providing heat to a dairy was tested by a research group at Cornell University [19–21]. Conversion of electrical energy to thermal energy by resistance heating has been tested a few times [22]. At one time, a company marketed such a wind system.

5.10.4 Wind Hybrid Systems

A large market exists for wind-assist to diesel-generated electricity for isolated communities, businesses, farms, and ranches [23]. There are around 2 billion people without electricity, and hybrid systems consisting of wind, photovoltaic, hydro or diesel, battery storage, and an inverter are now part of the planning process to provide alternating current (AC) electricity for villages with an energy use of 20 to 200 kWh/day [24, 25]. Hybrid systems have also been installed in very remote locations, such as remote military locations and telecommunication systems. For telecommunications the emphasis is on continuous power, so redundancy is important to achieve the high reliability.

NREL has a site for hybrid systems for village power, Renewables for Sustainable Village Power (RSVP). The RSVP Village Power Project Database contained around 150 projects (wind is part of 50 projects) from over 30 countries. Project information included basic, technological, economic, financial, host country, lessons learned, pictures and graphics, and contact information. The database is now archived and is not available online, and there have been a large number of projects installed since 2004. For example, China now has over 700 village installations (capacity, 16 MW) powered by mini hydro, PV, or wind/PV hybrid systems [26]. China has also installed a few wind/PV/diesel systems [27].

5.10.5 Summary

Applications will be considered in more detail after more is learned about design and construction of wind turbines. Wind power for generating electricity is the most used application. The problem of load matching in pumping water for irrigation has to be part of the design consideration.

5.11 STORAGE

Of course if a way could be found to cheaply store energy, then there would not be a need to construct new electrical power plants for some time. In addition, the economics of renewable energy, including wind systems, would improve and wind farms could provide firm power. Batteries are used with stand-alone systems and hybrid systems, and even provide load leveling for short-term fluctuations. XCEL Energy will begin a demonstration project consisting of 1 MW of battery storage to store energy from wind farms [28]. There will be 20 battery modules (50 kW each) that will store around 72 MWh. Other storage ideas have been to change the electrical energy to chemical energy, such as the production of hydrogen or fertilizer. Village power systems that include wind turbines and the production of hydrogen are now on the market. Another idea would be to store the energy in flywheels, which would be a good load match between the wind turbine and the load. Compressed air, pumped water storage, and superconducting magnets have all been considered, and some prototype systems with wind turbine input have even been constructed. In general, the efficiency of storage systems is around 60 to 70%.

LINKS

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Global Village Energy Partnership International, www.gvepinternational.org.
Renewables for Sustainable Village Power, www.nrel.gov/villagepower.
WindCAD performance models, Bergey Windpower. www.bergey.com/Technical.htm. Spreadsheet.

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PROBLEMS

1. Estimate the difference in the amount of material in the rotor for a giromill and a Savonius rotor with H = 10 m, D = 10 m.
2. A wind turbine is rated at 300 kW. Estimate annual energy production using the generator size method.
3. For a 1.5 MW wind turbine, estimate the annual energy production for a good site using the generator size method.
4. For a conventional HAWT, radius of 50 m, estimate annual energy output for a good wind region (use class 4, 5, or 6) from U.S. wind power map.
5. For a Darrieus unit, 34 m diameter by 42.5 m height, estimate annual energy output for two different regions from European wind map.
6. For a giromill, H = 10 m, D = 12 m, estimate annual energy output for two different regions from U.S. wind power map.
7. From manufacturer's curve (use Figure 5.16) for annual energy, estimate the annual energy production for a region where the average wind speed is 9 m/s.

8. Calculate the power from Figure 5.13 at 20 m/s for the VAWT for the following conditions. Remember, rpm has to be converted to rad/s.
   a. Wind turbine is operating at 160 rpm (line A).
   b. Wind turbine is operating at maximum power coefficient (line B).
   c. Wind turbine is operating at constant torque (line C) of 6,000 Nm.
9. From Figure 5.13, the design wind speed is 12.5 m/s (where lines A, B, and C cross). What is the torque? What is the rpm? What is the power?
10. Calculate the wind speed frequency distribution for the data in Table 5.1.
11. Calculate the annual energy production for a mean wind speed of 8.2 m/s, average air density = 1.1 kg/m^3. Use the Rayleigh distribution to obtain a wind speed histogram. Use the power curve from Table 5.1.
12. Refer to Figure 5.15. What is the cut-in and rated wind speed for the 1,000 kW unit?
13. Refer to Figure 5.15. What is the cut-in and rated wind speed for the 400 kW unit?
14. For large wind turbines, what is the primary method of control for power output?
15. For large wind turbines, what is the primary method of control for shutdown for high winds?
16. For loss of load, fault on the utility line, how much time is available for shutdown of the wind turbine?
17. Are there any wind hybrid systems for village power in your country? If yes, select one project; briefly describe location, project power rating, main components (wind, PV, diesel, batteries), and approximate output, kWh/day.
18. Under innovative wind turbines, what would be two or three major problems with a tethered wind turbine?

6 Design of Wind Turbines

6.1 INTRODUCTION

The design of wind turbines has developed from a background of work on propellers, airplanes, and helicopters. Computer codes developed for analyzing aerodynamics, forces, and vibration have been modified for wind turbines. Theory and experimental procedures are well developed, and no scientific breakthroughs are needed for wind turbines. However, there are problems of predicting loads from unsteady aerodynamics. These loads lead to fatigue and less life than predicted by the design codes. Part of the time, wind turbine blades operate in regions of large attack angles, which is quite different than for airplane wings.

Someone made the comment that you could use brooms for blades and the rotor would turn. Of course, the efficiency would be low, control would be a problem, and the strength would not be adequate. A large number of airfoils were developed for wings on planes and sailplanes, which were later used for wind turbine blades.

In the beginning the aerospace industry thought that the design of wind turbines and their construction would simply be the transfer of technical knowledge from airplanes and helicopters. However, this was an erroneous conclusion. One big difference is that airplanes and helicopters move in response to large loads from wind gusts, whereas a wind turbine is tied to the ground. Because power in the wind increases as the cube of the wind speed, the blades must have the strength and flexibility to withstand the high variable loads, and then there must be a control mechanism for shedding power in high winds.

There has been a lot of research and development, primarily by national labs and universities, and later by the manufacturers of wind turbines, which has resulted in today's wind industry. The design of wind turbines requires a broad cross section of knowledge: aerodynamics, mechanical engineering, electrical engineering, electronics, materials and industrial engineering, civil engineering, and meteorology. The design process is iterative from first concept to the final design. Remember, it is easier to fix problems at the design stage than to have the cost of retrofits in the field.

6.2 AERODYNAMICS

The analysis of aerodynamic performance begins with a disk or area in a stream flow of air. Conservation of energy and momentum are used to determine the limit on the amount of extractable energy.

Forces of lift and drag on airfoils are measured experimentally in wind tunnels. As previous measurements were for use with airplanes, a lot of airfoil data [1] are available from national labs. Almost any shape can serve as an airfoil, even a flat plate, and the design of airfoils is almost an art. As wind turbine blades operate in different wind speeds than airplane wings, airfoil data with low Reynolds numbers [2] became available. Most of the lift and drag data were limited to attack angles up to stall and a few degrees pass stall, because after the stall point, the airplane loses lift, stalls out, and falls. Lift and drag data for attack angles up to 180° were only available for a few airfoils. Airfoils, which had a large ratio of lift to drag, were developed for sailplanes. Which airfoils are used for wind turbines depends on a number of factors, not just the ratio of lift to drag. As the requirements are different for wind turbines, starting in the late 1980s airfoils were designed specifically for wind turbines. A major change was to design airfoils that were less sensitive to surface roughness.

Different theories (strip theory, circulation, vortex shedding) and experimental data on airfoils are used to predict the rotor performance of wind turbines. This theoretical performance can be checked against the measured output of models in wind tunnels, truck testing for small-diameter units, or field testing (atmospheric) of wind turbines. At one time, a railroad flat car was used for controlled speed testing, as a somewhat larger turbine could be mounted. Overall efficiencies include those of the rotor, drive train, and energy converter (generator, etc.). The complete analysis on design of wind turbines, primarily rotors and structures, can be found in more advanced texts [3–12]; however, beginning physics can be used for a qualitative understanding of rotor performance.

6.3 MATHEMATICAL TERMS

Momentum of a particle is the mass times the velocity. Boldface in an equation indicates that it is a vector, which has both magnitude and direction. In two dimensions, it takes two components to define a vector, and in three dimensions, three components. In an analytical representation the vector can be represented by its components along two axes (perpendicular or orthogonal axes for this presentation).

$$\boldsymbol{p} = m\boldsymbol{v} \tag{6.1}$$

Any particle can be treated as a single particle with the mass, $\boldsymbol{M}$, concentrated at a point (center of mass, $\boldsymbol{R}$). Position vector is indicated by $\boldsymbol{r}$.

$$\boldsymbol{MR} = m_1\boldsymbol{r}_1 + m_2\boldsymbol{r}_2 + \ldots.. + m_i\boldsymbol{r}_i \tag{6.2}$$

Forces on particles make them accelerate. Newton's second law describes the dynamics or motion; force is the change in momentum over the change in time. In other words, to change the momentum of a particle requires a force. That could mean a change in speed or a change in direction of the motion of the particle. There is also a force if there is a change in mass, but for this discussion, mass is constant.

$$\boldsymbol{F} = \frac{\Delta \boldsymbol{p}}{\Delta t}, \text{ newton (N)} \tag{6.3}$$

Torque makes a particle turn around some point, which can be thought of as the lever arm times the force. A larger torque can be obtained by increasing the length of the lever arm or by increasing the force.

$$\boldsymbol{T} = \boldsymbol{r} \times \boldsymbol{F}, \text{ Nm} \tag{6.4}$$

where the cross-product means that two vectors produce a vector whose direction is perpendicular to the plane of the two vectors.

If a mass is attached to a rod, which is free to rotate about its end (Figure 6.1), and a force is applied, the torque will make the mass rotate, and there will be power available. The amount of power is the product of the torque and angular velocity (Equation 5.1). That power is available at the shaft. Most operations of transferring shaft power try to have a large ω because of structural considerations.

$$P = T\,\omega, \text{ W} \tag{6.5}$$

Also, the rotating object will have rotational kinetic energy.

$$KE_{\text{rot}} = 0.5 \text{ m } v^2 = 0.5 \text{ m } r^2\, \omega^2, \text{ J} \tag{6.6}$$

where the speed of the rotating mass depends on the radius, $v = \omega * r$.

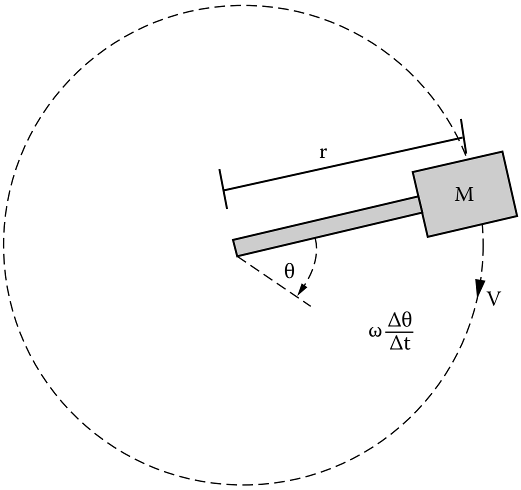


FIGURE 6.1 Mass rotating about a point.

The power coefficient is the power delivered by the device divided by the power available in the wind. Since the area cancels out, the power coefficient, C_P, is

$$C_P = \frac{\text{power out}}{\text{power in}} = \frac{\text{power out}}{0.5\rho v^3} \tag{6.7}$$

The work or energy to move an object is the force times the distance through which it moves. Remember, work is a scalar (it has only a value, no direction). Also note, if the force is perpendicular to the motion, there is no work done (no gain or loss of energy). An example is the motion of the moon around the earth.

$$W = \boldsymbol{F} \bullet \Delta\boldsymbol{r} = \boldsymbol{F} \bullet (\boldsymbol{r}_f - \boldsymbol{r}_i) \tag{6.8}$$

The dot between the vectors means only the parallel component of the $\boldsymbol{F}$ is used ($W = F \cos\theta\, \Delta\boldsymbol{r}$), where $\Delta\boldsymbol{r}$ = final position – initial position, and θ is the angle between $\boldsymbol{F}$ and $\boldsymbol{r}$.

Divide both sides of Equation 6.8 by time:

$$\frac{W}{t} = \frac{\boldsymbol{F} \bullet \Delta\boldsymbol{r}}{t}$$

Thus, the power is

$$P = \boldsymbol{F} \bullet \boldsymbol{v} \tag{6.9}$$

6.4 DRAG DEVICE

The power from a drag device (see Figure 5.1) can be calculated from the force on the device and the velocity of the device, $\boldsymbol{u}$. From Equation 6.9, $P = F * u$, since force and speed are in the same direction. The force/area of the air on a stationary object in a wind speed, v, is

$$\frac{F}{A} = 0.5\, \rho\, v^2\, C_D \tag{6.10}$$

where C_D is the drag coefficient. Drag coefficients, C_D, for different shapes are given in *Marks' Handbook* [13], but the simplest procedure is to use $C_D = 1$ for round pipes and wires and for flat plates perpendicular to the wind. Flat plates at an angle to the wind will experience some lift and drag like an airfoil, and these data are available.

The force/area is also the pressure, so the wind blowing against an object creates a pressure. If the winds are high enough, as in hurricanes and tornadoes, the pressure will destroy buildings and topple trees and power poles.

From Equations 6.9 and 6.10, the power loss due to drag from struts can be calculated. Notice that it is proportional to velocity cubed:

$$P = 0.5\,\rho\, v^2\, C_D\, A \quad v = 0.5\,\rho\, v^3\, C_D\, A \tag{6.11}$$

The power loss from struts for a 4 kW giromill was so large that the struts were redesigned to an airfoil shape to reduce drag. Notice that fuel efficiency for vehicles can be improved by reducing the drag coefficient for vehicles and by slowing down.

The power coefficient for a drag device can be calculated from the relative wind speed, as seen by the drag device and the speed of the device. The relative velocity of the wind as measured by a sensor mounted on the drag device is

$$v_r = v_0 - u$$

again, where v_0 is the wind speed and u is the speed of the device. Then the power per unit area from Equation 6.9 is

$$\frac{P}{A} = 0.5\,\rho\, v_r^2\, C_D\, u = 0.5\,\rho\,(v_0 - u)^2\, C_D\, u \tag{6.12}$$

Notice that at $u = 0$ and $u = v_0$, the power is zero. In other words, there is no power output if the drag device is not moving, and the drag device cannot move faster than the wind. From Equations 6.7 and 6.12, the maximum power coefficient for a drag device can be calculated. The maximum power coefficient, $C_{P(\max)} = 4/27 = 0.15$, which occurs when the drag device is moving at $u = 1/3$ the wind speed. This maximum power coefficient is for a drag coefficient around 1. Some drag devices can have a drag coefficient greater than 1, so the maximum power coefficient could be as high as 20%. The maximum power coefficient can be found using calculus or can be estimated from a spreadsheet or graph of P/A versus wind speed (Equation 6.12) for various values of u, from 0 to v_0. Low efficiency is another reason there are not commercial drag devices for generating electricity.

6.5 LIFT DEVICE

A lift device can produce on the order of 100 times the power per unit surface area of blade versus a drag device. See Rohatgi and Nelson [14, chap. 6] for more details.

EXAMPLE 6.1

Suppose we have a two-blade wind turbine, each blade is 5 m long, 0.1 m wide. As a drag device, the capture cross section is 1 m^2. As a lift device in a HAWT, its capture cross-sectional area is 78.5 m^2. If the difference in efficiencies is included, the ratio of the power out per blade area for the lift device over the drag device is over 300.

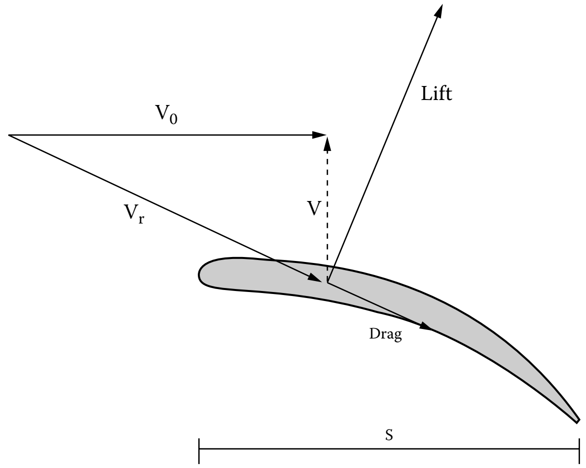


FIGURE 6.2 Lift translator. Direction of motion, V, is perpendicular to the ground wind, V_0. *S* is length of the cross-sectional area of the blade or sail.

An example of a lift device is a sailboat, a lift translator (Figure 6.2), where the sails form an airfoil. Notice that a sailboat moving downwind (a drag device) moves much slower than a sailboat as it moves perpendicular to the wind (a lift device). Besides sailing ships, there have been proposals to use lift translators for generating power. The problems are the large speeds of the devices, as lift devices can move faster than the wind, the proximity to the ground, and the necessity for having a predominant wind direction. Some lift translators were actually built, but never operated successfully.

The simple analysis for a lift device assumes streamline flow (irrotational, incompressible fluid) and conservation of energy and momentum. The wind speed interacts with the disk (propeller, rotor, screw, or whatever), and there is a pressure drop across the disk (Figure 6.3). The thrust (force) loading, *T*, is uniform across the disk. Also, there is no friction or drag force. At large distances behind the disk, the wind speed and pressure will have the same values as at a long distance in front of the disk. As stated earlier, the pressure, *p*, is the force/area.

From conservation of momentum, momentum in = momentum out. The mass flow, $\Delta m/\Delta t$, across any area is constant. Across the area of the disk, the mass flow is the product of air density (ρ), area (A), and wind speed; so for the three regions

$$\frac{\Delta m}{\Delta t} = \rho\, A_0\, v_0 = \rho\, A\, u = \rho\, A_2\, v_2$$

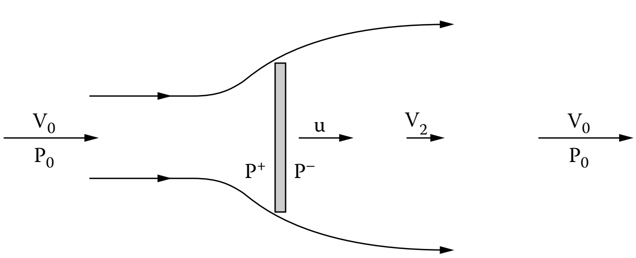


FIGURE 6.3 Wind speeds and pressures at infinity, at the disk, and behind the disk.

Use Equation 6.3:

$$T = \frac{\Delta p}{\Delta t} = \frac{\Delta m}{\Delta T}(v_0 - v_2) = \rho A u (v_0 - v_2) \tag{6.13}$$

Also, the thrust loading on the disk due to the pressure difference across the disk is

$$T = A\,(p^+ - p^-) \tag{6.14}$$

Bernoulli's theorem relates the velocity and pressures in streamline flow (kinetic energy and pressure are constants for horizontal flow). If the velocity increases, then the pressure decreases; the two are related through conservation of energy and momentum. The wind speed and pressure upstream and downstream of the disk are related by:

Upstream	Disk	Downstream
$0.5\rho v_0^2 + p_0 = 0.5\rho u^2 + p^+$		$0.5\rho u^2 + p^- = 0.5\rho v_2^2 + p_0$

From the two equations, take the pressure difference ($p^+ - p^-$) and substitute into Equation 6.14:

$$T = 0.5\rho A\left(v_0^2 - v_2^2\right) \tag{6.15}$$

The thrusts are equal, so set Equation 6.13 equal to Equation 6.15:

$$\rho A u (v_0 - v_2) = 0.5\rho A\left(v_0^2 - v_2^2\right) = 0.5\rho A (v_0 + v_2)(v_0 - v_2) \tag{6.16}$$

From Equation 6.14 the wind speed at the disk is the average of the wind speeds before and after the disk (wake).

$$u = 0.5\ (v_0 + v_2) \tag{6.17}$$

The axial interference factor is defined by what ratio the wind speed is reduced by the disk.

$$\alpha = \frac{v_0 - u}{v_0} = 1 - \frac{u}{v_0} \text{ or } u = v_0(1-\alpha) \tag{6.18}$$

Substitute into Equation 6.17 and the wake wind speed is

$$v_2 = v_0(1-2\alpha) \text{ or } \alpha = \frac{v_0 - v_2}{2v_0} \tag{6.19}$$

If the disk or rotor absorbs all the energy, $v_2 = 0$ and $\alpha = 0.5$. That is physical nonsense, as all the mass would pile up at the rotor. The power is equal to the change in kinetic energy from upstream to downstream:

$$P = \frac{\Delta KE}{t} = \frac{KE_{us} - KE_{ds}}{t} = 0.5\frac{m}{t}v_0^2 - 0.5\frac{m}{t}v_2^2 = 0.5\rho A u\left(v_0^2 - v_2^2\right)$$

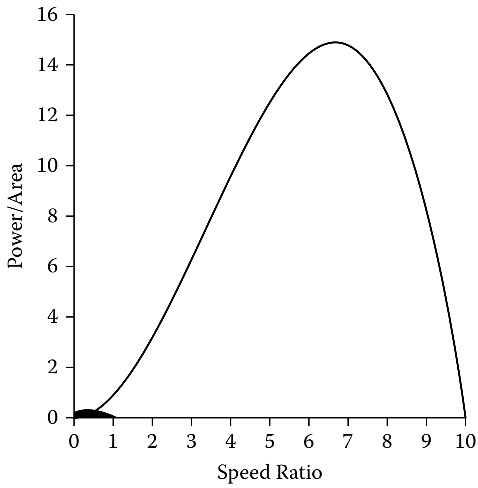


FIGURE 6.4 Comparison of power/area for a translating drag device (small solid curve) and a translating lift device versus speed ratio of the device to the wind.

and the value of the axial interference factor is substituted into the equation to obtain the power/area for a lift device:

$$\frac{P}{A} = 0.5\rho v_0^3 4\alpha(1-\alpha)^2 \tag{6.20}$$

A lift device can produce much more power per area of blade than a drag device (Figure 6.4). Notice the small black line is for the drag device, which reaches a maximum of around 0.22 at a speed ratio = 0.3. The maximum for the lift device is around 15 at the speed ratio 2/3 of the ratio of lift to drag coefficients. For this example, the power per area of blade was calculated for the drag device with a drag coefficient of 1.5, and for the lift device, the ratio of lift coefficient to drag coefficient was 10. Thus, the lift device can easily produce fifty times the power per blade area—another reason drag devices are not used to produce electricity, although a company in South Africa has a farm windmill that has an option for an electric generator.

6.5.1 Maximum Theoretical Power

The maximum power/area can be found by plotting the curve *P/A* versus α (Equation 6.20) or by using calculus. The answer is $\alpha = 1/3$ or 1. Of course, $\alpha = 1$ means that there is no reduction of wind speed and the disk does not take out any power. For $\alpha = 1/3$, the maximum power is

$$\frac{P}{A} = 0.5\,\rho\,v_0^3\,\frac{16}{27} \tag{6.21}$$

Therefore, the maximum power coefficient, from Equation 6.6, is $C_P = 16/27 = 0.59$. Real rotors will have smaller power coefficients due to drag, tip and hub losses, losses due to rotation of the wake, and frictional losses; however, measured values can reach 50% (which includes drive train and generator). This is another reason lift devices are used to generate electricity, compared to drag devices, as the maximum theoretical power coefficients are 50% versus 20%. However, the farm windmill, which has some of the same characteristics as a drag device (large solidity, low tip speed ratio) is well designed for the application of pumping low volumes of water.

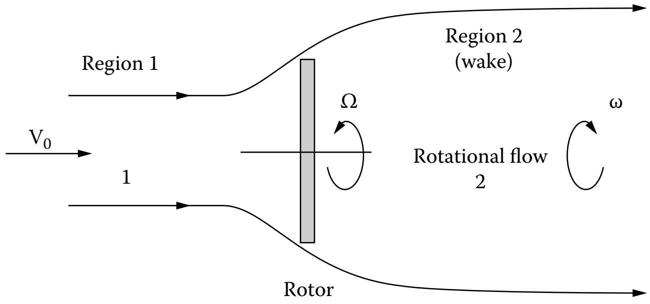


FIGURE 6.5 The rotor imparts a rotation to the wake.

6.5.2 Rotation

Angular momentum is

$$\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p} \tag{6.22}$$

Angular momentum, like momentum, is always conserved.

From conservation of angular momentum, since the disk is rotating, there will be a rotation imparted to the wake in the opposite direction of the disk (Figure 6.5). From the conservation of energy,

$$KE_{\text{up}} = \text{energy extracted (by rotor)} + KE_{\text{wake}} + KE \text{ (rotation of wake)}$$

The torque acting on the rotor makes it rotate and power can be extracted. In order to obtain maximum power, a high angular velocity, Ω, and a low torque, T, are desirable because a large torque will result in a large wake rotational energy (angular velocity of the wake = ω).

$$\text{Power (rotor)} = T\Omega$$

A similar analysis, as previously described, is used to obtain the power extracted where conservation of angular momentum is included. An annular ring is considered, and an angular (tangential) induction factor, α', is used. The main difference is that the rotor velocity is a function of the radius, so the values have to be calculated for the annular ring.

6.6 AERODYNAMIC PERFORMANCE PREDICTION

The ratio of lift to drag for airfoils is around 100, so the two forces, which act at the quarter chord of the airfoil, are represented by a force that makes the blade rotate, tangential force, and a force trying to push the rotor over, perpendicular force. So if these lift and drag forces are calculated for a blade, then the tangential and perpendicular forces are calculated and the performance of the rotor can be predicted. If the angle between the blade path and the wind at the blade is Φ (see Figure 5.9), then the tangential and perpendicular forces are

$$\begin{aligned} F\text{ (tan)} &= L \sin \Phi - D \cos \Phi \\ F\text{ (per)} &= L \cos \Phi + D \sin \Phi \end{aligned} \tag{6.23}$$

Notice that the perpendicular force will be larger than the tangential force, and at 90° there is only drag.

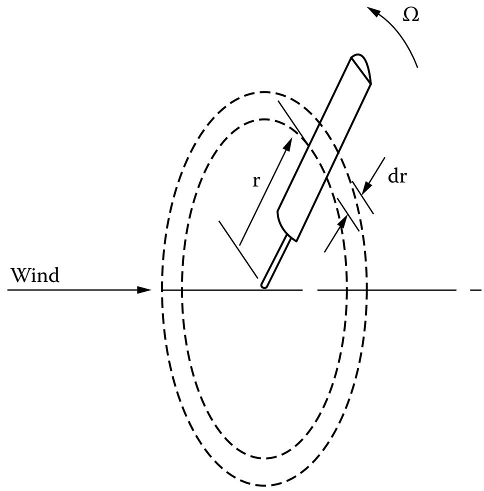


FIGURE 6.6 Diagram of blade element.

There are a number of computer programs for predicting aerodynamic performance of wind turbines [15]. These are based on momentum theory, also referred to as strip theory. The theory assumes that each element of the blade (Figure 6.6) can be analyzed independently from the others, and the two-dimensional data for lift and drag coefficients can be used at the center of the section. Performance predictions of power, torque, force, and power coefficient can be obtained for a blade (rotor) using a numerical technique. Values are calculated for sections of the blade and then summed to obtain the total performance.

Drag and lift coefficients versus angle of attack and Reynolds number are available for lots of airfoils. In general, the coefficients are given for attack angles from around zero to a few degrees past stall. Stall is where the lift decreases and drag increases steeply. So the problem, in the calculation for performance prediction, is to use the correct inflow angle to the blade, as the angle depends on the wind speed at the blade. So the relative wind speed has to be corrected for the actual speed at the blade, which uses the axial interference factor, α, and the rotational interference factor, α'. At each section of the blade, an iterative procedure is used to calculate the angle of the inflow to the airfoil. Because sections of the blade may operate at high angles of attack, for those attack angles, lift and drag data from a flap plate or other actual measured data from some airfoil are added to the tabular values. Tip losses and hub losses can be included along with wind shear and yaw (off-axis components). The main limitations with the programs are the treatment of unsteady aerodynamics in the region of dynamic stall and the use of 2-D data for lift and drag.

Rotors for vertical-axis wind turbines present another problem since the blades go through attack angles of 360° and the blades are curved for the Darrieus wind turbine. A number of performance models for the Darrieus rotor have been formulated [3, 16–18]. In general, symmetrical airfoils are used, so lift and drag data are needed from 0 to 180°. The operation of vertical-axis wind turbines also means at an attack angle of 90°, there is no lift, so the torque and power are negative, a cyclic variation on every revolution [19].

From observations of the flow field of a Savonius rotor, an analytical model was developed for the analysis of performance [3]. Two major discernable features of the flow field are: vortices are shed from the vane tips when the vane is approximately at right angles to the flow, and these vortices are counterrotating, and the vortices move rearward at approximately the free stream speed. The model was adequate in that it predicted a power coefficient around 0.30 at a tip speed ratio around 1, which is in line with field data and wind tunnel tests for Savonius rotors.

Dynamic stall produces higher loads on the blades and larger power output than the predictions from the performance codes using the steady-state data for lift and drag. Dynamic stall may occur during operation in high winds due to a wind gust for constant-pitch blades, or for variable-pitch blades in the run position. During this increasing angle of attack a vortex forms near the leading edge and moves to the trailing edge of the blade, resulting in higher lift, hence the name. Once the vortex is shed off the trailing edge, deep stall occurs. The other condition for occurrence of dynamic stall in high winds is during shutdown, as variable-pitch blades are moved to the feather position. The Westinghouse wind turbines, rated at 600 kW, in Hawaii had this problem as power spikes to 800 kW occurred during shutdown. Their solution was to change the blade pitch in the run position to lower the rated power, so when the spike occurred during high wind shutdown, the loads and power were not too high. Now lift and drag data for some airfoils are available as the attack angle is changing, which show the dynamic stall, and these data can be used in the performance prediction codes.

The dynamic stall vortex has been visualized and also noted by the analysis of time-varying surface pressure data from field tests and wind tunnel experiments [20]. Blades with pressure taps were used for the Unsteady Aerodynamics Experiment [21], which included a test of an extensively instrumented wind turbine in the giant NASA–Ames wind tunnel, 24.4 by 36.6 m. Results from computer models at high wind speeds under stall were significantly different, as power predictions range from 30% to 275% of the measured values. So the aerodynamic performance prediction programs are used as a design tool, not the final answer.

Aerodynamic performance prediction programs [3] are now available for personal computers with menu-driven interactive editing and graphical display to facilitate its use as a design

TABLE 6.1
Sample Output from PROP93

Proppprint3
Blade element data for delta beta = 0.00, *X* = 6.11, yaw = 0.00

Element	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Theta	180	180	180	180	180	180	180	180	180	180
Vel	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
A	0.296	0.140	0.188	0.204	0.230	0.213	0.195	0.206	0.231	0.308
AP	0.073	0.021	0.016	0.012	0.010	0.008	0.006	0.006	0.006	0.007
CL	0.813	1.005	1.160	1.206	1.334	1.311	1.168	1.037	0.918	0.772
CD	0.014	0.098	0.053	0.043	0.020	0.019	x0.016	0.014	0.013	0.011
PHI	49.92	42.48	27.54	20.14	15.45	13.03	11.35	9.74	8.34	6.72
ANG	7.92	19.18	15.74	14.84	13.35	12.93	11.35	9.74	8.34	6.72
TC	0.384	0.526	0.622	0.656	0.707	0.665	0.609	0.610	0.609	0.572
QC	0.040	0.059	0.073	0.075	0.083	0.079	0.074	0.073	0.069	0.056
PC	0.243	0.363	0.443	0.459	0.508	0.485	0.453	0.443	0.421	0.344
TD, lb/ft	2.64	6.03	11.90	17.57	24.37	28.01	30.31	35.04	329.6	41.60
QD, ft-lb/ft	4.38	10.92	22.21	32.26	45.86	53.47	59.02	66.73	71.85	65.54
PD kW	0.024	0.298	0.606	0.880	1.251	1.458	1.610	1.820	1.959	1.788
Rey, $*10^6$	0.920	0.862	0.922	0.931	0.910	0.868	0.890	1.004	1.132	1.132
Rotor 2 blades	**Pitch**	**X**	**TC**	**QC**	**PC**	**V0 m/s**	**TD lb**	**MD ft-lb**	**QD ft-lb**	**PD kW**
	0.0	6.1	0.614	0.070	0.427	10.0	752	3,984	1,372	23.3

Note: Output for one blade (Carter 25, 10 m diameter, pitch = 0°), divided into ten stations, and then the total is summarized at the bottom. Wind speed is 10 m/s and tip speed ratio, *X* = 6.11.

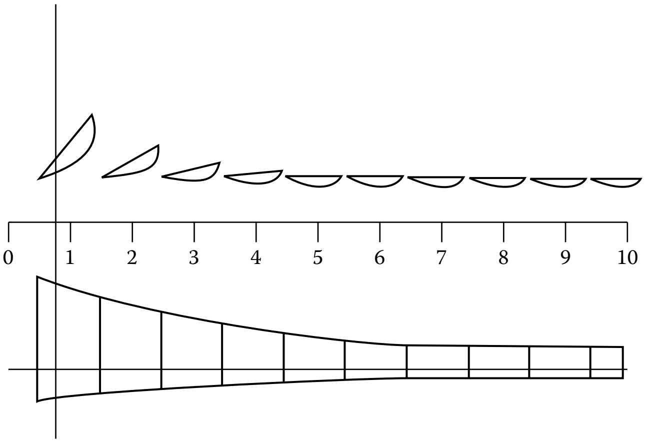


FIGURE 6.7 Twist and planform for Carter 25 wind turbine blade. Blade is divided into ten sections for analysis, and the station is at the midpoint of the section.

tool: PROP93 [22]. The inputs to the program include the blade characteristics (number, length and hub cut-out, planform, twist at the section, and pitch), lift and drag coefficients of airfoils for different angles of attack, and operating characteristics, such as tip speed ratio, rpm, and wind speed. The tabular output, in metric or English units, of PROP93 can be directed to the screen, printer, or a data file. Notice for the selected input in the example (Table 6.1), the rotor is predicted to produce 23.3 kW at 10 m/s. Graphs of the standard output parameters can be displayed as functions of blade station, pitch, wind speed, or tip speed ratio. Calculated values can then be compared with experimental values. These programs, which are steady state, do not predict the high loads seen in the field due to gusts and in changing the pitch to feather in high winds (dynamic stall).

Graphs of the planform (Figure 6.7) lift and drag data can be produced. Sample output graphs (Figures 6.8 to 6.10) are for a Carter 25 wind turbine, NACA 2300 series airfoil. Smoother graphs

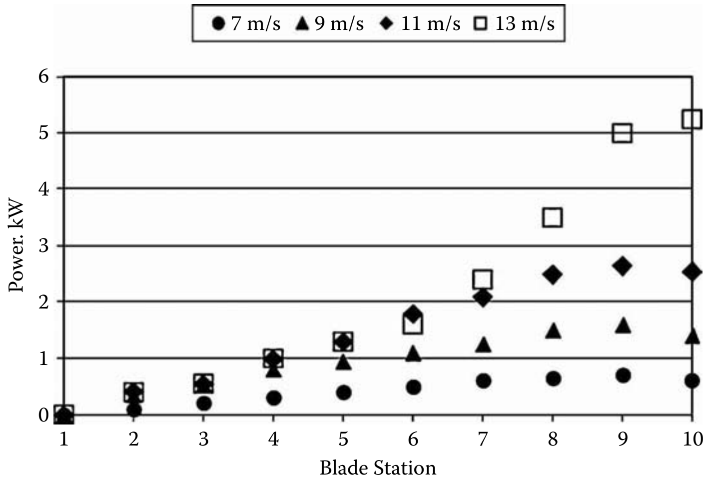


FIGURE 6.8 PROP93: Prediction of power output for one blade by blade station for four wind speeds, tip speed ratio = 6.1.

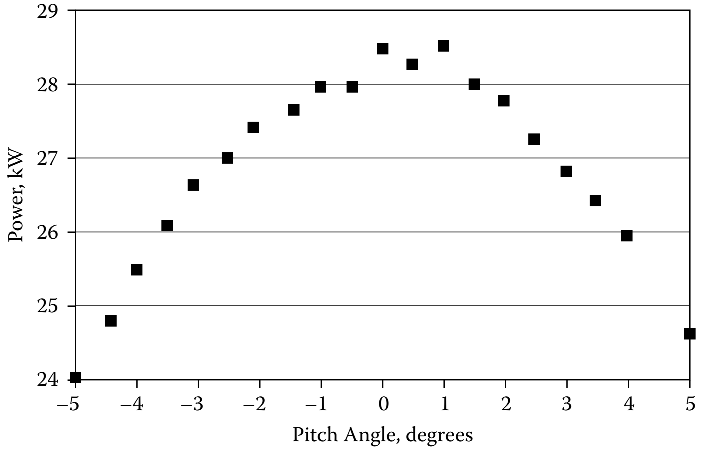


FIGURE 6.9 PROP93: Prediction of rotor power output for different pitch angles at 10 m/s. The Carter 25 wind turbine is a fixed-pitch, constant-rpm machine.

would be obtained by using twenty data stations. These blades had large twist and larger chord toward the root, and then the same chord and twist from the midpoint, which produced an aerodynamic efficiency close to the theoretical limit. Notice the twist is to obtain the correct angle of attack due to the different inflow wind due to the contribution of the blade speed, which is slowest at the root. Also, twist on the inward part of the blade increases the torque for starting rotation. Note that for constant-pitch blades with little twist, there is not enough starting torque and the rotor needs to be motored for start-up. For variable-pitch blades, the blades are in the feather position, which produces enough torque for start-up. Notice that for constant tip speed ratio, the power continues to increase with wind speed (Figure 6.10).

Tangler and Kocurek [23] provided guidelines for input of post-stall airfoil data for the prediction of peak and post-peak rotor power for performance programs using blade element momentum theory. A steady-state data set from the rotor test in the Unsteady Aerodynamics Experiment was

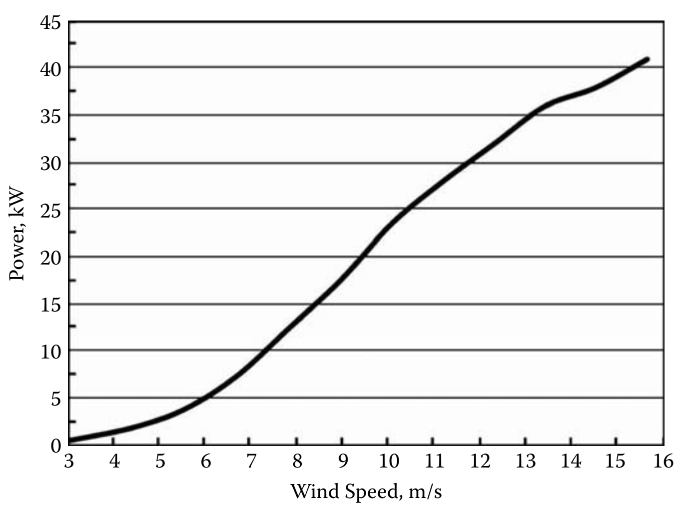


FIGURE 6.10 PROP93: Theoretical power curve for Carter 25 rotor, tip speed ratio = 6.1.

used for the global post-stall method for the prediction of post-stall 3-D airfoil characteristics to be used with the 2-D airfoil data.

PROPID [24] is a program for personal computers for the rotor design and analysis of horizontal-axis wind turbines, and the executable program is available online [25]. The strength of the method is its inverse design capability. PROPID is based on the PROPSH blade element/momentum code, and it includes a 3-D post-stall airfoil performance synthesization method for better prediction of peak power at high wind speeds.

Most wind turbine blades use the same airfoil for the entire blade; however, twist and chord length change from the root to the tip of the blade. The surface of the blade should have a smooth transition along the length. The Alternative Energy Institute also fabricated test blades for the Carter 25, which used new airfoils designed specifically for wind turbines by NREL [26]. The criteria for the design of thin airfoils were high lift/drag for the inboard blade portion, restrain maximum lift coefficient of the outer part of the blade to limit peak power, and provide insensitivity to surface roughness. Because three different airfoils were used, a computer program was developed to calculate blade fairness (no waves) along the blade. The program used cubic spline under tension [27, 28] and is available from the Alternative Energy Institute. The basic input to the program consists of specified airfoils, blade radius, root cut-out, and wind distribution. Additional input can be specific: spanwise airfoil stations, specified twist, and taper distributions. Different tension parameters result in a different continuous spanwise airfoil distribution. Optimization is achieved by iteration through computer codes to determine the surface based on annual energy output and predicted blade load history for a specified wind distribution. Computer design of blades is of little value if the blade cannot be practically constructed. Therefore, various input constraints are allowed on twist, taper, and sharpness of edges and corners.

The blade fairness program determined the airfoils at ten sections from the three input airfoils (Figure 6.11). The templates were cut out on a numerical control milling machine and assembled

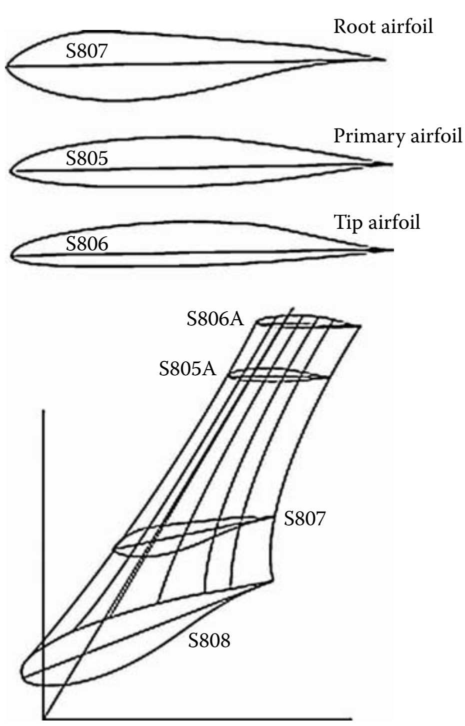


FIGURE 6.11 Thin airfoil series for wind turbine blade, and their input placement for a 5 m blade.

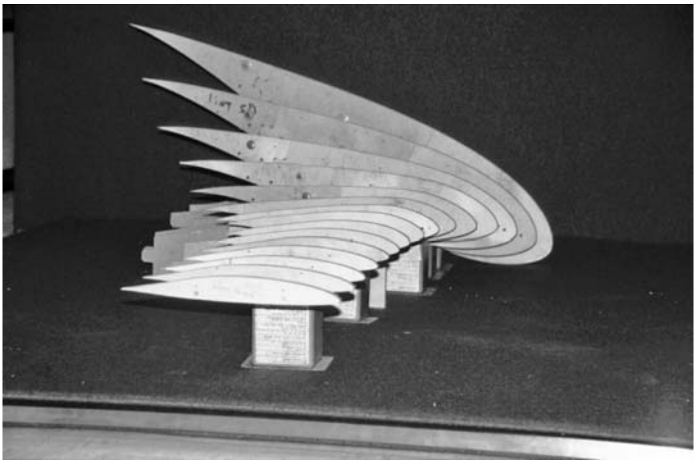


FIGURE 6.12 Blade templates for Carter 25 wind turbine, fabricated by AEI. There are three different airfoils, and thus there are different shapes along with different chords and twists at the ten stations.

with the proper twist (Figure 6.12). Then the blade templates were used to construct a plug, from which two molds, top and bottom, were constructed. After fabrication of the blade skins, they were attached to a Carter 25 spar and hub and tested in the field in a side-by-side comparison with a production unit [29, 30]. Data were collected at low, medium, and high wind speeds for clean, medium, and heavy surface roughness conditions. The roughness conditions were simulated with the application of grit on 2.5 cm wide tape on the upper (0.02 chord) and the lower (0.05 chord) leading edge. Results of the tests showed little power difference at low wind speed, the reduced power from the outer part of the blade could not be tested since the teetering hub reduced high flap loads, and the new airfoils were much less sensitive to surface roughness for medium and high wind speeds.

Essentially the same amount of power can be obtained from one blade rotating fast or more blades rotating slower, or from the same number of blades with different chord lengths. From the performance prediction programs, as solidity increases for a given rotor area, the tip speed ratio that gives the maximum power coefficient becomes smaller. For a given size rotor operating at fixed rpm, different size generators (rated power) can be placed on the unit by increasing the rated wind speed. In the past a number of wind turbines were built with the same diameter, 10 m; however, they had the following rated powers: 8, 12, 15, 25, 40, and 90 kW. Today, most wind turbines have rated powers at wind speeds from 10 to 13 m/s.

The design engineers of wind turbines have a number of parameters to select just for the rotor: airfoil, planform, solidity, number of blades, radius, tip speed ratio (variable or fixed), etc. The most efficient blade from an aerodynamic basis is generally more difficult to construct from a practical and manufacturing standpoint. Early blades were made from wood, the same as propellers, and a commonly used airfoil was the NACA 4400 series, because the bottom side of the airfoil was flat. Other airfoils with better lift to drag were used, such as the NACA 23000 series and the LS1 airfoil. These airfoils had camber, curved on the bottom side, which made them somewhat more difficult to construct. An aerodynamic efficient blade will have the largest twist and chord at the root, which then decreases toward the tip; however, because of other considerations, in general, the inner part of the blade is only designed for some efficiency and starting torque, because the outer third of the blade generates most of the power. Therefore, that part of the blade must be aerodynamically efficient. Finally, the design of the tip of the blade is important for noise considerations and to reduce tip losses if possible. The outer portion of the General Electric blade is now swept back and the Skystream has sweep blades, which means the outer portion is curved like a scimitar (sword).

Other parameters, for example, are the design point, wind speed for the rated power (which primarily determines rotor area), and tip speed ratio, which is determined by the solidity of the rotor. In general, the tip speed of the blades is limited to roughly 70 m/s, as the blade tips cause excessive acoustical noise at higher tip speeds. For offshore wind turbines, noise is not an important issue. Besides the rotor design then, there are the rest of the components: hub, which may include components for adjusting pitch of the blades; drive train and gearbox in most cases; generator; yaw control; tower; and the control system.

6.7 MEASURED POWER AND POWER COEFFICIENT

A common specification is the power output of the wind turbine versus wind speed, a power curve. The power curve generally includes all efficiencies from wind to electrical output, not just the rotor efficiency. Since all wind turbines must control power output at high wind speeds, at some point the efficiency is lower. Control can be implemented by changing blade pitch or by operating fixed-pitch blades at constant angular speed. Operating at fixed pitch is also called stall control. Power curves are obtained by the method of bins, so in reality, a power curve is not a line but a band of values.

The experimental power and power coefficient curves (Figure 6.13) are for a wind turbine that has an induction generator, operation at constant angular speed, and fixed pitch, which means it is stall controlled. Therefore, it reaches maximum power coefficient at only one point, and the decreased aerodynamic efficiency at wind speeds above this point make the power coefficient also decrease. The increased power in the wind and the decreased aerodynamic efficiency combine to give a constant power output above 12 m/s. The high efficiency, which includes drive train and generator, is because this unit has an almost optimal blade; taper, twist, and thickness.

Besides the tip and hub losses of the blades, there will be a further reduction of the power coefficient due to the inefficiencies of the mechanical system (drive train, coupling) and the generator. Under the optimum design conditions, the modern two- or three-bladed rotors at tip speed ratios in the range of approximately 4–10 will have power coefficients of about 0.4 to 0.5 (Figure 6.14). The power coefficients for the farm windmill and the Savonius rotors are essentially the same, with a maximum just over 0.3. The maximum power coefficients for the vertical-axis wind turbines are just over 0.4, which makes them less than those for the horizontal-axis wind turbines. This is one of the reasons that in 2008, vertical-axis wind turbines are not commercially available for wind farms.

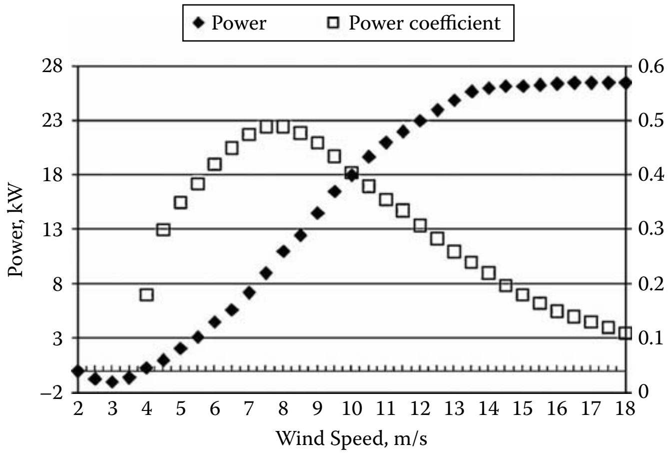


FIGURE 6.13 Experimental power and power coefficient for a Carter 25, rated 25 kW, 10 m diameter. Notice at 3 m/s the turbine uses power (energy for the field coils of the induction generator).

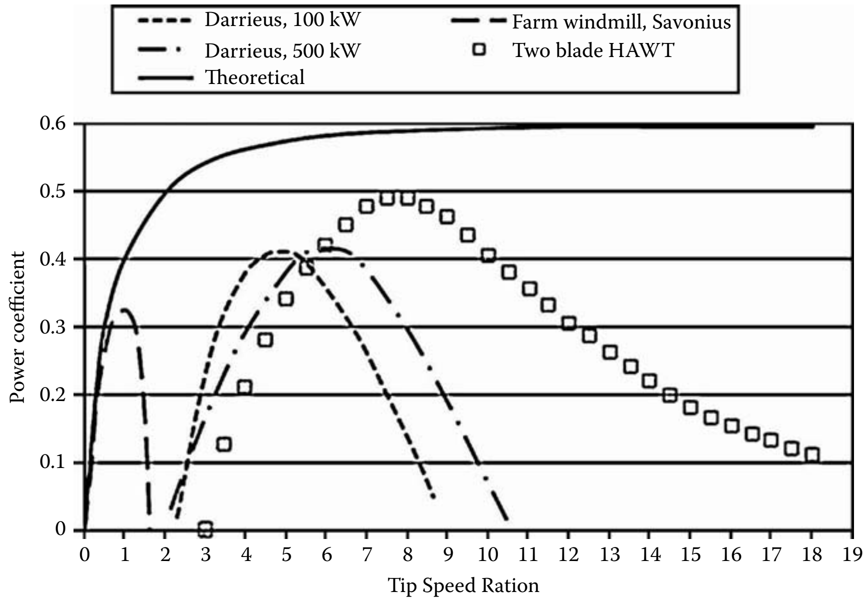


FIGURE 6.14 Experimental power coefficients for different rotors compared to the theoretical value: farm windmill [31], Savonius [32], 100 kW Darrieus [33], 500 kW Darrieus [19], horizontal-axis wind turbine, Carter 25 (data from Figure 6.12).

The three methods of regulating output are passive stall, where the wind turbine operates at fixed rotational speed with fixed-pitch blades; active stall, where the wind turbine operates at fixed rotational speed with adjustable pitch; and variable pitch, where the wind turbine operates at variable rotation speed with adjustable pitch blades. The last method is the most efficient aerodynamically, but the method of control chosen is always a trade-off between energy production and cost.

Control of rotor rpm using adjustable pitch includes full-span control, where pitch motors are located in the hub; variable-pitch tips; and ailerons (flaps on airplane wing) to control aerodynamics, even though it is not adjustable pitch. The last two have pitch motors in the blade. Now for large wind turbines, the most common method is full-span control, although wind turbines have been built with the other two control methods. The MOD-2 and MOD-5 had tip control.

Ailerons are moved to the low-pressure side of the blade to reduce lift, in contrast to flaps on planes, which are moved in the opposite direction to increase lift. NASA–Lewis investigated ailerons both theoretically and experimentally for application to medium and large wind turbines [34]. Zond built twelve 500 kW units with aileron control, and they were installed near Fort Davis, Texas, as part of the Utility Wind Turbine Verification Program [35]. However, after 4 years of operation they were dismantled, with one of the reasons being the maintenance problems with the ailerons. Finally, there was the Italian Gamma 60, 1.5 MW, wind turbine with fixed-pitch blades where the control was to yaw the rotor. One problem with that is the difference in lift on the blade on each cycle.

There have been efforts to develop passive pitch control techniques that adjust the blade pitch angle without a need for actuators [36]. One concept is the self-twisting blade in which the blade spar at the hub is flexible, and the thrust and centrifugal forces on the blade cause it to twist to the feathered position. United Technologies Research Center built a 10 m diameter unit with the two blades (constant chord, no twist) attached to a flexbeam (Figure 6.15), which was attached in the middle to the drive shaft. There was enough twist to provide torque for start-up, and pendulum weights outside the plane of rotation moved toward the plane of rotation and provided proper pitch angle for the run position, and also, the weights provided control at high winds by twisting

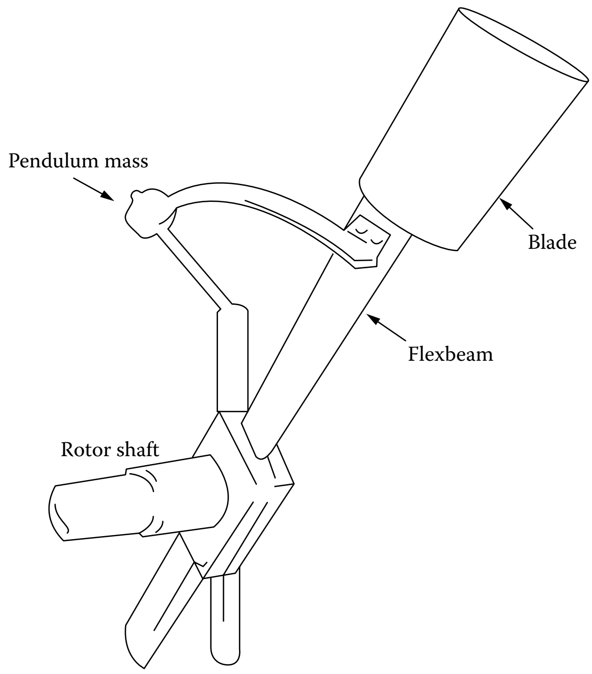


FIGURE 6.15 Passive control with flexbeam and pendulum weights, unit was constant-rpm operation.

the blades toward stall. One problem was that over time, the flexbeam moved toward a different set twist, which reduced the starting torque. The Proven wind turbine has a flexible hinge near the root of the blade [37]. As rotor rpm increases, the blades are forced outwards, which changes the pitch of the blade toward stall. So even in high winds, the rotor rpm is limited, and it can continue to produce power.

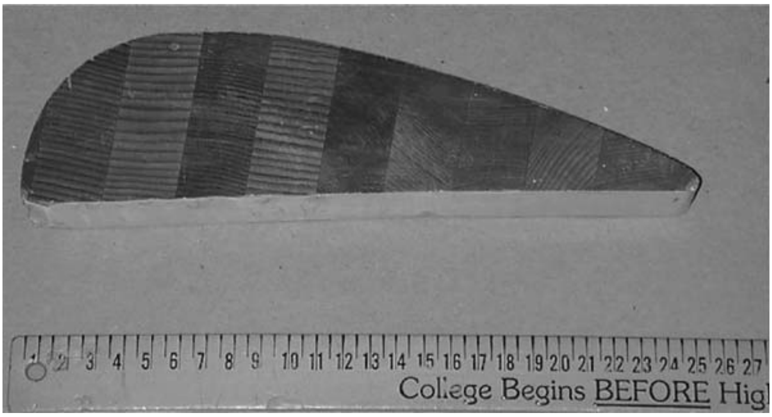
6.8 CONSTRUCTION

6.8.1 Blades

For years, small wind turbines blades were made of wood, carved from a single piece or from a wood block glued together from several pieces. The material properties of wood are good: strength, flexibility, and resistance to fatigue. Machines could carve up to four blades from a master blade. However, for large blades, solid wood was not acceptable, as the weight became too large. For larger blades, one construction was similar to an airplane wing, a spar and ribs with a covering. The spar is the load-bearing part and the ribs form the airfoil shape. As noted earlier, fabrication of blades depends on design, materials, and the construction processes, all of which are related. Wind turbine blades have been made from a number of materials: aluminum cover, fabric cover, or metal cover on rib and spar (like an airplane wing); a sail wing, which is fabric attached to a leading edge spar; laminated wood composite (shell); fiberglass-reinforced plastics (FRPs), also carbon fibers; pultruded FRPs; extruded aluminum (blades for vertical-axis wind turbines); and blades from injection molds for small wind turbine blades. Pultruded blades are where the fiberglass and other parts are pulled through a dye and the epoxy is applied at the same time, and blades are cut to length. Extruded blades are where the material is pushed through a dye, and for the Darrieus wind turbine, the blades are bent to curvature afterwards. Cross sections of some different blades illustrating different manufacturing processes are presented in Figure 6.16.

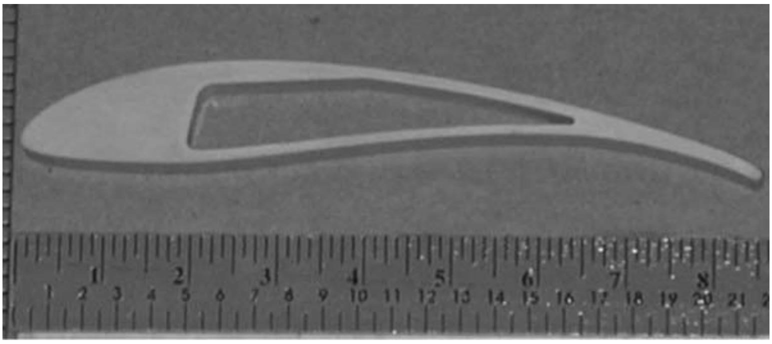
(a)

Blade from injection mold, has carbon filaments, for 300 W unit.



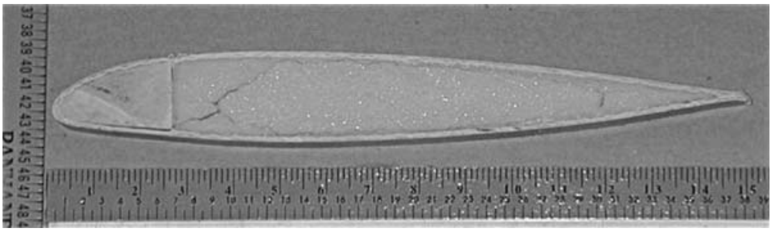
(b)

Solid wood, 4400 series airfoil, for 4 kW unit.



(c)

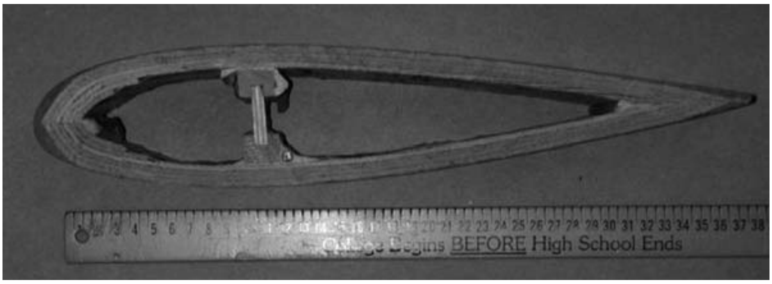
Pultruded FRPs, special airfoil, for 10 kW unit.



(d)

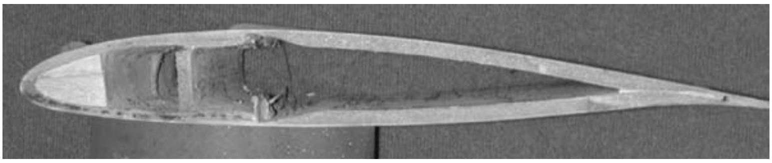
Pultruded FRPs, airfoil 23012, notice weight in nose and foam to keep skins from flexing, for 25 kW unit.

FIGURE 6.16 Blade cross sections from different manufacturing processes.



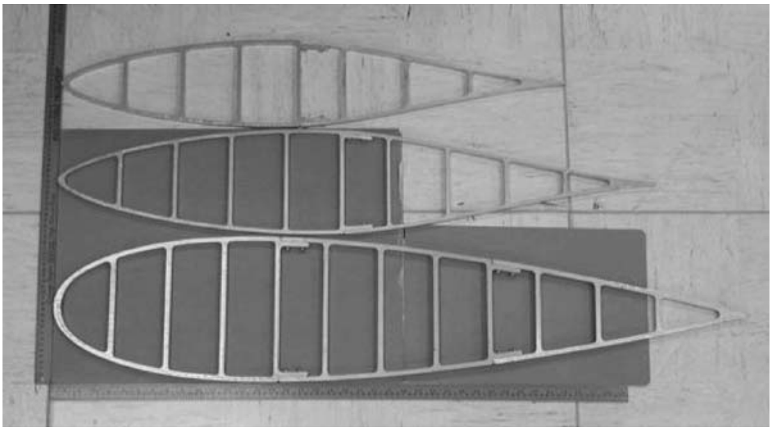
(e)

Wood, laminated composite, for 50 kW unit.



(f)

FRPs, airfoil LS1, hand lay up in three molds, top and bottom skins are attached to nose, D-spar with lead weight, for 300 kW unit.



(g)

Extruded aluminum, bottom from three pieces, the others from two pieces, for VAWT 34 m test bed, 500 kW.

FIGURE 6.16 *(Continued)*

A blade on a wind turbine goes through more fatigue cycles in 1 year than the wings on an airplane during its lifetime; therefore, fatigue is the major concern since the wind loads are large and variable. Even though metal blades have been built for wind turbines, their fatigue properties are not satisfactory, which resulted in too many failures. Carbon filaments are used in blades because they are stronger, even though they are more costly than glass filaments. The limitation on the pultruded FRP blades is that the blades are constant chord with no twist. For FRP blades there is the cost for the master mold, and there is a trade-off between automated winding of filaments and hand lay up. Molds are expensive and dies for the extruded aluminum blades are even more expensive.

FIGURE 6.17 Blade cross sections for megawatt wind turbine.

The material for blades is predominantly FRPs, for both the spar and the blade skin, which also supports the load. For the large wind turbine blades the construction is quite different than airplane wings. One basic concept is two glass fiber shells attached to two rigid beams, or a glass fiber shell with one beam (Figure 6.17). The technology, from design to process, is discussed by LM Glasfiber, the world's leading supplier of blades [38]. There has also been a switch from wood to FRP blades for small wind turbines. Blades of composite wood laminate, 6.5 m long, have been successful on a 50 kW unit.

Sandia Laboratories is concentrating on the aerodynamic and structural design of wind turbine blades [39]. Topics include adaptive structures, thick airfoils, material and fatigue, manufacturing research, design tools and applications, and sensors and nondestructive inspection. Reports in all of these areas are listed. Another aspect of the program is the long-term inflow and structural test, a joint project of Sandia and NREL to collect experimental inflow and turbine response data. One of the instrumented wind turbines is a GE 1.5 MW unit.

One of the main concerns is the procedure and mechanism for the shutdown for overspeed. If there is a lost of load, for example, the utility transmission line goes down due to an ice storm, during high winds with the wind turbine operating at rated power, then the power of the rotor has to be controlled with 5–10 s. If the condition results in so much power that it can not be controlled, even with the application of a mechanical brake, then the unit will self-destruct or a few high wind speed shutdowns will place so much stress on the drive train that it has to be replaced. For light-weight blades on wind turbines operating at constant rpm the time period is 4–5 s. The Alternative Energy Institute and USDA, Agricultural Research Service, have installed and tested over sixty prototype and first-production wind turbines, from 50 W to 500 kW. Almost all the units had some kind of failure within 1 year, and some of the failures resulted in loss of the rotor or even the destruction of the unit. When a rotor is in a runaway condition, the only thing you can do is get up wind and wait a while.

If a mechanical brake is part of the system for overspeed control, then it needs to be on the low-speed shaft, because if it is on the high-speed shaft and the drive train fails, then the brake is useless. It does not have to be a mechanical failure; for example, a 500 kW VAWT was lost because of a sequence of events that the software control program did not anticipate. The procedure for shutdown was to cut off the load and apply the mechanical brake. A high wind gust called for shutdown; however, it was a short gust, and the software said to release the brake, but the load was not reconnected because the time delay had not been reached. The turbine went into high rpm and the brake was applied again; however, due to the high power the brake soon burned up and the rotor was in the runaway condition, and within a short period, one blade broke loose and cut the guy wires and the unit fell.

All the blades need to have the same pitch setting or there will be a cyclic forcing function, which will then affect the drive train, etc. The extreme case was a 40 kW wind turbine where the three blades had a dihedral spar with change in position to feather for shutdown, and a rapid change to feather for overspeed. An attachment mechanism that connected rods to the middle of each blade had some play in it, so the pitch of each blade changed on every rotation and it was different from one side to the other. In moderate winds, the stable rotor position was yawed 45° to the wind, and besides the wear problem that presented, the unit did not produce much power.

Another concern is the yaw rate, especially for flexible blades. For example, the rotor has angular momentum, and when the brake is applied, the wind turbine will tend to rotate about the yaw axis. The rate of yaw, which is motor driven on large turbines, is limited, and on some smaller turbines the rate of yaw is limited by a yaw damper. The rate is limited because a change in angular momentum gives a torque.

$$\boldsymbol{T} = \Delta \boldsymbol{L}/\Delta t \tag{6.24}$$

where the torque is in the direction perpendicular to the plane of rotation of the rotor. Therefore, a large change in angular momentum of the rotor, due to a large change in wind direction or a change in yaw due to shutdown for overspeed, results in a force perpendicular to the plane of rotation. For flexible blades, this force could be large enough such that the blades could strike the tower. In the worst case, the blades break off at the root. Another example of fast yaw rate is for small wind turbines with flexible blades, downwind, with coning. Suppose the wind turbine is not operating due to no or little wind at night. The next day the winds are from the opposite direction and the unit starts with the rotor in the upwind orientation, which is possible, and the rotor will even track the wind; however, it is an unstable condition and eventually the wind direction changes or wind speeds increase enough for the rotor to suddenly change from the upwind to the stable downwind condition. This very fast yaw rate results in large flat forces on the blades, which means the blades are bent a large amount. The solution is to have a yaw damper, move the rotor farther from the tower, or have stiffer blades.

The guided tour of the Danish Wind Industry Association is excellent, and they have a section on testing wind turbine blades [40]. One problem with fatigue testing of large blades by vibration is the long time required to reach enough cycles where fatigue becomes noticeable.

Nondestructive testing by using acoustic emission is one way to monitor the progression of fatigue, and may even predict where the failure will occur [41]. Two fiberglass blades were tested by dynamic loading on a full-scale blade testing facility. The acoustic emission signatures focused on counting, amplitude distribution, and location, which provide assessment of damage status, failure modes, and failure locations. The damage development in composite laminates under fatigue progresses from matrix cracking, crack coupling with interfacial debonding, delamination, fiber breaking, and fracture. A general observation is that low acoustic emission amplitudes are associated with matrix damage, while high acoustic emission amplitudes are related to fiber failure. Mechanical properties such as natural frequency, elastic modulus, and tip deflection were measured during the fatigue tests, and a change in those properties indicates degradation.

Blades are loaded to static failure in flapwise bending, and some blades are tested to failure for edgewise bending. The National Wind Technology Center, NREL, has a facility for static and dynamic load testing of blades, which includes nondestructive techniques such as photoelastic stress visualization, thermographic stress visualization, and acoustic emission. Two new facilities, one in Massachusetts and the other in Texas, for testing the blades up to 70 m length are in the process of development [42]. New blade designs, 12 m long for constant rpm, 100 kW unit, using carbon filaments for more strength at less weight, were fabricated and then tested [43]. All the blades survived the specified test loads and two designs exceeded it significantly.

Of course in the final analysis, it is energy produced by the wind turbine at the most economical \$/kWh. A rotor design study considered four basic configurations: upwind three blades, upwind two blades, downwind three blades, and downwind two blades [44]. The cost of energy was estimated with improvements, as compared to baseline turbines of 750 kW, 1.5 MW, and 3.0 MW. Two of the conclusions were that the cost of energy would be reduced by up to 13%, which was small relative to the magnitude of the load reduction, and more than 50% of the cost of energy was unaffected by rotor design and system loads.

6.8.2 Rest of the System

For large wind turbines, the most common configuration is three blades made from FRPs, upwind, drive train, asynchronous generator, and tubular steel tower. The driver is the rotor, and these dynamic loads are transferred to the rest of the system: drive train, generator, and tower. The difference between variable- and constant-rpm operation is that part of the wind loads can be absorbed by inertia of the rotor in variable-rpm operation. This reduces the severity of the loads for the drive train and generator.

Computer codes are available for the prediction of the wind turbine loads and responses. The NWTC has a tool kit for creating wind turbine models [45] for input into a multibody dynamics code (commercial). FAST (Fatigue, Aerodynamics, Structures, and Turbulence) can be used to model two- and three-bladed horizontal-axis wind turbines. The code models the wind turbine as a combination of rigid and flexible bodies. For example, two-bladed, teetering-hub turbines are modeled as four rigid bodies and four flexible ones. The rigid bodies are the earth, nacelle, hub, and optional tip brakes (point masses). The flexible bodies include blades, tower, and drive shaft. The model connects these bodies with several degrees of freedom: tower bending, blade bending, nacelle yaw, rotor teeter, rotor speed, and drive shaft torsional flexibility. The flexible tower has two modes of vibration, and the blades have two flapwise modes and one edgewise mode. Flutter is the coupling between blade flap and edge modes of vibration, and it was actually used as a method of overspeed control for a 300 W wind turbine. The blades were constructed from carbon filaments, formed in an injection mold, so the high strength allowed flutter. In all other cases, when a blade enters flutter, it generally will fail within a short time period.

All wind turbines and blades have natural frequencies (modes) of vibration. The models predict the modes, and they can also be found experimentally. So operation, especially constant-rpm operation, needs to avoid the major modes, for example, the natural frequency of guy wires for vertical-axis wind turbines. For constant-rpm operation, the drive train may incorporate a torque damper. Monitoring of acoustic emissions can be used to determine future problems in the drive train, thereby reducing costs by preventive maintenance.

There are various towers for wind turbines—pole, guyed pole, pole or guyed pole with gin pole—so operation and maintenance can be at ground level (Figures 6.18 and 6.19), guyed lattice, lattice, and tube towers. Most towers are made of steel, although concrete has been used and fiberglass is being considered. Primarily lattice towers were used in the early wind farms in California; however, the later, large wind turbines with hub heights from 50 to 100 m used tubular steel towers. So far, the record hub height is a 160 m lattice tower for a 2.5 MW wind turbine, constructed by Fuhrländer.

Towers have to be strong enough to support the weight on the tower top and to resist the movement of the wind forces trying to push the tower over, which during operation at rated power in high winds can be quite large. There are different foundations, and a lot of rebar and concrete are required for the large wind turbines. Examples of foundations are pier and bell (at the bottom) for each leg for lattice towers; different type of anchors, primarily piers for guyed pole towers; and for

FIGURE 6.18 Small wind turbine, 1.8 kW, mounted on 10 m pole tower, no guy wires, with gin pole.

FIGURE 6.19 International Wind Systems, 300 kW, on 49 m pole tower with guy wires and gin pole.

FIGURE 6.20 Placing rebar for pad foundation for 2 MW wind turbine. When finished pad will require 32 metric tons of rebar and 270 m^3 of concrete.

large turbines with tubular towers, foundations are pier, pier with concentric cylinders, or pad on the ground (Figures 6.20 and 6.21). Piers can be drilled with augers in the appropriate ground, not solid rocks. The hole for a pier, 5.5 m in diameter and around 9.5 m deep (Figure 6.22), for a 3 MW wind turbine was drilled with a giant auger. One advantage of concentric cylinders is less concrete, as the inner can is backfilled with dirt. Also, the rods can be stressed after the concrete is poured to obtain a stronger foundation.

FIGURE 6.21 Pad foundation for 2.3 MW wind turbine. Notice the copper wire for grounding.

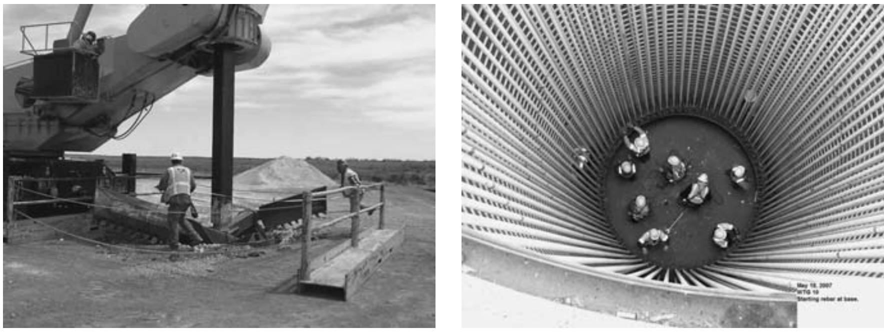


FIGURE 6.22 Pier foundation, concentric cans, for 3 MW wind turbine.

For those wind turbines with downwind rotors, there is a reduction of wind speed due to tower shadow, and there will be a cyclic driving force. One aspect is the generation of noise as the blades pass behind the tower, a repetitive sound. Repetitive sounds are more annoying than the normal chaotic noises generated be the passing wind. For most wind turbines the noise level attenuates to an acceptable level not too far from the wind turbine. However, the MOD-1, a downwind unit, emitted low-frequency sound waves, and under certain atmospheric conditions, the noise was at unacceptable levels at considerable distances from the turbine. It was strong enough to shake the dishes on the shelves of some homes. The solution was to reduce the rotor speed (less power), which required the replacement of the generator.

6.9 EVOLUTION

Since 1970 the design of modern wind turbines evolved from two different ends, utility-scale, large wind turbines and small wind turbines. The large wind turbines were primarily funded by governments, and only prototypes were built and tested, while the small wind turbines were built in large numbers by private manufacturers for the emerging commercial market.

In the United States, NASA–Lewis began with the MOD-O design, a two-blade, downwind turbine, 100–200 kW, which progressed to the design of the MOD 5, a two-blade, 7,000 kW unit. This design was reduced to 3,200 kW, and one prototype was built, which had steel blades with teetered hub, upwind, tip pitch control. The tip pitch control was driven by motors in the blades, which made maintenance a problem. The Hamilton-Standard WTS-4 was a 4,000 kW wind turbine with two blades, downwind, pitch control, and teetered hub.

The Schachle-Bendix wind turbine had an interesting concept: a variable-speed, hydraulic drive in the power train, which was connected to hydraulic drives on the ground to drive the generator. The losses in the hydraulic drive were high, and the unit only reached a power output of 1.1 MW rather than the designed 3 MW. The unit was mounted on a tripod trust tower, which rotated on a track, so the tower was yawed for control.

In Europe several large prototypes were built. In Denmark the wind turbines were the Nibe A and Nibe B, three blades, upwind, 630 kW, fixed-pitch blades for A and variable-pitch blades for B; Tvind, three blades, variable pitch, upwind, 2,000 kW; and Tjaereborg, three blades, upwind, 2,000 kW. In Sweden four 2,000 to 3,000 kW wind turbines were built. One had an angle gear drive to the generator in the top of the tower, so slip rings were not needed for the transfer of power. A second unique feature was a carriage assembly on rails on the side of the tower to raise and lower the entire assembly, nacelle and rotor. In Germany the largest wind turbine was the Growian I, two blades, variable pitch, downwind, 3,000 kW. Other megawatt prototypes were built in Italy, the Netherlands, Spain, and the United Kingdom. The largest VAWT was built in Canada, a 4 MW Darrieus unit.

A table of wind energy systems larger than 500 kW through 1993 lists information on thirty-five units [7, Table 3-2]. Divone describes the evolution of modern wind turbines from 1970 through 1990, with emphasis on description and operational notes of large units [7, Chapter 3].

The other end was the design and construction of wind turbines from 20 to 100 kW for the commercial market. All sorts of different designs were built and sold. In the United States there were two blades, fixed pitch, with teetered hubs, downwind; three blades, fixed pitch, downwind; and three blades, variable pitch, downwind, of which U.S. Windpower installed over 4,000 units in California. In Europe the three-bladed, upwind, constant-rpm, stall control units predominated. The different designs and their evolution through the mid-1980s are clearly shown by data sheets of wind turbines in Europe [46]. The technical data on wind turbines in commercial operation in the United States [7, Appendix C], also through the mid-1980s, include the total number of units installed of a given configuration. With the wind farm market in California and afterwards the wind market in the 1990s in Europe, there was the continuing evolution toward larger wind turbines, and by 2008, the predominant wind turbines were megawatt size, three blades, rigid hub, variable pitch (full-span control), variable- and constant-rpm operation, upwind. So in the evolution of wind turbines, the manufacturers of small wind turbines became the winners over the large prototypes. Surprisingly, U.S. Windpower, the early leader in number of units installed, also built over 300 larger units (300 kW), but was unable to continue in business.

A Vestas, 90 m diameter, 3 MW wind turbine was installed near Gruver, Texas, during the winter (Figure 6.23). For installation, an 800-metric-ton crane was needed, and it took twenty trucks to haul the crane to the site and another ten trucks for the turbine and tower. The weight of the main

FIGURE 6.23 Photos showing different stages of erection of 3 MW wind turbine.

components are nacelle, 70 metric tons; rotor, 41 metric tons; and tower, 160 metric tons. The tower, which is 80 m tall, was composed of four sections on a foundation that required 460 m^3 of concrete, which included a small pad for the transformer.

6.10 SMALL WIND TURBINES

Generally small horizontal-axis wind turbines are kept facing into the wind by a tail. The control mechanism to reduce power in high winds is that the rotor axis is offset from the pivot point, axis of connection to the tower (Figure 6.24). Therefore, there is more force on one side of the rotor than the other, which tries to move the rotor parallel to the wind; however, the wind force on the tail keeps the rotor perpendicular to the wind. For high winds the unequal force on the rotor is greater than the force of the tail; therefore, the rotor moves parallel to the wind. For very small rotors the tail may be fixed, and during medium to high winds with rapid change in direction, sometimes these wind turbines will turn completely around the yaw axis, a 360° revolution. Most of the wind turbines have a hinge for the tail, and for high winds, the rotor moves to a position closer to parallel to the tail, called furling [47–49]. Then when the winds decrease, the tail returns to a position perpendicular to the rotor by a force due to springs or gravity. Dampers, like shock absorbers, can keep this movement from happening too rapidly, both for furling and for restoration to normal operation. The farm windmill uses springs, the length of which is adjustable for the restoring force. One mechanism to use gravity is to have the tail hinge at a slight inclined angle to the vertical plane.

Performance was measured for a 2 kW wind turbine for water pumping for changes in the parameters of the offset of the rotor axis to the yaw axis, length of tail boom, area of tail, and pitch angle [50]. Four different tails and two different yaw axis offsets were tested because the furling behavior was critical to the performance [51]. Overall, nine different configurations were tested, which included two sets of blades with different pitch angles to try to improve the performance at low wind speeds.

The pivot point does not have to be around the vertical axis (yaw); it can also be about a horizontal axis, which would produce vertical furling. The rotor and generator on the North Wind high-reliability turbine had a horizontal pivot for the rotor and generator, a coil spring damper, and the restoring mechanism was gravity. Another horizontal pivot was unique in that the rotor

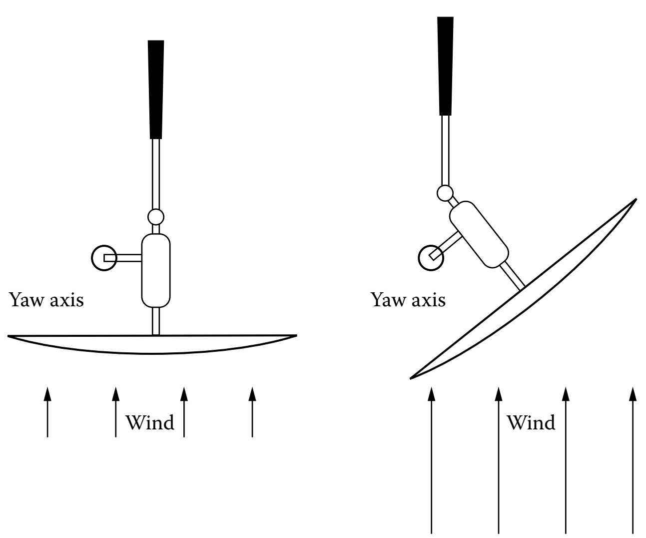


FIGURE 6.24 Diagram of rotor axis offset from yaw axis with hinged tail for furling.

FIGURE 6.25 Rotor axis offset from horizontal pivot point for control.

was downwind and the tail with flat plate and fins hung down (moderate winds to 13 m/s). In high winds the force of the wind on the rotor and also on the flat part of the tail moved the tail and rotor, alternator to the horizontal position, and vertical furling (Figure 6.25). There is no hinge on the tail and the restoring force is gravity.

Small wind turbines are mostly mounted on pole and lattice towers. Very small wind turbines are mounted on almost anything, even on buildings, and of course on sailboats they are mounted on a short pole. A short pole is sometimes referred to as a stub mast.

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   "Drive System Dynamics"
   "Experimental Investigation of a Horizontal Axis Wind Turbine"
   "Nonlinear Response of Wind Turbine Rotor"
   "Effects of Tower Motion of the Dynamic Response of Windmill Rotor"
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PROBLEMS

1. A blade is 12 m long, weight = 500 kg, and the center of mass is at 5 m. What is the torque if the force is 320 Nm?
2. Find the power loss for three struts on a HAWT. Struts are 4 m long, 2.5 cm in diameter. Rotor speed is 180 revolutions per minute. Use numerical approximation by dividing strut into 1 m sections and calculate at midpoint of section. Then add the values for each section. $C_D = 1$.
3. Calculate the power loss for the struts on a VAWT. Center tube, torque tube, diameter = 0.5 m. Struts are at the top and bottom, 2 m long from torque tube to blades, diameter = 5 cm, rotor speed is 80 rpm. $C_D = 1$. Calculate numerically (see problem 2) or use calculus.
4. For those who know calculus, find the value of u (speed of drag device) that produces the maximum C_P for a drag device. Use Equation 6.10, where v_0 is the wind speed at infinity. For those who do not know calculus, find the value of u that produces the maximum C_P for a drag device by plotting the curve (Equation 6.12) for different values of u (between 0 and 1).
5. Aerodynamic efficiency can be maintained for different solidities of the rotor. If solidity increases, will you increase or decrease the tip speed ratio?
6. Explain the difference in performance of a wind turbine if it
   a. Operates at a constant tip speed ratio.
   b. Operates at constant rpm.
7. What is the maximum theoretical efficiency for a wind turbine? What general principles were used to calculate this number?
8. If the solidity of the rotor is very small, for example, a one-bladed rotor, what is the value of the rpm for maximum C_P compared to the same size rotor with higher solidity?
9. For those who know calculus, calculate the value of axial interference factor for which C_P is a maximum for a lift device. Then show that this gives a maximum $C_P = 59\%$.
   For those who do not know calculus, find the value of α that produces the maximum C_P by plotting the curve (Equation 6.20) for different values of α.
10. A rotor reaches maximum C_P at a tip speed ratio of 7. Calculate rotor rpm for four different wind turbines (diameters of 5, 10, 50, and 100 m) at wind speeds of 10, 20, and 30 m/s.
11. A wind turbine that operates at constant rpm will reach maximum efficiency at only one wind speed. What wind speed should be chosen?

For problems 12–18, specifications for a wind turbine are induction generator (rpm = 65), fixed-pitch, rated power = 300 kW, hub height = 50 m, rated wind speed = 18 m/s, tower head weight = 3,091 kg; rotor: two blades, mass of one blade = 500 kg, hub radius = 1.5 m, rotor radius = 12 m.

12. How fast is the tip of the blade moving?
13. How fast is the blade root (at hub radius) moving?
14. Put the mass at the midpoint and calculate the kinetic energy for one blade. Assume the mass of the blade is distributed evenly over ten sections. What is the kinetic energy for one blade?
15. At rated wind speed, calculate the torque since you know power and rpm (remember angular velocity, rad/s).
16. At 10 m/s, what is the thrust (force) on the rotor trying to tip the unit over? Calculate for that wind speed over whole swept area.
17. If the unit produced 800,000 kWh/year, calculate output per rotor swept area.
18. Calculate the annual output per weight on top of tower, kWh/kg.

For problems 19–25, specifications for a wind turbine are induction generator (rpm = 21), variable-pitch, rated power = 1,000 kW, hub height = 60 m, rated wind speed = 13 m/s, tower head weight = 20,000 kg; rotor: three blades, mass of one blade = 3,000 kg, hub radius =1.5 m, rotor radius = 30 m.

19. How fast is the tip of the blade moving?
20. How fast is the blade root (at hub radius) moving?
21. Place the mass at the midpoint of the blade and calculate the kinetic energy for one blade. Assume the mass of the blade is distributed evenly over ten sections. Now what is the kinetic energy for one blade?
22. Calculate the torque at the rated wind speed. You know the power and rpm (remember angular velocity, rad/s).
23. At 15 m/s, what is the thrust (force) on the rotor trying to tip the unit over? Calculate for that wind speed over the whole swept area.
24. If the unit produces 2,800,000 kWh/year, calculate the specific output, annual kWh/rotor area.
25. Calculate the annual output per weight on top of tower, kWh/kg.
26. For a 12 m blade, center of mass at 5 m, weight = 500 kg, calculate the angular momentum if the rotor is operating at 60 rpm.
27. For the blade in problem 26, the angular momentum is around $8 * 10^4$ kg m^2/s. Calculate the torque on the blade at that point if the angular moment of the rotor is stopped in 5 s. Use Equation 6.24. Then estimate the force trying to bend the blade.
28. Why are the blades for large wind turbines made from fiberglass-reinforced plastics?
29. Why are yaw rates limited on large wind turbines or yaw dampers installed on small wind turbines?
30. How does furling work on small wind turbines?
31. For loss of load on small wind turbines connected to the utility grid, how long can it take for overspeed shutdown?
32. For megawatt-size wind turbines, what is the most common configuration?
33. Go to the Proven Energy website for blade design. Make a paper model of the blade to see the principle for passive control.
34. List two methods of nondestructive testing and briefly describe them.

7 Electrical

7.1 FUNDAMENTALS

Electricity and magnetism are concerned with charges and the movement of charges. The fundamental ideas of electricity and magnetism are discussed in introductory physics texts. The following terms are given as a background for generators and controls.

Current: The current is the flow of charge, q (electrons in most cases), past some point. Charge is measured in coulomb. Direct current (DC) is when the flow is in one direction, and alternating current (AC) is when the flow changes direction. The frequency, number of cycles per second, is measured in hertz (Hz).

$$I = \frac{\Delta q}{\Delta t}\text{, ampere (A)} \tag{7.1}$$

For electric utilities in the United States, the voltage and current change sixty times per second, 60 Hz. Other countries use 50 Hz for their utility systems. If the utility voltage or current is plotted versus time, it looks a sine curve (Figure 7.1).

Voltage: It takes energy to move charges around, and the potential energy (PE) to move charge divided by the charge is called the potential difference and is measured in volts. For AC, the voltage also changes with time, just like the current.

$$V = \frac{PE}{q}\text{, volts (V)} \tag{7.2}$$

Resistance: There is a resistance to the flow of charge across different elements in a circuit. A circuit consists of a source (voltage), current through the wires, and a load or resistance.

$$R = \frac{V}{I}\text{, ohm }(\Omega) \tag{7.3}$$

In metals the amount of current is linearly proportional to the voltage, a relationship known as Ohm's law.

$$V = IR \tag{7.4}$$

Also, in metals the resistance increases with temperature, which means more energy is lost as the temperature increases, because of the current.

Power: The power in a circuit is the voltage times the current:

$$P = VI \tag{7.5}$$

The power lost due to heating of the conductor (metals) depends on the square of the current:

$$P = VI = I^2R \tag{7.6}$$

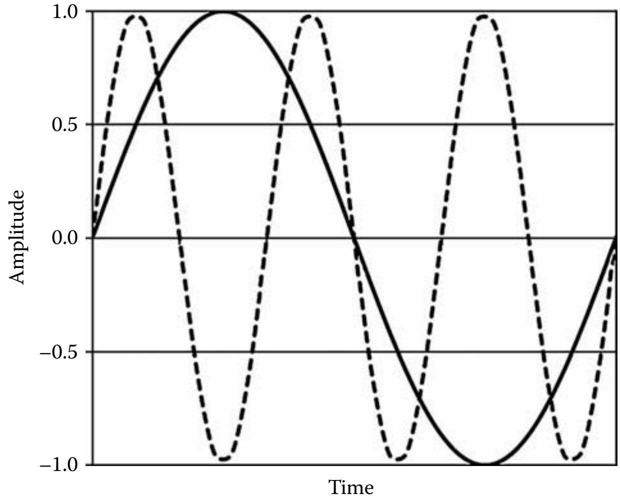


FIGURE 7.1 Two sine waves with different frequencies.

The implications are that electric power needs to be transmitted at high voltages. In the summer time, as air temperature increases, the transmission lines are further limited in the amount of power they can carry. High current and high temperatures also lead to more sag in the transmission lines. Wind turbines with generators at 240 or 480 V need to be fairly close to the load or the utility line. With higher voltages, smaller-diameter wire can be used. Transformers change the voltage, so wind farms will have a transformer with every large turbine to increase the voltage for transmission. The transformer may be at the top in the nacelle, which means the power wires down the tower can be smaller.

Capacitance: Capacitors are devices for storing charge. An example of a capacitor is two metal plates separated by a small distance. Capacitors are not used for long-term storage because the charge leaks away.

Inductance: Inductors are devices for storing magnetic fields. An example of an inductor is a coil of wire.

Electric field: Electric fields, $\boldsymbol{E}$, originate or terminate on charged particles. If a charged particle feels a force, it is in an electric field.

$$\boldsymbol{E} = \frac{\boldsymbol{F}}{q} \tag{7.7}$$

Magnetic field: Magnetic fields, $\boldsymbol{B}$, are due to moving charges or intrinsic spin (a property of particles just like charge is a property of particles). Some materials have a magnet field, and they are called permanent magnets. Permanent magnet alternators use rare earth atoms, which are more expensive than iron, nickel, and cobalt. If a moving charge feels a force at right angles to its motion, it is in a magnetic field. Also, changing electric fields create changing magnetic fields, and changing magnetic fields create changing electric fields. Maxwell formulated the theory of electromagnetism in all of its elegance of four equations, appropriately called Maxwell's equations. This is the theoretical basis for all of the electric power industry and communication by electromagnetic waves, which we accept as commonplace today.

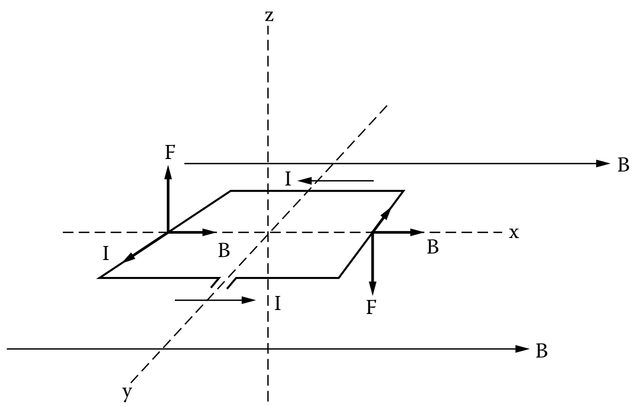


FIGURE 7.2 Forces on the sides of a current-carrying loop in an external magnetic field. The resultant of the set of forces gives a torque, ***T***, which makes the loop rotate, a motor.

If charged particles are placed in external electric fields, and if moving charged particles are placed in external magnetic fields, there is a force on the charged particles. The amount of force depends on the strength of the electric and magnetic fields, the amount of charge, and the velocity of the charge.

$$\boldsymbol{F} = q\boldsymbol{E} + q(\boldsymbol{v} \times \boldsymbol{B}) \tag{7.8}$$

This equation is the basis for understanding the conversion of electric energy to mechanical energy, a motor, and the conversion of mechanical energy to electric energy, a generator.

Motor: A loop of wire has moving charges (current) in it due to a connection to an electric plug. The loop is in an external magnetic field; therefore, there is a force on the charges and a torque on the wire, a motor (Figure 7.2). The torque on the loop is given by the current in the wire, ***I***, the area of the loop, ***A***, and the strength of the magnetic field, ***B***. Now in the motor there is a coil of wire, many loops. Check the links to see how an electric motor works.

$$\boldsymbol{T} = \boldsymbol{I}\,(\boldsymbol{A} \times \boldsymbol{B}) \tag{7.9}$$

Generator: A loop of wire is moved (rotated) by an external force (Figure 7.3). The shaft power, $P = T * \omega$, which in this case comes from the wind turbine rotor, either directly or through a gearbox. The charges (electrons in the wire) are moving in an external magnetic field, and there is a force on the charges, a generator. Of course, there is not just one loop of wire, but many loops in a coil. If there is just one coil, it is a single-phase generator. If there are three coils of wire, then it is three-phase generator.

The external magnetic field can be produced by permanent magnets or electromagnets. A current in a coil produces a magnetic field, and with an iron core in the coil, the magnetic field is stronger. The number of these coils is referred to as poles. So the current from the utility grid or a part of the generator current is used to produce the magnetic fields. Check the links to see how an electric generator works.

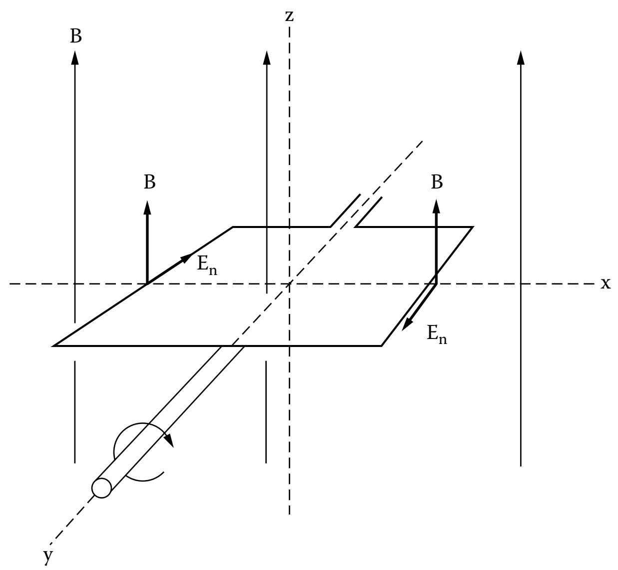


FIGURE 7.3 Rectangular loop rotated by outside force with angular velocity, ω, in a uniform external magnetic field, a generator.

7.1.1 Faraday's Law of Electromagnetic Induction

Another way of looking at electromotive forces is by Faraday's law of electromagnetic induction. The amount of magnetic flux, Φ_M, is equal to the strength of the magnetic field times the area:

$$\Phi_M = \boldsymbol{B} \bullet \boldsymbol{A} = BA\cos(\theta) \tag{7.10}$$

where θ is the angle between $\boldsymbol{B}$ and $\boldsymbol{A}$. The electromotive force is then equal to the negative change in magnetic flux with time:

$$\varepsilon = -\frac{\Delta\Phi}{\Delta t} \tag{7.11}$$

In generators and motors, the magnetic field and area can be kept constant, and the angle between the two changed by rotating a loop of wire. This gives an alternating voltage and current, which vary like a sine wave.

Induction is where you have two coils, where the changing magnetic flux in one coil causes a changing current in the next coil. A transformer works by induction. If the load is pure resistance, then the voltage is in phase (0 phase angle) with the current. For a capacitor the voltage lags the current by 90°, and for an inductor the voltage leads the current by 90° (Figure 7.4). In the figure, all the voltages are set with an angle of zero and the current is then shown in relation to the voltage (starting at a different angle for the sine curve). Check the links for the relation between voltage and current.

7.1.2 Phase Angle and Power Factor

The instantaneous voltage and current are given by

$$v = V_p \sin(\omega t),\ i = I_p \sin(\omega t + \phi)$$

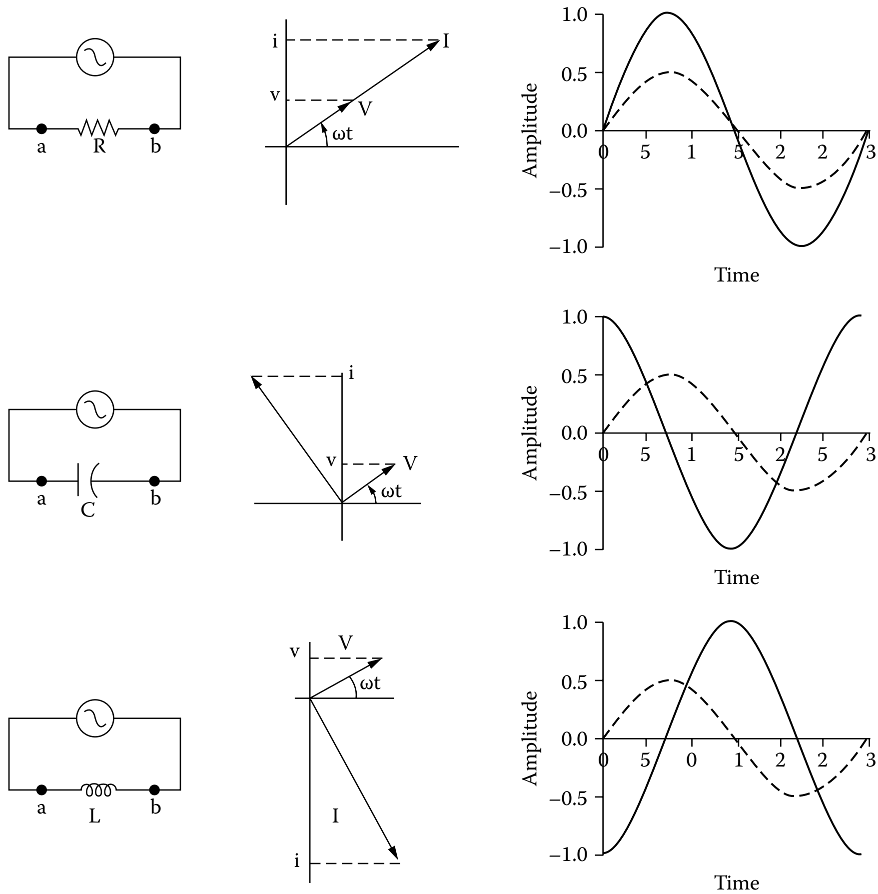


FIGURE 7.4 Current and voltage across a resistor, capacitor, and inductor, showing the phase relationship between the voltage and current. Voltage, dashed line; current, solid line.

where V_p and I_p are the peak values; ω, rad/s, is the angular velocity (which is 2π times the frequency); and the angle, ϕ, is the difference in degrees between the instantaneous voltage and current (the sine wave for voltage and the sine wave for current). For a resistor the voltage and current are in phase and the average power over one cycle is

$$P = V * I = V_p \sin(\omega t) * I_p \sin(\omega t) = 0.5\ V_p I_p \tag{7.12}$$

For capacitors and inductors, the voltage and current are 90° out of phase and the average power is zero:

$$P = V_p \sin(\omega t) * I_p \sin(\omega t + 90) = V_p \sin(\omega t) * I_p \cos(\omega t) = 0$$

In all real circuits there is inductance, capacitance, and resistance, so the current and voltage will not be completely in phase (Figure 7.5). The instantaneous power to an arbitrary AC circuit oscillates because both the voltage and current oscillate:

$$p = vi = V_p \sin(\omega t) * I_p \sin(\omega t + \varphi) \tag{7.13}$$

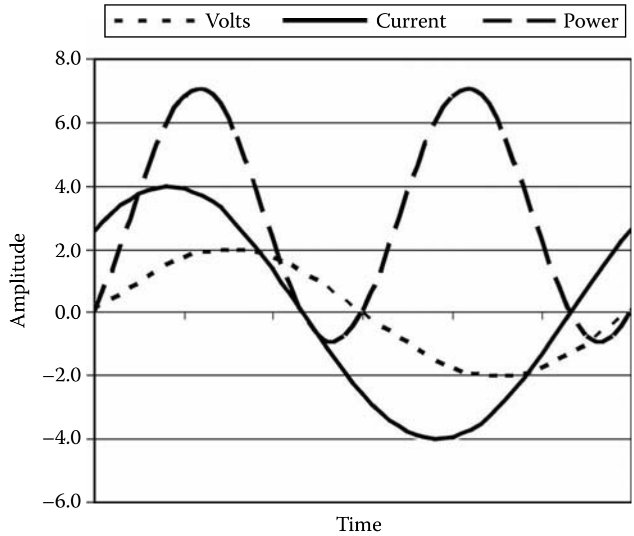


FIGURE 7.5 Instantaneous power in an arbitrary AC circuit.

The average power is found by integrating over one cycle:

$$P_{\text{avg}} = \frac{V_P I_P \cos\phi}{2}$$

However, what is measured for AC circuits are average values of current and voltage, which are given by the root mean square values:

$$V = (v * v)^{0.5} = \{V_p \sin(\omega t) * V_p \sin(\omega t)\}^{0.5} = V_p/2^{0.5} = 0.707\ V_p$$

However, that is for single-phase. For three phases, the measured current is reduced by $3^{0.5}$. So, for a three-phase transfer of power, each leg is transferring a current equal to the (coil current)/1.73, and therefore the wire size needed is smaller. The real power generated or consumed is given by

$$P_{\text{avg}} = V\,I\cos\varphi \tag{7.14}$$

where $\cos\varphi$ is the power factor. Adding a number of induction generators to the utility line can change the power factor and reduce the actual power delivered, a concern of the utility company, since the utility grid supplies the reactive power for the induction generators. Therefore, some wind turbines and most wind plants have capacitors added to the wind turbine or to the electric substation. There are a number of electrical conversion systems for wind turbines [1–8].

7.2 GENERATORS

The main classifications of generators are direct current, synchronous, and asynchronous generators (subdivided into induction generators and permanent magnetic alternators). The operation is constant or variable rpm, and as noted, the constant-rpm operation only reaches maximum power coefficient at one wind speed (Figure 6.13). The variable-rpm operation up to the rated wind speed is along the line of maximum power coefficient (Figure 5.11); however, above that wind speed not all the available power is captured. *Note*: For this chapter, *wind rotor* will refer to the hub and blades, and *rotor* will refer to the rotating part of a generator. The electrical conversion is with constant-wind rotor rpm with squirrel cage induction generators or synchronous generators, or with variable-wind rotor rpm with doubly fed (wound rotor) induction generators, permanent magnet alternators, or direct-drive generators [9]. The variable-frequency output is then converted to constant frequency. So there is a trade-off between wind rotor efficiency and the cost and efficiency of conversion for variable frequency to constant frequency. The AC synchronous generator needs to be regulated to the correct rpm and synchronized with the grid. Induction generators are essentially constant rpm with a small variation, the slip. They are tied to the frequency of the grid as the grid supplies the reactive power for the field coils of the generator.

Rural electric grids may only have one phase, so a wind turbine connected directly to these utility lines would need a single-phase generator. If the wind turbine is connected through an inverter, then the inverter can take care of the phase.

A generator is composed of the armature (coil of wire around metal core) and the field. Power is taken from the armature, and the field, which controls the power, can be permanent magnets or an electromagnet, an energized coil of wire. In the latter case, there are two coils of wire in the generator, with one being stationary (stator) and the other rotating (rotor). In a DC generator, the armature rotates and power is taken off a commutator by brushes. Brushes need maintenance; therefore, alternators are used. In an alternator, the field rotates and the variable AC output is converted to DC by a rectifier circuit, which is then converted into constant voltage and constant frequency by an inverter.

The advantage of the DC generator, permanent magnetic alternator, and doubly fed induction generator is the variable-rpm (constant-C_P) operation, which is aerodynamically more efficient. For small wind turbines (watts to 10 kW, 50 kW under development) the elimination of a speed increaser is another advantage. Jacobs used a direct-drive, self-excited generator where the residual magnetization gives the initial voltage output. Feedback from this is used to increase the field and give more power output. The generator output can be single-phase or three-phase. The Danish Wind Industry Association has a good explanation of types and operation of generators (see "Links" section).

For HAWTS, the power is transferred to ground level through slip rings, or the power cord has enough slack to twist during yaw revolution. The second method has the desirable feature of eliminating the slip rings, always a potential problem for control signals and even for power transfer. However, strict observation schedules on length of the power drop cord or a trip relay for yaw have to be maintained.

A number of wind turbines also use direct drive with a permanent magnet alternator. Output is rectified to DC and then converted to AC by an inverter. Output is 120 or 240 V AC, single- or three-phase, for small wind turbines.

Synchronous generators and self-commutated inverters require a means of disconnect for safety during faults on the utility line because they are power sources. Induction generators at constant-rpm operation drop offline during utility grid faults because the power for the field coils comes from the grid. For small wind turbines, synchronous generators will probably not be acceptable for interface with the grid, primarily due to complications of the control of the wind rotor rpm.

7.2.1 Induction Generator, Constant-RPM Operation

Induction generators (Figure 7.6) are used for wind turbines because induction motors are mass produced, inexpensive, have reduced operation and maintenance costs, and controls are simple. The induction motor/generator is brought up to synchronous speed and is then connected to the utility line. All the features of synchronous generators for control of speed, excitation, and synchronizing are eliminated as the utility line provides this aspect.

The rotor is in the center of a four-pole stator, where magnetic fields of the stator are supplied by the three-phase utility grid. The rotor cage consists of a number of copper or aluminum bars that are

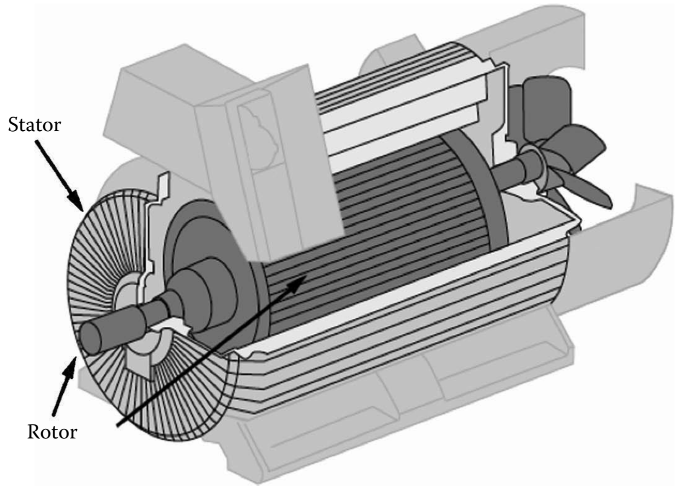


FIGURE 7.6 Cut-away drawing of induction generator.

connected by aluminum end rings. The rotor has an iron core consisting of thin insulated steel laminations with holes for the conducting bars. AC voltages across each pair of terminals create a rotating magnetic field and produce rotation in the center rotor, phase separation of 120° (Figure 7.7).

The rotating magnetic field induces currents in a set of copper loops in the rotor, and magnetic forces on these current loops exert a torque on the rotor and cause it to rotate (as a motor). When it is forced to rotate past the synchronous speed (900, 1,200, or 1,800 rpm), it becomes a generator. The relationships of power, torque, efficiency, and rpm are given in Figure 7.8.

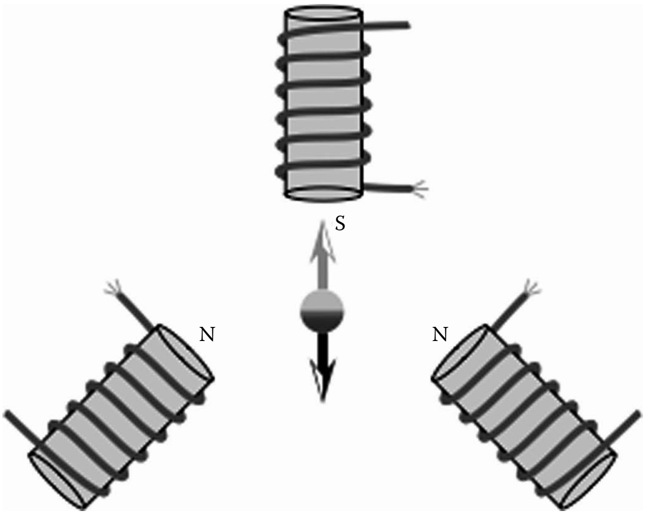
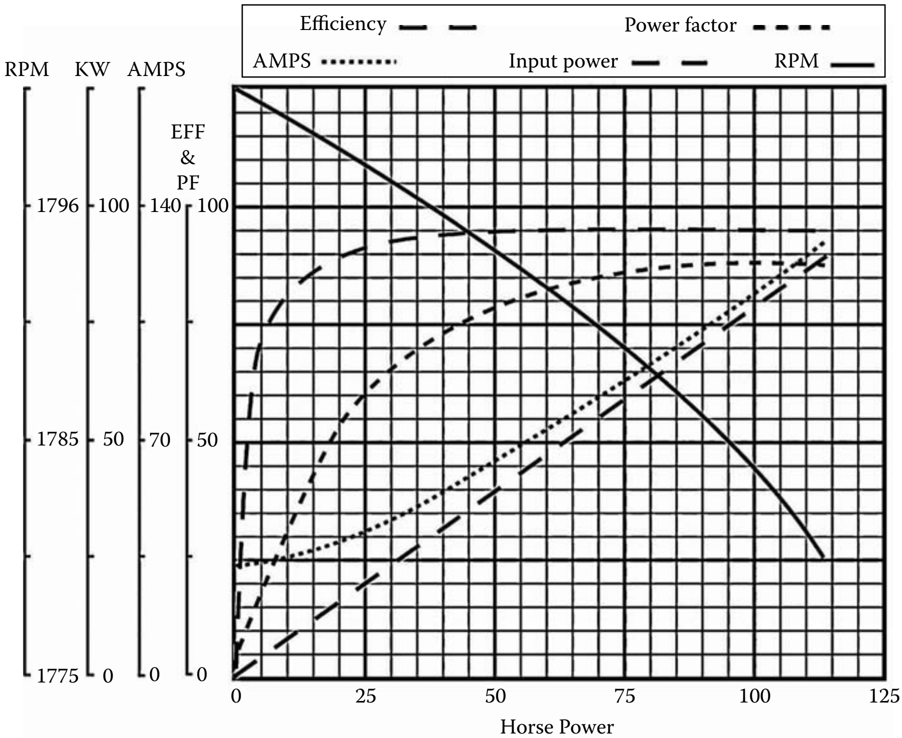


FIGURE 7.7 Schematic drawing of a three-phase AC generator. Rotating magnetic field produces AC voltages across each pair of terminals; phase separation of 120°.



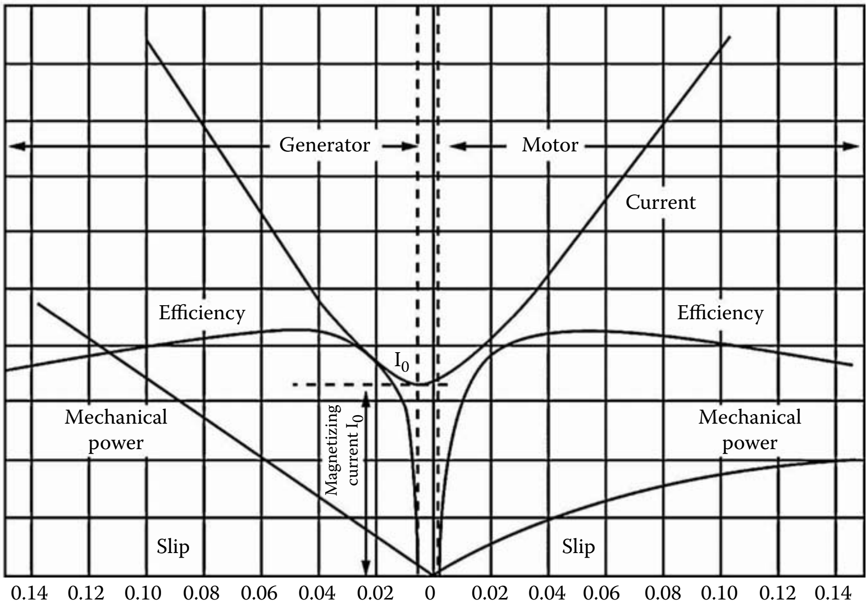


FIGURE 7.8 Operating characteristics of induction motor (420 V, 75 kW). The curves for the induction generator are essentially a mirror image, as shown by the bottom graph.

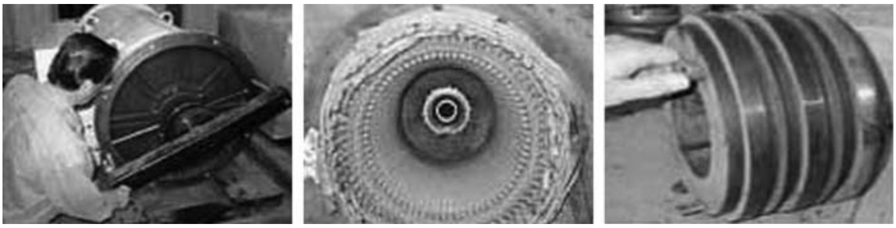


FIGURE 7.9 Induction generator, 750 kW; stator; and slip rings for transferring power. (Photos by Wade Weichmann. With permission.)

Some large wind turbines had two generators, one for low wind speeds and the other for high wind speeds. A common design for newer machines is pole changing, and therefore they are able to run as a small or large generator, for example, 400 or 2,000 kW, at two different rotational speeds. The use of one, two, or pole switching generators depends on the energy produced and the extra cost of each option.

The switching mechanism must not allow the generator to operate below synchronous speed or it would be a gigantic fan. The control mechanism needs to measure rpm, with some leeway for wind speeds at the cut-in value, to turn the generator on and off, and at the high wind speed to cut out and restart the generator after the winds have declined. Some wind turbines use the motor/generator for start-up, as their blades do not have enough starting torque. When the winds become high enough (cut-in wind speed), the blades are turned by the motor/generator, and then as rpm increases due to wind power, and the motor/generator goes past the synchronous speed, it now becomes a generator. The time delay reduces on-off cycling when the winds are just around those cut-in and cut-out wind speeds. There was a case where a small (5 kW) downwind wind turbine would start in the upwind position due to the winds being shifted by 180° from when the turbine shut down. The upwind position is an unstable condition for a downwind rotor with coning. The control system indicated start-up; however, the blades were inefficient in that position and the wind turbine used 2 kW of power—it really was a big fan.

Induction generators (Figure 7.9) are the most common generators for wind turbines from 25 kW to megawatts because the controls for synchronization to the line are simple, and they are rugged and mass produced. When there is a failure on the utility grid, they automatically disconnect and do not present a safety problem. The induction generators decrease the power factor, and correcting capacitors are installed on individual wind turbines or at the wind farm.

It is possible to have a resonance condition with inductance and capacitance; however, the variability of the wind ensures that the induction generator output decreases rapidly when there is a fault on the utility line. Remember, the induction generator is essentially a constant-rpm operation for the rotor, which is fixed by the frequency of the utility grid. The wind rotor/generator combination reaches peak efficiency at only one wind speed.

7.2.2 Doubly Fed Induction Generator, Variable-RPM Operation

There is a gearbox connected to a standard (mostly 1,500 rpm) doubly fed induction generator. The stator is directly connected to the utility grid and the rotor of the generator is connected to a converter. An rpm range of 60 to 110% of the rated rpm is sufficient for good energy production. At wind speeds above the rated wind speed, the blades are pitched to reduce aerodynamic efficiency. Variable blade pitch is also used for start-up, shut down, and overspeed.

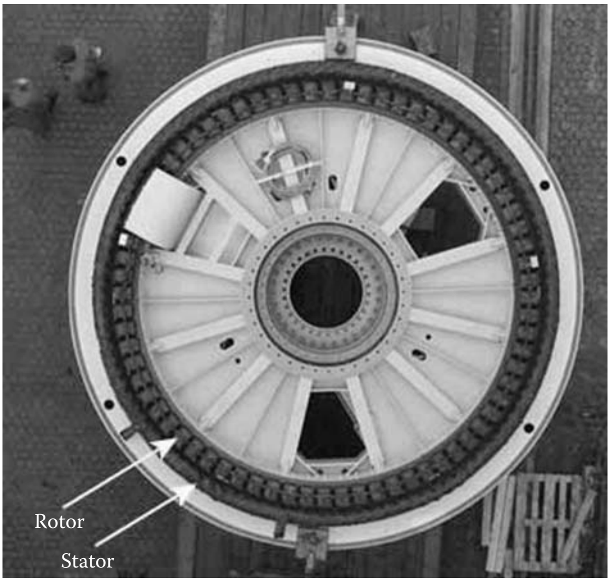


FIGURE 7.10 Ring generator for gearless Enercon, E66. Size can be estimated from the two men in the upper left corner. (Photo by Thomas Schips. With permission.)

7.2.3 Direct-Drive Generator, Variable-RPM Operation

There is no gearbox and the generator operates at the same rpm as the wind rotor, 10 to 25 rpm, for megawatt wind turbines. These generators are very large (Figure 7.10), and the output is converted to constant frequency and voltage by power electronics. Again, control is by pitch of the blades. So here the trade-off is between no gearbox and a large generator with power electronics.

7.2.4 Permanent Magnet Alternator, Variable-RPM Operation

This is also a direct-drive system with no gearbox, and it is common on small wind turbines. The most common control for high winds is by furling using a tail. However, Southwest Wind Power has a downwind unit where electrodynamic braking is used for high winds and shutdown. Some larger permanent magnet alternators are available (500 kW), and General Electric has a 2.5 MW unit. The advantages of permanent magnet excitation are lower losses, lower weight, and lower cost. A disadvantage is that the excitation cannot be controlled.

7.2.5 Generator Comparisons

All the above generators have been used in wind turbines. So there is a trade-off among (1) cost, size, and weight, (2) suitability for grid frequency, (3) blade noise, (4) energy production, (5) reliability and maintenance, (6) power quality, and (7) grid faults [9]. Many manufacturers have changed from constant- to variable-rpm operation because of energy production and smoother power due to inertia of the wind rotor. In the final analysis, the choice for the electric conversion depends on energy produced (annual) and the cost per kilowatt-hour from the wind turbine.

7.2.6 Generator Examples

At rated power, generators are very efficient; however, at low power levels the efficiency decreases. Therefore, some wind turbines have two generators, one for lower wind speeds. The Vestas V47 had a 200 kW and a 660 kW generator. Another way is to switch between number of poles, six poles for low wind speed and four poles for higher wind speeds. The Bonus generator was 260/1300 kW.

The generator for the MOD-5B was rated at 3.2 MW, and was a variable-speed (1,330–1,780) wound-rotor induction generator. A cycloconverter system maintained a constant-frequency output. The Westinghouse, 600 kW, wind turbine had a synchronous generator, and frequency was controlled by the variable pitch of the blades. A power control algorithm limited high instantaneous power output (spikes caused by wind gusts) by derating the maximum power by 10% when a power spike exceeded 800 kW.

Large wind turbines can be operated at variable-rpm, maximum C_P operation. This means low-rpm generators with a large number of poles. Project Eole located at Cap Chat, Canada, was a large VAWT rated at 4 MW. Since this was a direct-drive system, the generator was quite large, 12 m in diameter with 162 poles. The output was rectified to DC and then inverted back to 60 Hz AC. The unit only operated for around 10,000 hours, and power output was limited to 2.5 MW.

Enercon, a German manufacturer, developed large-ring generators to eliminate the gearbox on large wind turbines. The output is rectified and then converted to constant frequency. Over 10,000 units have been installed from 300 kW to megawatt units. In 2007, it built a 6 MW unit, 126 m in diameter (E126).

The Sandia VAWT test bed (34 m diameter, rated at 500 kW), which was located at USDA-ARS, Bushland, Texas, was designed as a variable-speed, constant-frequency system. The system was a load-commutated inverter, AC-adjustable speed drive, with a synchronous motor/generator rated at 625 kW. Such systems are currently operated in industrial applications. Power electronics and inverters allow wind turbines to operate at either constant or variable rpm.

Jay Carter Sr. developed a wind turbine with the same rotor, hub, and drive train, which has two induction generator options: six poles, 30 kW (wind rotor 60 rpm) for medium wind speed regimes, and four poles, 50 kW (wind rotor 90 rpm) for good wind speed regimes (Figure 7.11).

Higher-voltage generators are used in some wind turbines. A Spanish manufacturer developed a geared wind turbine with a brushless synchronous generator and a full converter.

The size of the wires connecting the generator to the grid depends on the current and distance to the connection. For small wind turbines, manufacturers will recommend wire sizes for different wire runs; however, that can be checked against tables (Table 7.1).

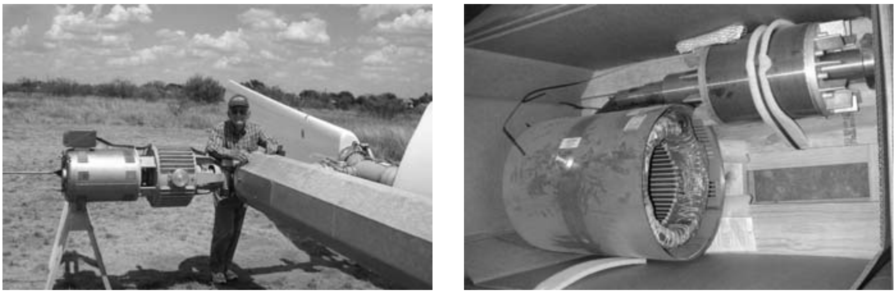


FIGURE 7.11 Left: Generator, gear box, and Jay Carter Sr. Right: Stator and rotor of generator, 50 kW.

TABLE 7.1
Wire size, Copper, 480 V, Three-Phase, 2% Voltage Drop

Load, amps	Type Insulated	Overhead Bare, Covered	30	46	60	76	91	107	122	137	152	168	183
5	12	10	12	12	12	12	12	12	12	12	12	12	12
7	12	10	12	12	12	12	12	12	12	12	10	10	10
10	12	10	12	12	12	12	12	10	10	10	10	8	8
15	12	10	12	12	12	10	10	10	8	8	8	8	6
20	12	10	12	12	10	10	8	8	8	6	6	6	6
25	10	10	12	10	10	8	8	6	6	6	6	4	4
30	10	10	12	10	8	8	6	6	6	6	4	4	4
35	8	10	10	10	8	6	6	6	4	4	4	4	4
40	8	10	10	8	8	6	6	4	4	4	4	3	3
45	6	10	10	8	6	6	6	4	4	4	3	3	2
50	6	10	10	8	6	6	4	4	4	3	3	2	2
60	4	8	8	6	6	4	4	4	3	2	2	2	1
70	4	8	8	6	4	4	4	3	2	2	1	1	1
80	4	6	8	6	4	4	3	2	2	1	1	0	0
90	3	6	6	6	4	3	2	2	1	1	0	0	0
100	3	6	6	4	4	3	2	1	1	0	0	00	00
115	2	4	6	4	3	2	1	1	0	0	00	00	000
130	1	4	6	4	3	2	1	0	0	00	00	000	000
150	0	2	4	3	2	1	0	0	00	00	000	000	4/0
175	00	0	4	3	1	0	0	00	000	000	4/0	4/0	4/0
200	000	00	4	2	1	0	00	000	000	4/0	4/0	250	250
250	250	00	3	1	0	00	000	4/0	4/0	250	250	300	300

Source: From *Agriculture Wiring Handbook*. 3rd Ed, 1993. National Food and Energy Council, Colombia, Missouri.
Note: First column is the current; the next two columns give minimum size of wire to use for type of insulation and for bare wire. With longer wire runs, a larger-diameter wire is needed. The length of the total wire run is in bold, m. Other numbers are size of wire. 4/0 means 0000 size. A smaller number means a larger-diameter wire, and more zeros mean larger-diameter wire. After 4/0, the number is a thousand, circular mills.

7.3 POWER QUALITY

Wind turbines and especially wind farms, which in reality are wind power plants, must provide the power quality [10, 11] to ensure the stability and reliability of the system, which include power quality for other customers on the grid. The four types (Figure 7.12) of connection depend on the electrical conversion, generator, and connection (direct or partial and full converter). Induction generators require reactive power from the grid, and capacitor compensation is often used, at the wind turbine or at the substation. The power output of variable-rpm wind turbines is smoother, less flicker, than constant-rpm wind turbines because rapid changes in the power are smoothed out by rotor inertia. If the converter is large enough, variable-rpm wind turbines can also be used for voltage and frequency control in the grid. Power electronic converters produce harmonics that may need to be filtered.

The voltage at each wind turbine with the wind farm varies independently, and they may be shut down for various faults (see Section 5.6.2) or maintenance. The capacitor compensation may lead to the possibility of harmonics and self-excitation, with the constant-rpm, induction generators [10];

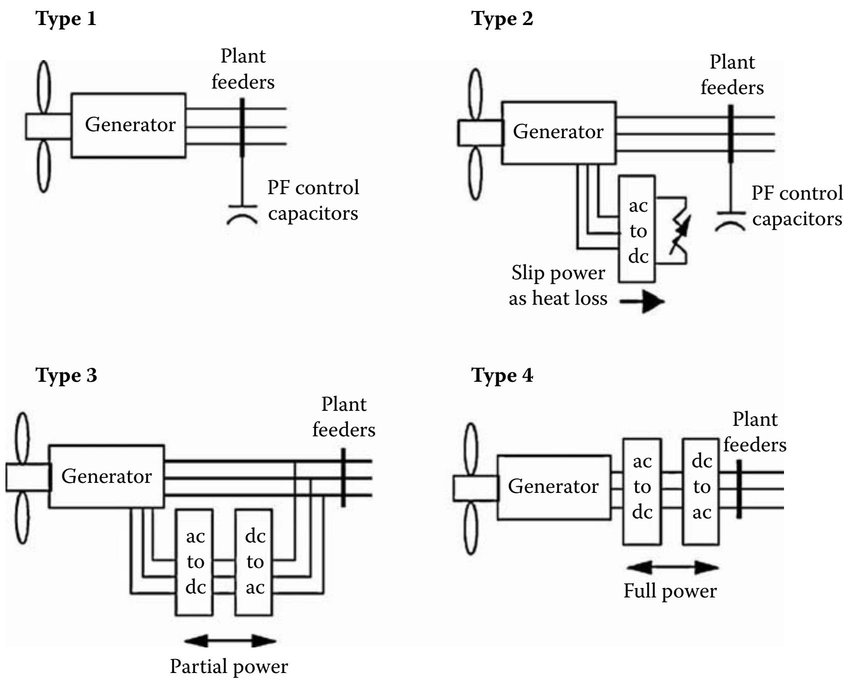


FIGURE 7.12 Four types of dynamic models, wind turbine connection to the grid.

however, the wind speeds are so variable it is improbable for self-excitation to last very long. Fluctuations in voltage and frequency need to be kept within ranges acceptable to the utility at the point of connection to the utility grid (Figure 7.13).

The faults on the utility grid will also cause a reaction from the wind turbines. A wind farm was monitored for 1 year [11], and there were 215 faults. At the monitoring node the voltage drop and spike in current describe the fault (Figure 7.14). The fault events mostly occurred far from the wind farm, and most were cleared within ten cycles. Therefore, voltage ride-through capability of the wind turbines is important. For the doubly fed induction generator, the rotor currents increase very rapidly and should be disconnected from the grid within milliseconds to protect the converter. When constant-rpm wind turbines come back online they need a lot of reactive power, which impedes the voltage restoration.

The loss of generation from the wind farm during fault varies from 0 to 100% of the wind farm capacity. In terms of loss of generation, the benefit of wind power generation is the amount of power

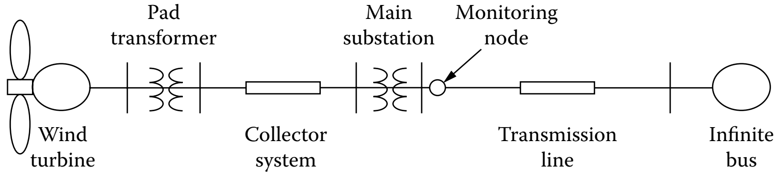


FIGURE 7.13 Typical network topology of a large wind farm.

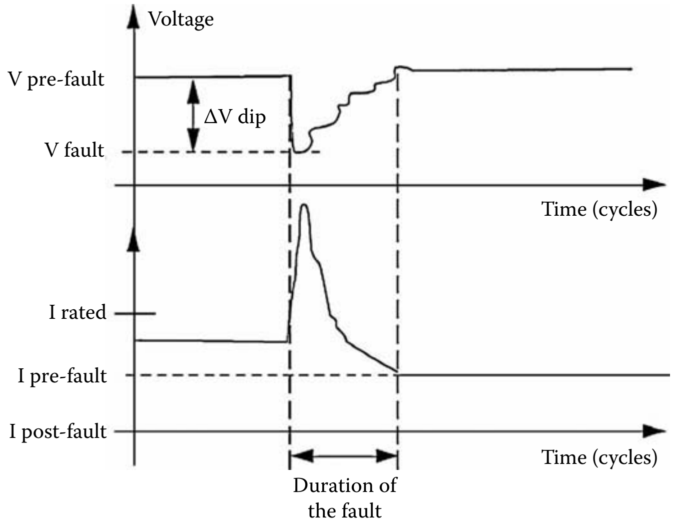


FIGURE 7.14 Illustration of voltage and current connection to wind farm after fault on utility line.

disconnected from the wind farm, as the loss of a single generator in a wind power plant may be less than 1% of the total generation. For the 1 year, only 1% of all the faults caused high power generation losses ($P_{gen} > 0.8\ P_{rated}$). In this type of discussion, many use wind plant rather than wind farm, because it really is a wind-powered electric generation plant.

7.4 ELECTRONICS

Electronics are used extensively in the control of the wind systems, and in general, the controllers contain one or more computer processing units (CPUs) and programmable logic controllers (PLCs), which can be hardwired, for wind turbine control and operation. Control systems run the gamut from simple controls for battery storage to supervisory control and data acquisition (SCADA) for entire wind farms. Electronics for power conversion and control are a major part of any wind turbine system, and solid-state inverters allow variable-frequency output to be connected to the utility grid. Induction generators on constant-rpm units may require a soft start to reduce mechanical stress and to reduce the interaction between the utility grid and the wind turbine during connection.

7.4.1 Controllers

The controller monitors the condition of the wind turbine, may collect statistics on its operation, and controls switches for different operations and functions. The controller contains one or a number of computer processing units.

The most simple is the controller to sense the voltage level of batteries, for both full charge and discharge, which may have light indicators to display that information. As the battery bank voltage approaches the regulation voltage, the wind turbine is furled manually, or the controller could switch power to a regular load or a dump load. If there is no load available, the wind turbine may be brought to a slow rpm. The controller could have an electrical braking mode, which is used for parking the turbine before climbing or lowering the tower to work on the turbine. Equalization of the batteries, which is the process to bring the batteries up to a high rate of charge, needs to be performed once a month. Then the water level should be checked and distilled water added as needed.

Control of the turbine for furling units is accomplished mechanically. If the unit is connected to the grid through an inverter, then the power output of the wind turbine is converted to DC and a disconnect switch is mandatory. Southwest Wind Power has a unique wind turbine where the DC rectifier, controller, and inverter are all inside the nacelle (for photo of unit, see Figure 6.17). The controller regulates an electromagnetic brake for shutdown and to limit rotor rpm in high winds. The connections are the disconnect switch to the grid and a wireless two-way remote to turn the unit on and off. Options are a wireless remote display to observe the performance in real time and collect kilowatt-hour data for day, month, and year. The remote may be connected to a personal computer (PC) for monitoring turbine performance, and software allows the user to obtain a power curve for the wind turbine.

For wind turbines with induction generators connected to the grid, the controller (Figures 7.15 and 7.16) has more sensors and functions, for example, measurement of wind speed and rpm to determine switches for start-up (motor) if needed, connection of the generator, and control for shutdown and overspeed. The controller will also have sensors for faults, any of which will shut down the wind turbine. The controller may provide communication to an external personal computer on site or far away. Additionally, the PC may be able to change the parameters of the controller.

For large wind turbines there are between 100 and 500 parameters to monitor, and there may be two controllers, one in the nacelle and one at the bottom of the tower, which is done with fiber optics on new wind turbines. On some models there is a third controller in the hub for pitch control. CPUs and sensors for safety or operation-sensitive areas are duplicated for redundancy. The controller communicates status and operating conditions of the turbine and provides fault alarms and service requests to the outside world, the owner or operator. Statistics are collected at the computer to provide a baseline for that wind turbine. Finally, for wind farms, supervisory control and data acquisition (SCADA) are part of the control system [12]. Several companies have SCADA systems for wind farms, which can even have different wind turbines. Operational information on each wind turbine is compared to the baseline database to alert wind farm operators of potential problems. At the control room, which could be on site or located at a city or even the headquarters, operators monitor each wind turbine in the wind farm and can turn them on and off. There have been instances of high winds and the transmission lines are full, so output from wind farms had to be curtailed, and wind turbines were shut down within a short period.

FIGURE 7.15 Disconnects and controller for a 50 kW wind turbine.

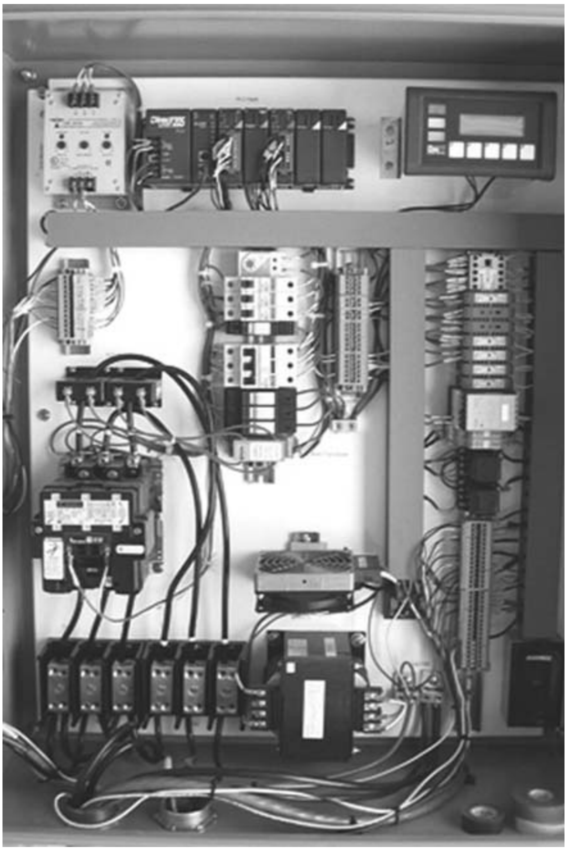


FIGURE 7.16 Controller for 50 kW wind turbine with induction generator, constant-rpm operation.

A management system would integrate the wind farm SCADA, on-site meteorological data, wind forecasting, and market price to enable operators to maximize energy production and the income from that production. Control strategies are proprietary as manufacturers pursue wind turbine operations to maximize energy production within the wind regime and to minimize wear and tear during very high winds.

7.4.2 Power Electronics

Power electronics convert the variable-frequency and voltage power from the generator to the utility grid, constant frequency and voltage within the ranges set by the utility to ensure power quality. Converters are classified by AC to AC without a DC link (output voltages are chopped from input voltages) and by AC to AC with a DC link (input voltages are converted into intermediate DC voltages that are stored and then converted to the output voltages).

An overview presents the types of three-phase AC–AC converters [13]. For large wind turbines, the power electronics allow them to operate more efficiently. For the doubly fed wound induction generator, a common system is where the converter is connected to the rotor of the generator and directly controls currents in the rotor windings so the mechanical and electrical rotor frequencies are decoupled. Only a fraction of the rated generator power passes through the converter, 20–40%. The operational speed range of the generator depends only on the converter rating.

7.4.3 Inverters

There are a number of inverters on the market; however, there are only a few manufacturers of inverters for wind turbines. Inverters need to be designed for the much different inputs of wind turbines, as inverters for PV have less stringent operating requirements. There are inverters for hybrid systems where power is taken from the battery storage. For wind turbines with permanent magnet alternators, the output is rectified to DC and the inverter converts that to the constant voltage and frequency of the grid. Since the wind turbine is controlled mechanically, the inverter controls the electrical aspect, synchronization of phase and power transfer. Some wind systems use battery storage before the inverter, which means a different design for the inverter. The early inverters used short-length, square wave pulses with proper timing on the cycle to input power to the grid. The square wave pulses add harmonics to the output. Later inverters have been improved and have efficiencies over 90% under 75% load with 2% harmonic distortion. At low winds and loads, inverter efficiencies will be less.

The field test of a wind turbine (permanent magnet alternator, three-phase, 10 kW) connected to the grid through an inverter (single-phase, 10 kW) indicated a problem with the inverter in wind speeds of 13 m/s and greater [14]. Less power was delivered because the inverter entered a pause mode, and if the pause mode happens too many times within a certain time period, the inverter quits functioning and has to be reset manually.

The main safety function of the inverter is to disconnect the wind turbine from the utility line when there is a fault on the utility line; otherwise, there would be hot wires, since the wind generator is still operating. There needs to be a disconnect (may be fused) between the wind turbine and the inverter, and a fused disconnect between the inverter and the utility grid.

7.5 LIGHTNING

Lightning is always a problem for electronics, especially for wind turbines connected to the grid, as lighting strikes on the grid will send spikes a long ways. A wind turbine is generally the tallest lightning rod around, so lightning protection, a path to ground, is imperative. Manufacturers' instructions on grounding and number and connection of copper rods (size and length) must be implemented, plus all other measures for lightning protection of controllers and inverters, from varistors to blow-out cans. Even then lightening can still cause problems with damage to controllers, electrical systems, blades, and generators. Apart from lightning current, the induced electromagnetic fields may damage the pitch control systems inside the hub. Damage due to lightning is the most costly repair, as replacement of blades and generators may require a crane.

A 1995 German study estimated that 80% of wind turbine insurance claims paid for damages that were caused by lightning [15]. Mean annual thunderstorm days and lightning flash density show those regions of the United States with the greatest risk from lightning for wind turbines. Lightning was monitored at wind farms in the Turbine Verification Project [16] by collecting data on direct strikes on wind turbines and utility line surges. The estimated average number of strikes per turbine per year ranged from 0.04 for California to 0.43 in Nebraska. The information also includes the cost of the repair [17]. Lightning protection for wind turbines has improved; however, lightning is capricious, and sometimes even the best protection is not sufficient. Blades should have internal lightning conductors running all the way to the tips of the blades. One example of lightning protection added after installation was that due to surges on the utility line damaging the controller. The solution was an underground copper grid, which connected all the guy wires plus the turbine tower.

7.6 RESISTANCE DUMP LOAD

Also, if a wind turbine uses resistive loads for overspeed control, the resistors have to be outside. During loss of load and high winds at the AEI Wind Test Center, the resistors, which were inside the control shed, along with the controller and inverter, became so hot the control shed caught on fire and burned to the ground. Luckily, the fire burned the insulation off the power wires from the wind turbine, and they shorted together and shut the wind turbine down before it was destroyed.

LINKS

ABB, www.ABB.com. Product guide, motors and generators, wind turbine generators.
Basic electricity, www.ent.ohiou.edu/~manhire/basic_ee.html.
Danish Wind Industry Association, www.windpower.org/en/tour.htm. Know-how, guided tour, generators.
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PROBLEMS

1. What is the voltage drop across a 100-ohm resistance if the current is 2 amps?
2. How much power is lost as heat through that resistance?

3. The maximum power rating of the Carter 25 is 30 kW, and it has a single-phase, 240 V generator. What is the maximum current produced? Remember the difference between root mean square values and peak values.
4. What are the peak voltages for 110, 240, and 480 VAC?
5. If the phase angle in a 240 VAC, 20-amp circuit is 20°, how much is the power reduced from maximum power?
6. What does a three-phase generator mean?
7. What is the angular velocity for 60 Hz frequency?
8. The synchronous point on an induction generator is 1,200 rpm. If the generator is rated at 500 kW, what is the shaft torque into that generator?
9. Look at Figure 7.8. At what slip is the efficiency maximized for generator operation?
10. If a 25 kW (rated) wind turbine has a three-phase, 480 V generator, what minimum size wire will be needed for each phase to connect the wind turbine to a load that is 50 m away? Remember, you need to count the length of wire down the tower, 25 m tall. Peak power can be 30 kW. Calculate maximum current and reduce it by a factor of 1.7 since it is a three-phase system. Each leg (wire) of the three-phase system carries 1/3 of the current. Use Table 7.1.
11. A 100 kW, 480 V generator, three-phase, is connected to a transformer within 10 m of the base of a wind turbine. Peak power can be 120 kW. Remember, you need to count the length of wire down the tower, 30 m tall. What minimum size wire is needed for each phase? Calculate current and reduce it by a factor of 1.7, since it is a three-phase system. Each leg of the three-phase system carries part of the current. Use Table 7.1.
12. What is power factor? What affects the value of the power factor for a wind farm?
13. List two advantages and two problems with induction generators, constant rpm, and stall control.
14. List two advantages and two disadvantages with doubly fed induction generators, variable rpm, and pitch control.
15. What happens at the wind farm when there are faults on the utility line?
16. Why are SCADAs used in wind farms?
17. What type of wind turbines use power electronics? Why?
18. List three functions for a wind turbine controller.
19. What is the function of an inverter? What type and size of wind turbines use inverters?
20. Lightning strikes a blade and essentially destroys it. If you have Internet access, use reference 17 and estimate the cost for replacing that blade.

8 Performance

It is important to remember that the load is part of the wind energy conversion system (Figure 8.1). The most common application is the generation of electricity, which is a good match between the characteristics of the rotor and the load. The other major application for wind power is pumping water, which is a poor load match when the rotor is connected to a positive displacement pump (constant torque device). However, the farm windmill is well designed to pump low volumes of water with a positive displacement pump, even though it is inefficient.

Overall, performance of a system is measured by annual energy production and annual average power for that wind regime. Compromises on efficiencies for each component of the system should be combined to maximize annual energy production within the initial costs and the life cycle costs. The last two factors may be opposed, as reducing the initial costs could increase life cycle costs. The comparison will be for wind turbines that generate electricity.

Power curves and power coefficients have been measured experimentally, and peak efficiencies for the system are around 0.40 for vertical-axis wind turbines to 0.50 for horizontal-axis wind turbines (see Figure 6.14). For constant rpm operation, such as an induction generator, the rotor will operate at peak efficiency at only one wind speed (see Figure 6.13). Also, for a variable speed rotor, the efficiency will decrease above rated wind speed as power output is limited to the rated value. To increase generator efficiency, some units have two generators, with one operating at low wind speeds and the other operating at high wind speeds. The Vestas V27 had a 50/225 kW asynchronous generator with synchronous speeds of 750/1,000 rpm. Another possibility to increase generator efficiency is to change the number of poles of the generator between low and high wind speeds. The Mitsubishi, 1 MW rated power, has an induction generator rated at 250/1,000 kW, with wind rotor speeds of 21/14 rpm.

8.1 MEASURES OF PERFORMANCE

Capacity factor: Capacity factor is the average power, which is equivalent to an average efficiency factor.

$$\text{CF} = \text{average power/rated power} \tag{8.1}$$

In general, capacity factors are calculated from the kilowatt-hour produced during a time period, since power = energy/time. The time periods vary; however, the most representative time period would be 1 year, although capacity factors for a month and a quarter have been reported. Capacity factors of 0.3 would be good, 0.4 would be excellent, while those of 0.10 would be too low.

For wind sites and wind farms with class 4 and above winds, annual capacity factors should be 0.35 or greater, and during windy months, the capacity factors can exceed 0.50. Capacity factors are somewhat arbitrary because of the different sized generators for the same rotor diameter. For the month of February 2002, Lake Benton I, Minnesota, reported a capacity factor of 0.49, and Lake Benton II, Minnesota, reported a capacity factor of 0.60. The difference was the wind turbines at Lake Benton II had a larger diameter, more swept area, for the same size generator.

Availability: The availability is the percentage of time the unit is available to operate and is a measure of reliability. For prototypes and early production models, the availabilities were low, 0.50 or even lower. Third-generation models have availabilities of 0.95–0.98. Manufacturers may define availability differently, so be careful in comparing availability of different wind turbines. Reliability and operation and maintenance affect the system performance.

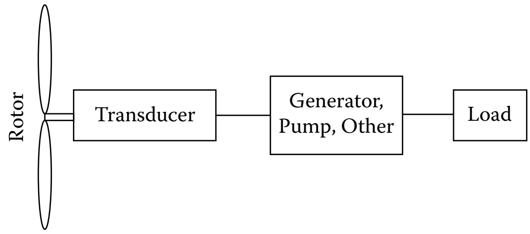

FIGURE 8.1 Schematic diagram of wind energy conversion system.

Connect time: The connect time, or energized hours, is the amount of time or percent of time the unit was actually generating power. In the Texas Panhandle, a typical unit should be generating power around 60% of the time. This is a large number and can be put into perspective by comparing wind turbines to automobiles (a mature industry). Suppose your car went 160,000 km (100,000 miles) with no maintenance. At an average speed of 50 km/h, that is only 3,200 h of operation, which is equivalent to just over a half a year operation for a wind turbine.

Lifetime: Wind turbines are designed for lifetimes of 20–30 years. This can be done within the statistical lifetime for the components [1] and with preventive maintenance. Some components, such as bearings in gearboxes, will have to be replaced within that time period. As noted above, 25 years of operation for a wind turbine would be equivalent to 8,000,000 km for a car, so there will be some major repairs.

Jamie Chapman, who was with U.S. Windpower at the time, made the following statement, "Estimated minimum standards for nonroutine maintenance are one down tower per 5 years and one up tower per year." Down tower means that the nacelle or rotor had to be removed, a major problem. Some first-generation wind turbines had quite a few problems, and those units were replaced within 5 years or dismantled. Others had major retrofits. Some of the early wind farms in California began replacing the 50–100 kW wind turbines with megawatt-size wind turbines, starting in 1998, which is called repowering. The smaller wind turbines were then refurbished for the distributed market.

Design of generators and gear trains is well known. Loads produced by the rotor are the major unknown factor, especially loads due to the turbulent character of the wind, stochastic loads. As the industry matured, engineers designed blades, gearboxes, and generators specifically for wind turbines. Airfoils have been designed for horizontal-axis wind turbines with characteristics to improve overall performance for increased energy production.

Reliability: Most of the first-generation wind turbines [2] suffered from a lack of reliability and quality control. Prototypes generally have failures within the first few months. Lack of reliability means larger maintenance and operation costs after installation. Manufacturers and dealers were caught in a bind, as retrofit programs in the field cost a lot of money. The most successful wind farms are those that have reliable wind turbines and a good operation and maintenance program.

If a dealer has to service a small wind system more than one time during the first year of warranty, he has probably lost money. Typical service charges are $60/h or greater, and a large service area means the dealer is spending most of his time on the road. As the cost of gasoline increases, service charges will increase.

Specific output: The most important factors for determining the annual energy production are the wind regime and the rotor swept area. One way to compare wind turbines is by annual specific output, kWh/m^2. Stoddard [3] tabulated some data for wind turbines in California, where the best values were 1,000 kWh/m^2. This still does not take out the factor of the wind regime; however, if the average of a large number of units is compared for similar locations, it will give a good estimate of performance. The annual kWh/(weight of rotor or weight on top of the tower) gives an idea of the goal for cost comparisons, as for a mature industry, the costs would be based primarily on $/(weight of material). Another specific output is kWh/kW; however, it is not as useful.

The wind turbines manufactured in Denmark were more massive and captured over 50% of the California wind farm market from 1982 to 1985. This was due to their more rugged construction, and they were more reliable. However, after 5 years, a major problem developed with deterioration of fiberglass-reinforced plastic (FRP) blades at the root due to fatigue. The repair and replacement market for blades was estimated at $80 million.

8.2 WINDSTATS

WindStats Newsletter [4] contains reports and wind energy production tables on thousands of wind turbines: ID, manufacturer, kilowatt rating, swept area, tower height, estimated annual energy production, monthly and quarterly energy production, quarterly capacity factor, specific output (kWh/m^2 and kWh/kW), annual production for the previous 1 or 2 years, and date installed. In addition for Denmark, there is information on reliability. The information for wind turbines in Denmark is available online. The quarterly reports of the California Energy Commission and the monthly values in the WINDSTATS provide better information on load matching to utilities.

8.3 WIND FARM PERFORMANCE

Capacity factors have improved with the newer and larger wind turbines, so it is expected that wind farms installed from 2000 on will have better capacity factors than the older installations The early wind farms in California had average capacity factors below 20%, while wind farms in good to excellent wind regimes with new wind turbines should have capacity factors from 35 to 40%. Availability and capacity factor are related, because if the wind turbines are having operational problems, availability and capacity factors will be low. For example, for the first year, there were problems at Horns Rev, an offshore wind farm in Denmark, so the capacity factor was only 26%; however, the next year it reached the expected value. At the offshore wind farm Scroby Sands (thirty wind turbines, 60 MW) in the United Kingdom, energy production was limited in the first year of operation. There were numerous mechanical problems, with 27 intermediate-speed and 12 high-speed gearbox bearings replaced, along with four generators. So the capacity factor for the first year was 29%, rather than the predicted 40%. Another example is a 38-turbine, 80 MW wind farm where there were software problems and then blade problems. One year after installation thirteen turbines were still not operational. All were expected to be operational in the second year.

8.3.1 California Wind Farms

The California Energy Commission (CEC) instituted a program in 1984 for Wind Performance Reporting System regulations [5]. All California wind projects greater than 100 kW that sell electricity to a power purchaser have to report quarterly performance. The quarterly reports contain the following information: turbine manufacturers, model numbers, rotor diameters and kilowatter ratings, number of cumulative and new turbines installed, the projected output per turbine, the output for each turbine model, and the output for the entire project. The annual report is a compilation of data from the four quarters and contains summary tables reflecting resource areas. The reports do not provide information on every wind energy project in California, as nonoperating wind projects and those turbines that do not produce electricity for sale, such as those installed by utilities, government organizations, and research facilities, do not file reports. Wind performance report summaries are available from 1985 [5].

Only small wind turbines, diameter of 10 to 18 m, 25 to 100 kW, were available in the early 1980s. At the end of 1985, the largest installed capacity was U.S. Windpower, 181 MW, followed by Fayette, 146 MW. The wind farms produced 0.65 TWh, which was 45% of that predicted by the plant operators. Average capacity factor was 13%, which was much lower than the 20–30% reported in technical reports. Foreign wind turbines, which were newer, had a capacity factor of 17%. The ten largest manufacturers had 80% of the installed capacity, and four of those had 53% of the installed capacity. The average installed cost of the 10,900 wind turbines was $2,000/kW, with a range of $700 to $2,300.

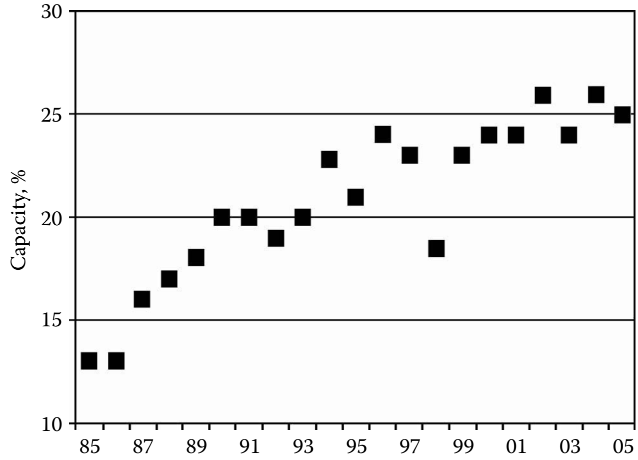

FIGURE 8.2 Average capacity factor for wind turbines in California, wind farms. (Data from California Energy Commission.)

By 1990 there were 1,500 MW installed in California, and they produced 2.68 TWh, enough to power the residential needs of San Francisco [5]. Kenetech, formerly U.S. Windpower, still had the largest number of units and largest installed capacity. The size of the wind turbines increased from 100 kW to 750 kW. In 2008, California wind farms were producing over 4 TWh/year, around 1.5% of the total electric production, and the size of new wind turbines had increased to megawatts.

The annual capacity factor is an average from operational wind turbines (Figure 8.2). In 1990, the better projects had capacity factors in the twenties, and for the third quarter, Kenetech had a value of 40% and Bonus had a value of 39%. An example of the problem with capacity factor is demonstrated by Fayette, which at one time had the second largest installed capacity; however, the capacity factor for Fayette was very low, 5%, as these turbines were overrated (90 kW, 10 m diameter). The vertical-axis wind turbines of Flowind also had a low capacity factor, 10%. The annual capacity factor increased to 30% with the new, larger wind turbines (Figure 8.3). The specific output, kWh/m^2, varied from low values to over 1,000 kWh/m^2 (Table 8.1).

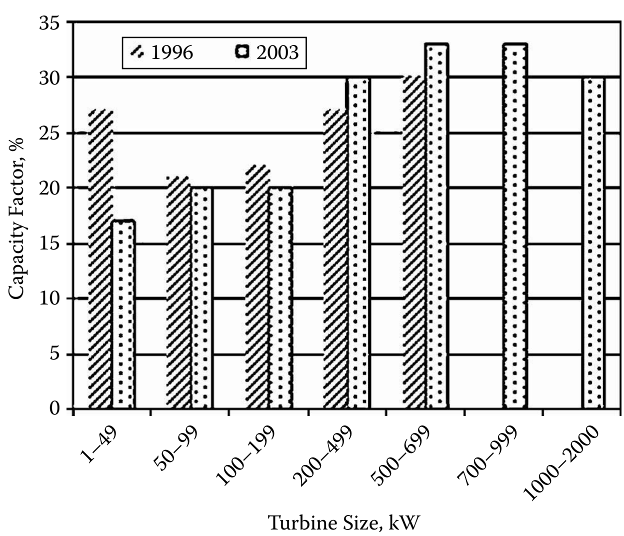

FIGURE 8.3 Capacity factor by range of wind turbine sizes, California.

TABLE 8.1
Specific Output, kWh/m² for Wind Turbines (Most, but Not All Manufacturers) in California, 1989

Turbine	Diameter m	Rated kW	No. Units	Capacity MW	Per Turbine kWh	Per Turbine kWh/m²
Fayette	10	90	1,363	123	41,000	522
Bonus 65	15	65	644	42	113,000	640
Vestas 15	15	65	1,330	86	53,000	300
Micon 60	16	60	531	32	95,000	473
Nordtank 60	16	60	152	9	170,000	846
Micon 65	16	65	126	8	184,000	916
Nordtank 150	16	65	375	24	100,000	498
Vestas 17	17	100	1,071	107	145,000	639
U.S. Windpower	18	100	3,419	342	220,000	865
Micon 108	20	108	967	104	230,000	732
Bonus 120	20	120	316	38	276,000	879
Carter 250	21	250	24	6	250,000	722
Nordtank 150	21	150	164	25	240,000	693
Flowind 19	21	250	200	50	142,000	410
Danwin 23	23	160	151	24	390,000	939
Vestas 23	25	200	20	4	434,000	885
WEG MS2	25	250	20	5	560,000	1,141
Mitsubishi	25	250	360	90	486,000	991
DWT 400[a]	35	400	35	14	1,000,000	1,040
					Average	756

[a] *Estimated kilowatt-hour.*

In the 1990s, the older wind turbines, primarily in the range of 50–100 kW (55% of the MW capacity installed), were being cannibalized for parts and uneconomic wind turbines were dismantled. The following trends are noted: wind turbines became larger (now megawatts), capacity factors were better, and reliability increased. Also, the drop in production in 1997 was due to older, smaller units being taken out of production and then replaced with bigger turbines in 1998.

As the poor-performing units were taken out of service and newer wind turbines installed, specific output (Figure 8.4) increased. The larger specific output shows the type of performance that can be expected with good wind turbines in an excellent wind regime. For both annual capacity factor and specific output, for the same turbines, there will be annual variations by year due to difference in the yearly wind regime and between locations, as wind is site specific.

8.3.2 Other Wind Farms in the United States

Wind farms generated an estimated 26.3 TWh in 2006, and some capacity factors were over 40% [6]. The capacity factor (Figure 8.5) and specific output (Figure 8.6) were analyzed for four wind farms (Table 8.2) in the Southern High Plains, same wind turbine, but with smaller rotor diameter and hub height for White Deer and part of Fluvana. Capacity factors ranged from 33% to 45%, and the largest annual specific output was 1,350 kWh/m². The yearly variation is the same across the region; however, the slight downtrend in capacity factor at White Deer may be due to a decline in reliability. Manufacturers are now offering wind turbines with different sized rotors for different wind regimes. For Texas, estimated energy output would improve with an increase of the wind turbine rotor diameter by 8%, rather than increasing hub height from 75 m to 100 m.

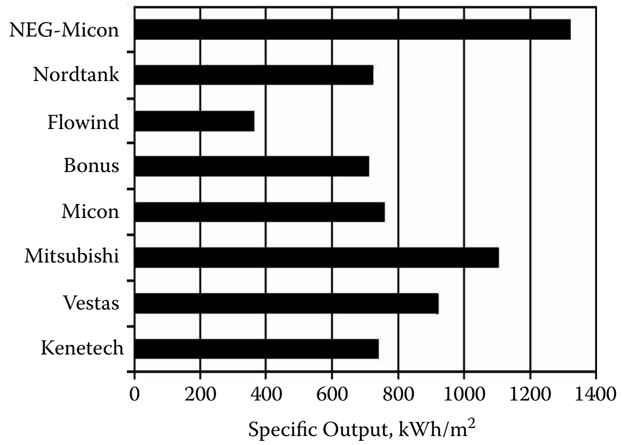

FIGURE 8.4 Specific output for manufacturers with largest installed capacity, California. NEG-Micon wind turbines are larger and do not include the older Micon units, range of 100 kW size.

Wind farms in the Turbine Verification Program had to provide public data on performance through the Electric Power Research Institute. The 12 Zond turbines near Fort Davis, Texas, had a capacity factor of 0.16 and a specific output of 568 kWh/m^2 over 3 years. These turbines were rated at 500 kW and had aileron control. Eleven Zond turbines with full-span pitch control near Searsburg, Vermont, had a capacity factor of 0.25 and specific output of 884 kWh/m^2 over 2 years. Part of the difference was due to the control method and the other due to the difference in the wind regimes.

8.3.3 Other Countries

In Denmark, the total installed capacity and number of turbines increased through 2002. During 2001 through 2003, 1,300 small wind turbines and those with poor siting were replaced with larger wind turbines, so the installed capacity still increased until 2003, and then leveled off at 3,130 MW,

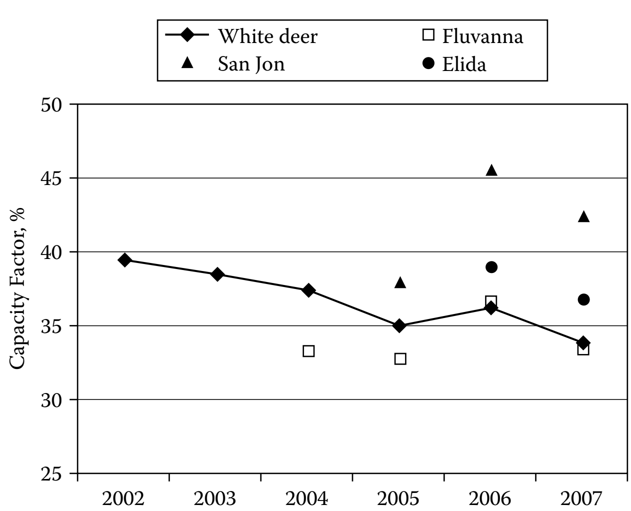

FIGURE 8.5 Annual capacity factor for wind farms in Texas and New Mexico.

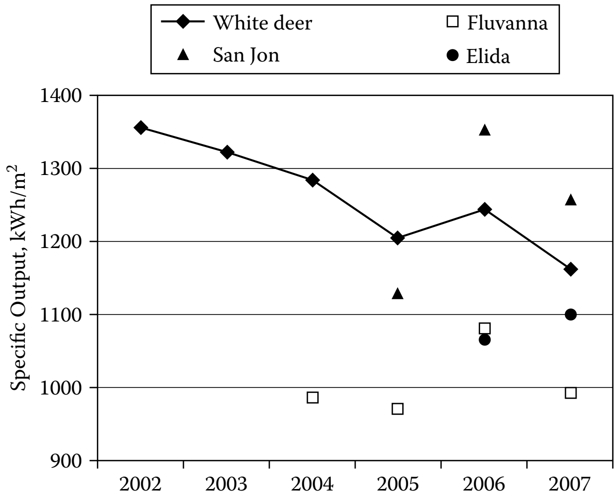

FIGURE 8.6 Annual specific output for wind farms in Texas and New Mexico.

but the number of turbines decreased from 6,400 to 5,267 (January 2007). This meant the average power per wind turbine increased from 1 MW to around 2 MW, which included the large wind turbines installed offshore. During the second stage, when offshore wind turbines are installed in 2009–2010, it is expected that wind energy will supply 25% of the electric consumption in Denmark. The average capacity factor was 25%, while the offshore wind farms in Denmark have capacity factors of 40–45%.

At the end of 2007, as in previous years, Germany had the largest installed capacity in the world. The 19,460 wind turbines (capacity, 22,247 MW) produced 39.5 TWh, which was over 7% of Germany's electricity consumption. From the energy production and installed capacity, the average capacity factor was 20.4%.

Some average capacity factors for other countries are for 2005, United Kingdom, 28%, and for 2006, Sweden, 19%, and Spain, 25%. Wind farms in Northern Ireland and Scotland have average capacity factors of 38–40%. The average capacity factor for New Zealand wind farms (322 MW) in 2006 was 41%.

The performance of the first year for the Nysted offshore wind farm was a wind turbine availability of 97% and a wind farm availability of 96% [7]. The energy production of around 50 GWh/month was within the predictions for the wind regime for the first half of 2004. The monitoring system noticed increased vibration levels in the gearboxes. As the gearbox was designed for easy

TABLE 8.2
Wind Farm Location, Installed Capacity for the Same Manufacturer, Mitsubishi, 1 MW

Location City	Wind Farm	Capacity MW	Rotor Diameter m	Hub Height m
White Deer, TX	Llano Estacado	80	56	60
Fluvana, TX	Green Mt., Brazos	60	56	60
		100	61.4	69
San Jon, NM	Caprock	80	61.4	69
Elida, NM	San Juan Mesa	120	61.4	69

change of the gears, two gearbox bearings were replaced in all the wind turbines. The nacelle crane was used, and average downtime was 48 h per turbine.

8.4 WAKE EFFECTS

The wake is expanding and the wind speed is reduced downwind, so if there are multiple wind turbines, how far apart should they be placed? Also, vortices are generated from the tips of blades, trailing edges of blades, and by the tower, and they increase the turbulence of the wake. So tips of airfoils and trailing edges are designed to reduce the vortices and to reduce the noise accompanying some vortices. The three primary methods of wake and array loss research have been numerical modeling, wind tunnel simulations, and field measurement. A database of literature on wind turbine wakes and wake effects through 1990 is available [8].

The wakes from wind turbines create turbulence and, along with the wind speed deficit, result in array losses, which are reflected in reduced annual energy production. Therefore, the placement of wind turbines in a wind farm is a trade-off between energy production and cost of installation. There will be reduced energy produced by downwind units, so the question is how much reduction for what spacing (within a row and between rows). In fairly flat areas, the rows will be placed perpendicular to the predominant wind direction, and within row spacing is two to four rotor diameters, and between row spacing is five to ten rotor diameters. Offshore wind farms generally have larger spacing; for example, Horns Rev in the North Sea off the coast of Denmark has a seven-rotor diameter spacing (within row and between rows). The physical factors controlling wake interference are downwind spacing, power extracted by the wind turbines, turbulence intensity, and atmospheric stability. Wind turbine wakes develop according to fairly well-defined regions at different downwind distances, and wake geometry models show this information [9]. Field tests on single and multiple wind turbines measured the velocity and power deficit downwind. The wake effects are still noticeable at ten rotor diameters downwind from a rotor. Wind turbines had close spacing between rows at wind farms in San Gorgonia Pass, California, due to the high cost of land, and energy production was reduced for the second row and even more for the third row, as it had the wake effects from both the first and the second row. Field measurements of wake effects inside of wind farms have generally been limited to two to four rows of wind turbines. Energy deficits of 10–15% in row 2 and 30–40% in row 3 have been reported for densely packed wind farms. Measurements of wake deficits downwind of large arrays indicate that the losses may be larger and extend farther downwind than expected. Energy deficits of 15% were estimated at 5 km downwind from a 50 MW array [10]. Early wind turbines were small, 25–100 kW, and later some larger wind turbines on taller towers were interspaced within a row.

It is more difficult to predict output and array losses without an extensive wind measurement program within the wind farm. There is an exception, and that is for offshore wind farms, as ocean waves provide data on wind speeds at 10 m height determined from satellite data (see Section 4.4). High-resolution data are used to estimate the wind resource of the Danish Seas. There has been some comparison of those data with met tower data taken offshore. Ocean wind maps covering the Horns Rev wind farm (400 m grid cells) in the North Sea and the Nysted wind farm (1.6 km grid cells) in the Baltic Sea were used to quantify the wake effect [11]. The Horns Rev wind farm has eighty turbines (80 m diameter, 2 MW) with an 8 by 10 array and a distance of 560 m between the turbines (7D spacing). The Nysted wind farm has seventy-two turbines (82.4 m diameter, 2.3 MW) with a 9 by 8 array, and the distance between turbines within a row is 480 m and between rows is 850 m (5.8D by 10.3D). The velocity deficit is around 10% at 0 to 3 km downwind, and the wind recovers to 2% of the upstream values at around 5 to 20 km downstream, which depends on the ambient wind speed, atmospheric stability, and the number of operating turbines [12]. The recovery is faster for unstable than for near-neutral conditions. In calm winds the turbines are clearly visible in the ocean wind speed maps.

The influence of wake effects on energy production [13] was estimated using data from met towers at the northwest and east of the Horns Rev wind farm and from the SCADA database, which contains all observed data for each wind turbine. For the majority of selected cases, the wind turbines were operating at high wind speeds. An analytical model links the small-scale and large-scale features of the flow in the wind farm with equidistant space between units within a row and equidistant space between rows. For wind perpendicular to the row, there is a large power drop between row 1 and 2 (around 30%), and then there is less power drop between subsequent rows, which is almost linear. From row 2 to row 9 the power drop is around 10–15%. For winds along the diagonal, the spacing is 9.3D; however, this gives only three lines with eight turbines. At wind speeds of 9–10 m/s there is a large power drop (25–35%) from line 1 to line 2, a slight drop in power from line 2 to line 5, and then essentially a constant drop from line 5 to line 8.

In the final analysis of performance, the issues are energy production, the return on investment, and the value of that energy, which should include externalities. Capacity factors give an indication about the wind regime and the relation between rotor area and generator size. However, the main measures of performance should be annual energy production and average specific output, kWh/m^2, per turbine type and model. Wind class should also be included as a check on comparison of performance of wind turbines.

8.5 ENERTECH 44

A long-term performance test of an Enertech 44 [14] provided monthly values of energy production, connect time, availability, and wind speed. The variation of power by month and year is shown in Figure 8.7. Connect time, which is the time the unit is connected to the grid, is around 60% (Table 8.3), or over 5,000 h per year. From 1989 to 1996, when the unit was rated at 40 kW, it averaged 78,000 kWh/year.

The prototype wind turbine (induction generator, constant rpm, stall control) was installed at the USDA-ARS, Bushland, Texas, in May 1982. All three models had the same size rotor, 13.4 m diameter. The original turbine was a 240 V, single-phase induction generator, rated capacity of 25 kW. The gearbox and generator were changed to a three-phase, 480 V, 40 kW induction generator (Table 8.4) in 1984, and later that year, a gearbox and a three-phase, 480 V, 60 kW induction generator were installed. In July 1988 the gearbox was replaced with the previous 40 kW gearbox, making the rated power closer to 50 kW.

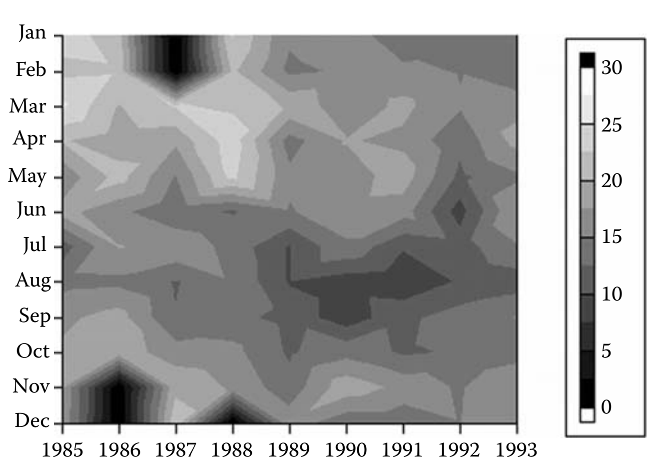

FIGURE 8.7 Average power (kW, legend on right) by month for Enertech 44.

TABLE 8.3
Enertech 44 Wind Turbine, Fixed Pitch, Induction Generator

Year	Operating Time h	Connect Time %	Energy kWh	Capacity Factor %	Availability %	Wind Speed m/s	Rated Power kW
82	3,218	63.0	48,092	40	99.9	5.7	25
83	5,567	63.6	63,710	29	92.6	6.0	
84	4,611	52.6	72,295		86.3	5.9	40
85	4,662	55.5	91,732	17	94.9	5.6	60
86	4,121	47.1	77,522	15	82.1	5.7	
87	3,850	44.0	65,638	12	81.0	5.6	
88	3,971	45.3	71,643		77.0	5.6	40[a]
89	5,893	67.3	83,452	19	99.4	5.3	
90	5,831	66.6	86,592	20	97.5	5.6	
91	5,705	65.1	82,390	19	96.6	5.9	
92	5,641	64.6	73,510	17	98.0	5.4	
93	5,754	65.9	88,363	17	96.4	5.7	
94	5,769	66.4	79,392	18	95.7	5.6	
95	4,099	46.8	51,931	12	72.8	5.7	
96	4,991	56.8	76,470	17	86.8	5.8	
97	4,608	52.6	56,958	13	75.4	5.5	Hybrid
98	4,944	56.4	68,885	16	93.2	5.5	
99	4,487	51.2	65,147	15	93.3	5.7	
00	4,241	48.3	66,589	15	85.3	5.7	
					Average	5.7	

Note: Data for 1982 is not a full year. Wind speed at 10 m height.
[a] *60 kW generator, 40 kW gearbox.*

TABLE 8.4
Performance, Enertech 44/40 kW, 44/60 kW, Bushland, Texas, April 1984–September 1986 (Anemometer at 10 m)

Date 44/40	No. Days	Operating Time h	Connect Time %	Energy kWh	Availability %	Average Speed m/s
3/20/84–4/01/84					Shakedown	
4/02/84–4/30/84	29	571	82	11,148	100	7.4
May	31	568	76	9,078	99.7	6.4
June	30	511	71	8,281	100	6.3
July	31	430	58	5,017	100	5.0
August	31	302	41	2,443	99.7	4.1
September	30	461	64	7,240	100	5.8
October	31	412	55	6,260	100	5.3
Summary	213	3,254	64	49,467	100	5.8
44/60						
11/17/84–11/30/84	17				Shakedown	
December	31	366	49	7,877	87.3	5.6
1985	365	4,897	56	91,732	94.9	5.7
January–September 1986	273	3,824	58	72,905	100	5.8
Summary	686	9,087	57	172,514	97	5.7

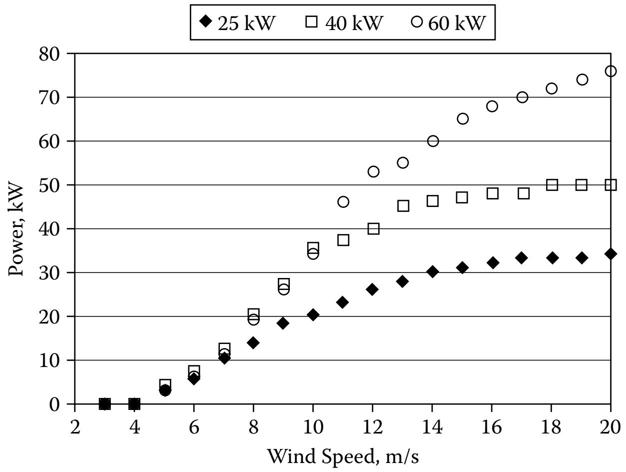

FIGURE 8.8 Power curves for Enertech 44 with different sized generators.

The availability was good, even though it was a prototype unit and there were several component failures. The downtime was estimated at 1% for routine maintenance and service, 1% for repair of component failures, and 1% for weather-related events, mainly icing. The other downtime was for replacing gears in the gearbox and installing different generators. Notice that 1992 was a low year for wind power. The unit was down over 2 months as a yaw bearing was replaced in 1995, down for 1.5 months for a major oil leak in 1996, and down for 2.5 months as a soft start was installed to reduce the loads on the motor/generator. After that the unit was connected part of the time to a wind-diesel test bed (a village grid), so it would not have the same connect time and energy production. The unit was down 0.5 month in 1999 due to control failure due to lightning. A report on the reliability is available from USDA-ARS, which includes causes for all downtimes for 20 years of operation. The unit is still in operation as of 2008.

With the small generator, the capacity factor is higher, but the annual energy production is better with the larger-sized generators. However, the energy differences between the 40 and 60 kW generators were not significant. The power curves (Figure 8.8) include all efficiencies, from wind to electric output. The same information is presented by the power coefficient curves (Figure 8.9).

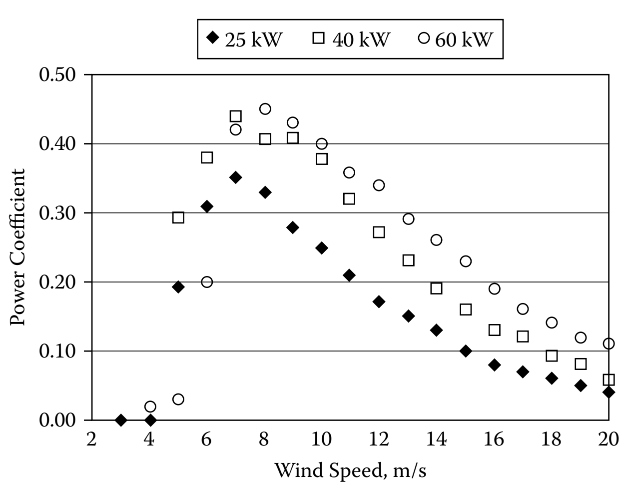

FIGURE 8.9 Power coefficient curves for Enertech 44 with different size generators.

In other words, there are not enough winds above 12 m/s for the larger generator to offset the differences in generator efficiency at lower wind speeds, and also, there would be increased cost for a larger generator and gearbox.

8.6 BERGEY XCEL

A Bergey Xcel wind turbine was installed at the AEI Wind Test Center in August 1991 and is still operating in 2008. The specifications are three-phase, 240 V, permanent magnet alternator, rated at 10 kW. The variable voltage, variable frequency is converted to DC, which is then inverted to 60 Hz for connection to the utility line. Power and wind speed were sampled at 1 Hz and then averaged over 15 min. This time sequence data were then averaged over 1 month for each 15 min period to give an average day for the month. As expected, the power (Figure 8.10) varied widely by season and time of day. From these data it is noted that spring 1992 was a below-average wind period.

Power curves indicate performance, and when compared to the manufacturer's curve, the measured power curve (Figure 8.11) at the site was lower, even when corrected to standard density [15]. This means that the energy production would be lower than that predicted from the manufacturer's power curve. Part of that is due to the efficiency of the inverter, especially at high wind speeds (see information on inverters in Chapter 7).

Power curves for shorter time periods will indicate performance of the wind turbine when compared to baseline experimental power curves at a site. Of course, there is some scatter of the data, especially at the high wind speeds with few data points. However, low power curves indicate

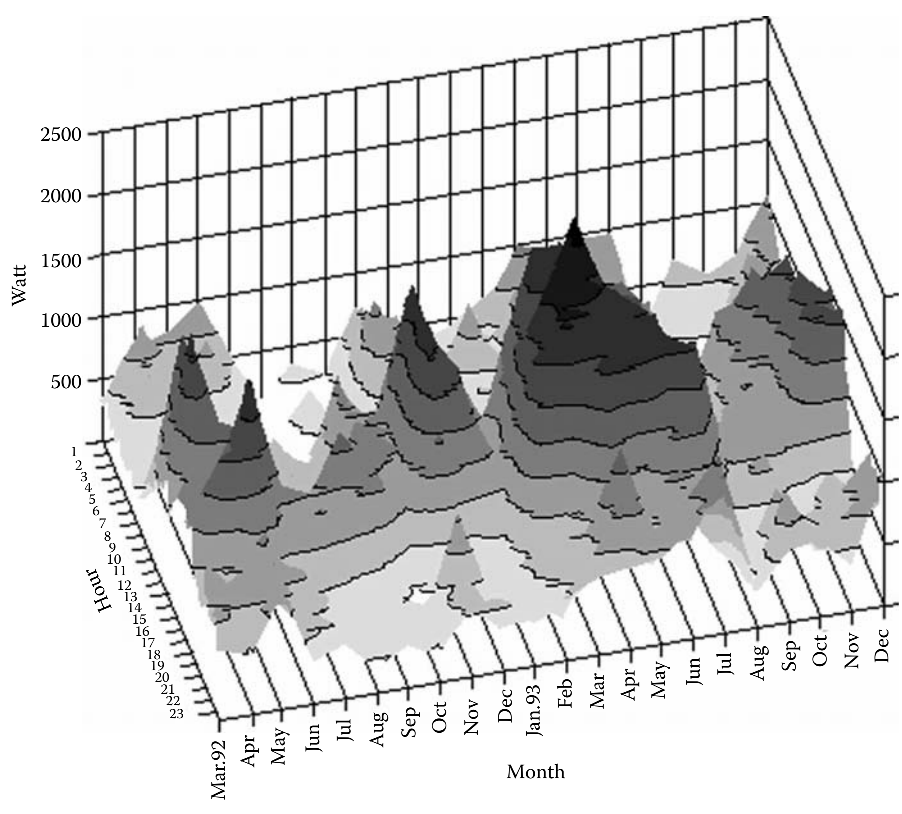

FIGURE 8.10 Power for Bergey Xcel, 10 kW, for average day, by month from March 1992 through December 1993.

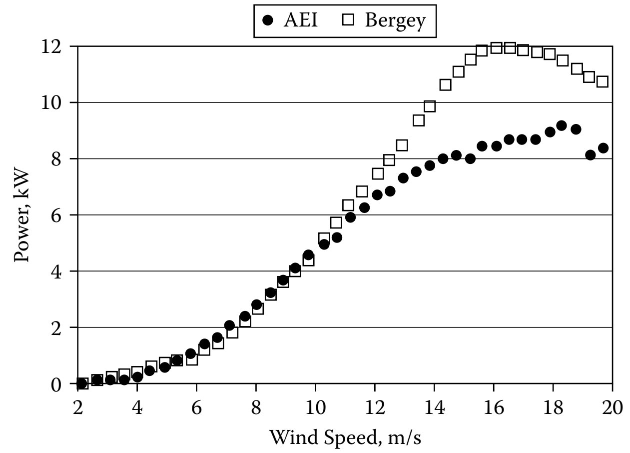

FIGURE 8.11 Power curves for Bergey Xcel at AEI Wind Test Center (1997–1999).

a problem. Power curves for each month were plotted and then averaged to obtain a baseline curve (Figure 8.12). Notice that something was definitely wrong with the system for the month of November.

8.7 WATER PUMPING

Water pumping by windmills is an old technology. There have been a number of suggested changes to the farm windmill; however, most have not been commercial. The electric-to-electric system for pumping larger volumes of water for villages and small irrigation [16] has been designed and prototypes have been tested. Now such systems are available in the commercial market. The performance for water pumping can be estimated by a flow curve for water and a wind speed histogram to estimate the amount of water pumped by month or year.

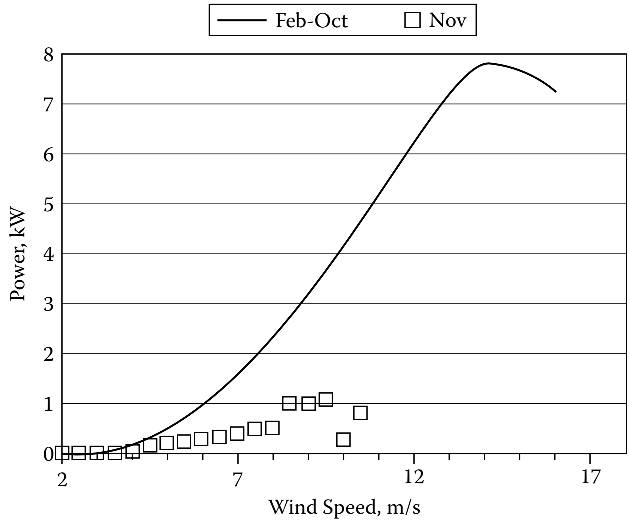

FIGURE 8.12 Power curves for Bergey Xcel, 10 kW, at Leroy, Texas.

8.7.1 Farm Windmill

The farm windmill is an old technology, with no design changes since the 1930s. It is well designed to pump small volumes of water for livestock and residences. It is comparable to a drag device, because of the large solidity (close to 1), and the wind rotor has a peak efficiency of 15–18% at a tip speed ratio around 1. The wind rotor efficiency is higher than the overall efficiency, because the pump efficiency limits the system performance. Since it is connected to a positive displacement pump, the rotor needs a lot of blades to obtain a high starting torque. For the mechanical farm windmill with a positive displacement pump, the water flow rate is directly related to the number of strokes per minute. Overall, efficiency or average annual efficiency (wind to water pumped) is around 5–6% [17]. The curve for water flow is similar to the efficiency curve. In general for the farm windmill, tables are provided to estimate performance for different wind regimes (Table 8.5). The same information is shown in Figure 8.13; however, the strong wind data from Table 8.5 were not plotted since they were close to the fair wind data.

Performance tests of eight farm windmills [18] show little difference between the four units, which had reciprocating pumps, two of which had the conventional reduction gear and two that did not. The windmill equipped with a Moyno pump performed well, but the three airlift units had poor performance. So the advantage of no moving parts in the well was offset by the lower efficiency of the pump and air compressor.

8.7.2 Electric to Electric

A very promising development is a wind, electric-to-electric, water pumping system [19]. The wind turbine alternator is connected directly to a motor, which is connected to a centrifugal or turbine water pump. This system is a better match between the characteristics of the wind turbine rotor and the load. The overall annual efficiency is 12–15%, which is double the performance of the farm windmill. The water flow is higher at the higher wind speeds for the wind–electric system (Figure 8.14), as there is more wind power in this region. This is also the region where the farm windmill is furled, limiting the power out.

The farm windmill and a 1.5 kW wind–electric system [20] using a submersible pump are essentially the same size, and the costs are almost the same. The wind–electric system pumped twice the

TABLE 8.5
Estimated Water Pumped by Farm Windmill

Depth m	Pump Diameter cm	Light Wind 3–4.5 m/s cubic m/h	Fair Wind 5–7.5 m/s cubic m/h	Strong Wind >8 m/s cubic m/h
9	3.6	8.1	12.5	13.7
17	2.7	4.6	7.1	7.8
24	2.2	3.2	4.9	5.4
38	1.8	2.0	3.1	3.4
49	1.6	1.6	2.4	2.6
67	1.3	1.1	1.8	2.0
79	1.2	0.9	1.5	1.6
91	1.1	0.8	1.2	1.4
110	1.0	0.6	1.0	1.1
140	0.89	0.5	0.7	0.8
171	0.84	0.5	0.7	0.8
183	0.78	0.4	0.6	0.6

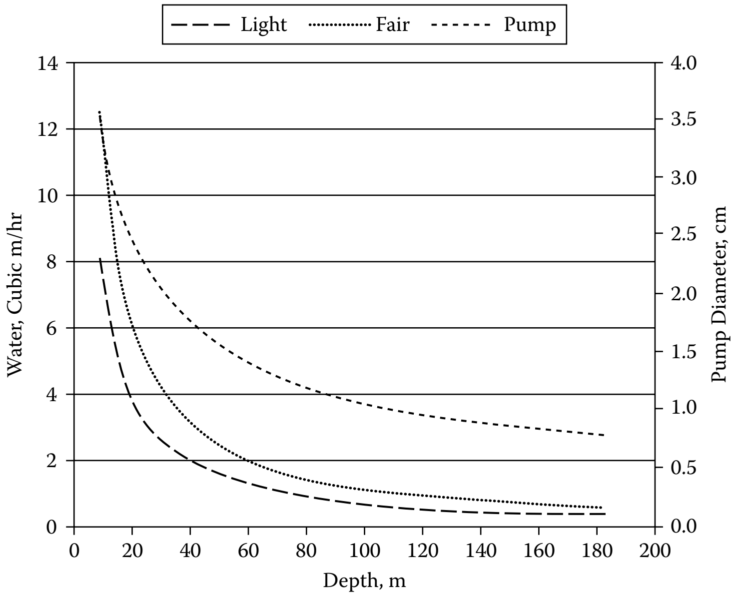

FIGURE 8.13 Pump diameter to use for depth and amount of water that farm windmill would pump in light and fair winds.

amount of water from the same depth (Figure 8.15); however, during the low wind month of August, the farm windmill pumped more water. The other aspect is that larger wind–electric systems can pump enough water for villages [21] or low-volume irrigation [22].

8.8 WIND-DIESEL AND HYBRID

Around 1.6 * 10^9 people do not have access to electric power because they are too distant from transmission lines of conventional electric power plants. Extension of the grid is too expensive for most

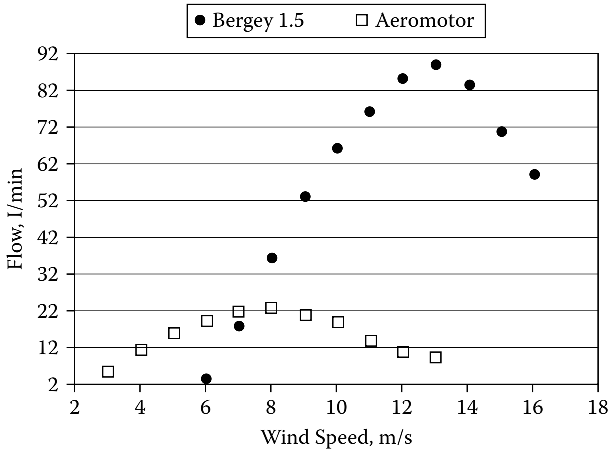

FIGURE 8.14 Water flow rates for a mechanical, multibladed windmill (Aeromotor) and a Bergey (1.5 kW) electric-to-electric water pumping system.

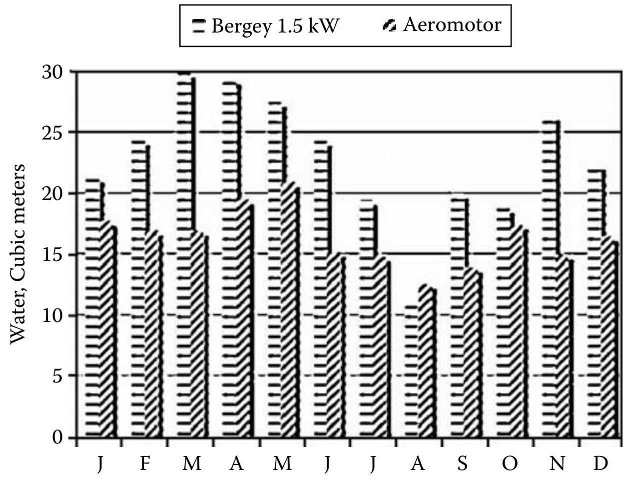

FIGURE 8.15 Predicted annual water pumped by 1.5 kW wind–electric water pumping system and farm windmill.

rural areas, and if extended, it is heavily subsidized. These people depend on wood, biomass, or dung for cooking and heating, mainly collected and cared for by women and girls.

For remote villages and rural industry the standard is diesel generators. Remote electric power was estimated at 10.6 GW in 1990. Of that there were 133,816 diesel gensets, ranging in size from 5 to 1,000 kW, with a power rating estimated at 9.1 GW. In Canada, there were more than 800 diesel generating sets with a combined installed rating of over 500 MW. Diesel generators are inexpensive to install; however, they are expensive to operate and maintain, and major maintenance is needed from every 2,000 to 20,000 hours, depending on the size of the diesel genset. Most small village systems only have electricity in the evening. Wind-diesel [23] is considered because of the high costs for generating power in isolated locations, and by 1986, more than a megawatt of wind turbines were installed with existing diesel systems.

The Kotzebue Electric Association (KEA), Alaska, grid has six diesel generators with a combined capacity of 11.2 MW. The annual average load is about 2.5 MW, with a peak load around 3.9 MW, and the minimum load is around 1.8 MW. Loads are greatest during the winter months for heating and lighting. KEA maintains a high reserve capability to prevent loss of power during the winter. Critical loads include the heating of the town water supply. Typically, KEA runs two generators continuously during the winter, with the rest as backup. KEA consumes, on average, 5.3 million L of diesel fuel, with an average efficiency of 4 kWh/L. The energy costs for the diesel generators were estimated at $0.50/kWh ($1998). There is a potential ecological problem, as huge bladders of diesel are stored on site during the short summer season when the river is navigable by barge to offload a year's supply of fuel at a time.

A demonstration project of adding wind turbines to an existing diesel plant is the KEA Wind Farm [24]. The ten wind turbines (Atlantic Orient, 50 kW, 15 m diameter) are located on a relatively flat plain 7 km south of Kotzebue and 0.8 km from the coast (Figure 8.16). The site is well exposed to the easterly winter winds and the westerly summer winds, with an annual average wind speed of 6.1 m/s. The cost of energy for the wind turbines was estimated at $0.13/kWh for the first 2 years of operation. The first three turbines were installed in July 1997, and seven more turbines were added in May 1999.

The ten wind turbines should reduce the annual fuel consumption by about 340,000 L, which is about 6% of normal fuel requirements. At the 1998 cost of fuel to KEA, $0.25/L, this would save KEA and its member–owners around $84,600 each year. In addition to direct fuel cost savings,

FIGURE 8.16 Atlantic Orient (50 kW) wind turbines at Kotzebue wind farm.

KEA will save money in reduced costs of storage and pollution control requirements associated with diesel fuel.

In the year 2000, the ten wind turbines produced 1.1 MWh of electricity, which saved 265,000 L of diesel fuel. The wind turbines were shut down during part of the summer due to construction on the distribution system, so availability was only 85% during that period. KEA added two more AOC turbines in the spring of 2002. Because of the cold-weather, high-density air, they had to change the control system to reduced peak power output. A Northern Power wind turbine (100 kW), three more 50 kW units and one remanufactured V17, 65 kW, were installed, so by 2007 there was a total of seventeen wind turbines at the site. In 2007 they generated 667,580 kWh of energy, which resulted in a savings of 172,240 L of diesel fuel. Installing foundations in permafrost and operating in cold climates present problems not found at lower latitudes. With the price for diesel fuel escalating to $1.25/L in 2008, wind–diesel becomes more economical.

A number of prototype and demonstration hybrid systems (wind, PV) have been installed; however, performance for most projects has been poor. In the past, hybrid systems [25] have had a high failure rate, with failures due to faulty components, poor maintenance, and inadequate support by systems suppliers after installation. Hybrid systems will be covered in more detail in Chapter 10.

8.9 BLADE PERFORMANCE

A smart rotor blade [26] would have active control of the aerodynamics with spanwise distributed devices: trailing edge devices and camber control, micro tabs, boundary layer control (suction, blowing, synthetic jets, vortex generators), and structural integration. Besides lift and drag data for airfoils, including some data for changing attack angles, blade performance has been evaluated through research and field experiments. These include effects of surface roughness, boundary layer control, flow visualization, pressure taps, and vortex generators.

Data from pressure taps on a blade were used to obtain lift, drag, and pitching momentum coefficients during normal operation and dynamic stall [27]. The blade was the new S809 thin airfoil, constant chord, no twist, on a three-bladed, downwind rotor (10 m diameter), constant rpm, and variable pitch. Dynamic stall occurred at 30° yaw angle and during high angles of attack.

8.9.1 Surface Roughness

Performance will be reduced by the airfoil sensitivity to blade roughness. Just as for wings on airplanes, ice reduces performance drastically (Figure 8.17), to the point where the rotor will not turn. Also, falling chunks of ice from large blades present a safety hazard. If icing is a major problem, then it might be economic to have heated blades. Black blades have been used on some wind turbines to assist thawing when the sun comes out.

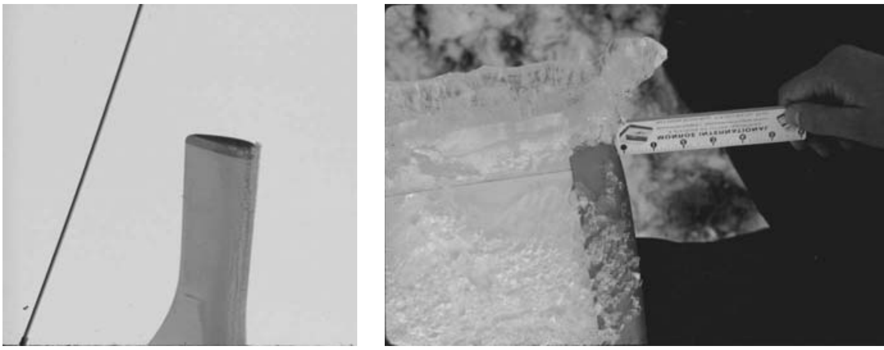

FIGURE 8.17 Ice on Carter 25 blade. Blades did not rotate at all with this much ice.

Accumulation of surface debris, caused by insects, grease, dust, and air pollution, on the leading edge of blades causes energy losses, as noted by wind farm operators. A 60 kW wind turbine at USDA-ARS showed a monthly energy loss of over 20%, and energy losses of 40% were observed when the wind speeds were above 13 m/s [28]. Insects on the blades (Figure 8.18), like on the windshield of your car, can reduce performance by 30% or more. Insects' impact on the leading edge can be severe; however, data are difficult to obtain on amount and height of the contamination [29]. Adhesive tape was wrapped around the leading edge of blades at equally spaced radial locations. Strips were collected and scanned by laser profilometry. The results showed that grit can adequately model surface roughness for wind tunnel and field testing. An artificial scale for roughness—light, medium, and heavy—was developed by NREL from testing on wind turbines in California. This corresponded to using number 80 rock tumbler grit at approximately 100–150, 250–300, and 500–600 particles per 5 cm^2.

Power was measured for two 24-hour periods, with the data averaged over 5 minutes for the Entertech 44, dirty blades, and then after a rain cleaned the blades (Figure 8.19). Insects on the blades reduced the peak power by around 20 kW (Figure 8.20), a reduction of 40%. The power curves for the data show the same information (Figure 8.21). This is another reason for wind farms to have a baseline power curve for each turbine, and then weekly power curves can be compared to that baseline for performance checks.

In California wind farms, after an insect hatch, they washed the blades (Figure 8.22) to improve energy production. Active stall wind turbines attempt to compensate automatically for reductions in power output in wind speeds above the rated wind speed. Since insects on the blade reduce the aerodynamic efficiency, the active stall will compensate for this by changing the pitch angle toward zero degrees. The compensation by active stall was evaluated on a NEG-Micon 72C wind

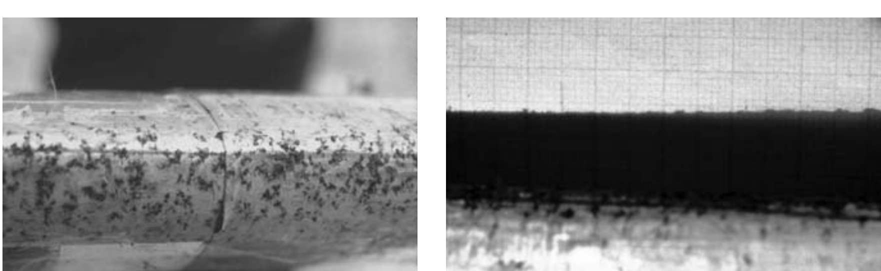

FIGURE 8.18 Left: Bugs on leading edge of PM blade. Right: Graph paper on ground shows shadow of leading edge bugs, which protrude 1 to 3 mm.

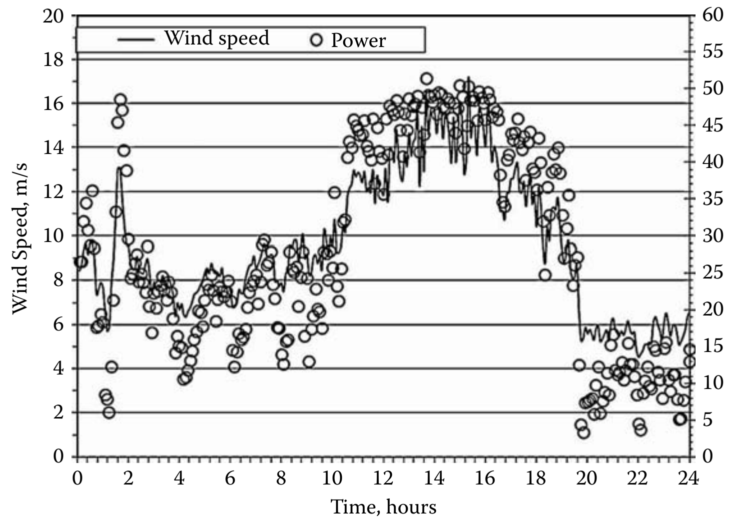

FIGURE 8.19 Enertech 44 performance with clean blades after rain, April 17, 1986. Maximum power is close to 50 kW, the rated power.

turbine (72 m diameter, 1,500 kW) [30]. There was no reduction in the power curve because the active stall provides complete compensation for moderately contaminated blades, and there was a slight reduction around the knee of the power curve for severely contaminated blades. There was a slight reduction in the power curve in the lower wind region for extremely contaminated blades. However, the power still reached nominal rates at a wind speed larger than the rated one, but there was a significant reduction in high winds beyond that point. The compensation for blade roughness is another reason for using active stall over passive stall. The effect of blade roughness on energy production is the reason airfoils with less sensitivity to blade roughness have been designed specifically for wind turbines.

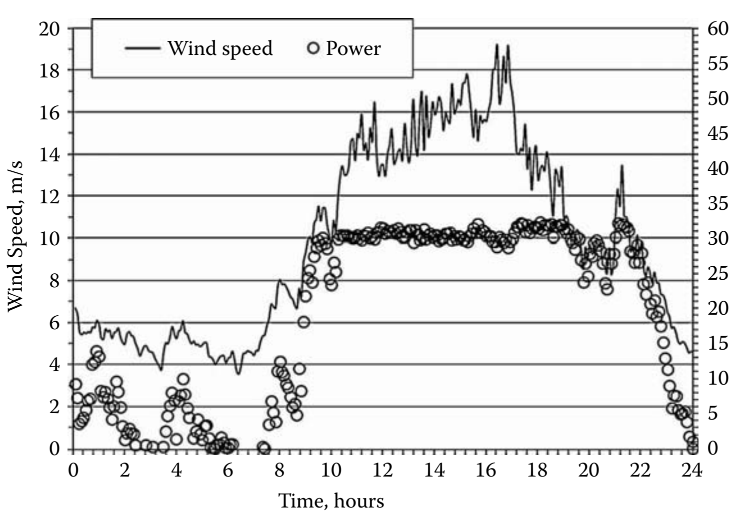

FIGURE 8.20 Enertech 44 performance with dirty blades, April 13, 1986. Maximum power leveled off around 32 kW.

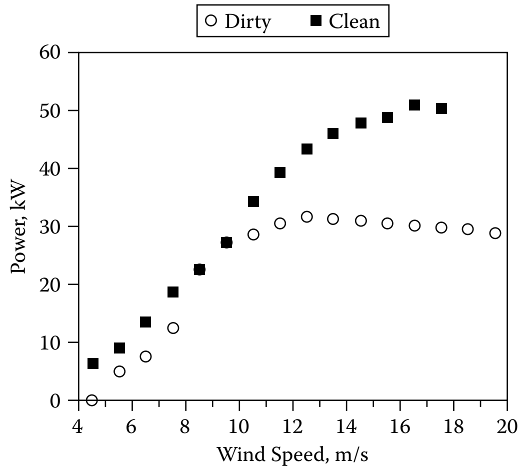

FIGURE 8.21 Enertech 44 power curves from data in Figures 8.19 and 8.20.

8.9.2 Boundary Layer Control

Boundary layer control is all those methods that can be used to reduce the skin friction drag, by controlling the transition to turbulent flow, and reduce the development of turbulent flow and the separation of both laminar and turbulent flow. Boundary layer control tries to keep the flow attached further along the chord, thereby increasing lift and reducing drag, and by keeping dynamic stall from happening. Dynamic stall, which is seen as a hysteresis loop of lift caused by changing high angles of attack on blades, causes high loads. One method of boundary layer control is by suction or blowing air through holes in the blade. Suction can prevent laminar and turbulent separation by removing flow of low momentum. The pressure difference needed for suction on blowing can be obtained by the centrifugal force acting on the air inside the blade, or a pump can supply the difference.

FIGURE 8.22 Notice spray from tower to clean blades, powered by truck on the ground, San Gorgonio Pass, California.

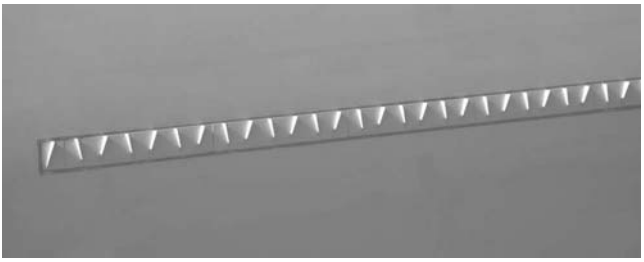

FIGURE 8.23 Shape and orientation of vortex generators on blade of GE wind turbine (77 m diameter, 1.5 MW).

8.9.3 Vortex Generators

A vortex generator mixes the faster-moving laminar flow with the boundary layer, which delays flow separation from the blade and stall. Typically there are counterrotating pairs of vortex generators on the low-pressure side of the blade, with $\pm 20°$ angles of incidence at 10% chord on the inner portion of the blade (Figure 8.23), which is thicker and more prone to dynamic stall. Vortex generators were installed on the MOD 2 and the MOD 5 wind turbines, and the performance was improved [31]. A Carter 25 wind turbine has an optimal blade with a large amount of twist and taper at the root. When vortex generators were tested on the unit, the maximum power was increased; however, power below the rated wind speed was reduced because of the added drag of the vortex generators. In other words, the inner portion of the blade did not enter stall and did not need the vortex generators. In general, vortex generators improve blade performance by 4–6%. A unique concept is air-jet vortex generators [32], which in wind tunnel tests gave an improved performance over the vane vortex generators. They were installed on a 150 kW wind turbine and increased the maximum power; however, the potential benefits were not conclusive, probably due to the placement of air-jets on the outer part of the blade, rather than on the inboard section. Production blades now have vortex generators (Figure 8.24).

8.9.4 Flow Visualization

The performance of blades, rotors, and towers can be checked by flow visualization: smoke, tuffs, stall flags, pressure-sensitive liquid crystals, and oil streak. Tuffs are driven by frictional drag, while

FIGURE 8.24 Vortex generators on inner portion of blade of GE wind turbine (77 m diameter, 1.5 MW).

stall flags are pressure driven. The stall flag responds to separated flow with an optical signal, which exceeds the tuft signals by a factor of 1,000 [33]. Smoke shows the stream flow for airfoils in wind tunnels and the generation of tip vortices from ends of blades and their propagation downstream [34]. Smoke released from tethered smoke generators was used to observe the evolution of tip vortices from the MOD-2 [35]. The vortex became unstable when it passed through the wake of the turbine tower.

Blades on downwind turbines pass through the wake of the tower, so there is a change in attack angle and flow across the blade, which also generates noise. Flow visualization was used to study the flows [36] over the blades of an Enertech 21 (6.4 m diameter, 5 kW), with and without tip brakes; a Carter 25 (10 m diameter, 25 kW); and an Enertech 44 (13.4 m diameter, 50 kW). All three units were downwind, constant-rpm wind turbines. A video camera and a 35 mm camera were mounted on a boom attached to the root of the blade. Tuffs and oil flow revealed the nature and many of the details of the flows, such as laminar separation bubbles, turbulent reattachment, and complete separation over part or almost all of the blade. Full or partial reattachment due to tower shadow was observed on each unit (Figure 8.25). Spanwise, flow was observed near the leading edge of the Enertech 21, and almost the whole blade was in stall at high wind speeds. The tip brakes on the Enertech units are important in retaining attached flow near the tip. The oil streak pattern after 4 minutes in winds from 7 to 15 m/s on the Enertech 44 blade shows that below 0.5 blade length, the flow is completely separated. However, the flows on the highly twisted and tapered Carter 25 blade are attached in medium winds. The flows show a turbulent type edge separation, which begins at about half the radius and progresses forward. Pressure-sensitive liquid crystals were tried, but field results were not good, as the lighting has to be just right to observe the color changes.

It should be noted that vortices, alternating on each side, will be shed by cylinders in wind flow, which can induce vibration in the cylinder. On the VAWT 34 m test bed, a spiral staircase on the torque tube eliminated these vortices.

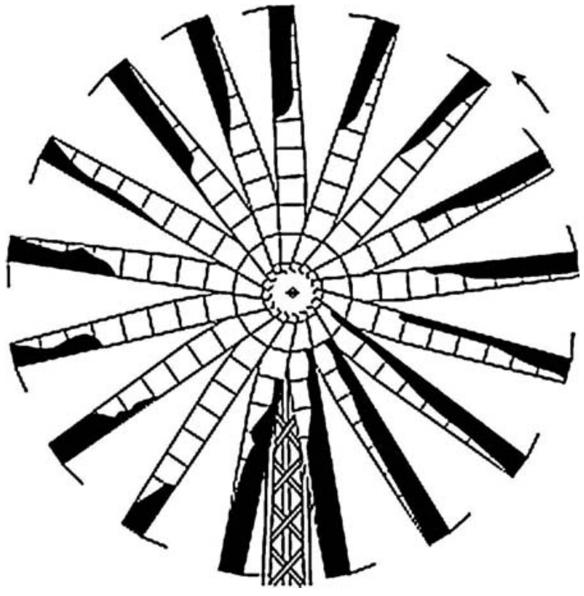

FIGURE 8.25 One blade of the Enertech 21 over one revolution. Shaded areas show representative pattern of attached flow. Note the strong reattachment due to tower shadow.

8.10 COMMENTS

Wind turbine and wind farm performance (annual, quarterly, monthly, or by period of peak demand) will determine economic viability and will help in comparisons of wind turbines. The main performance factors are the amount of energy produced and the cost of that energy compared to other sources. Of course, electricity is the major application, with water pumping secondary. Capacity factors in good to excellent wind regimes should range from 30 to 40%, and annual specific outputs should be over 1,000 kWh/m^2. For wind farms, availabilities of 98% and turbine lifetimes of 25 or more years should be the norm with good preventative maintenance programs.

LINKS

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PROBLEMS

1. From Table 8.1 calculate annual specific output, kWh/kW, for two different wind turbines.
2. From Table 8.1, calculate capacity factor for Fayette, Vestas 23, Bonus 120.
3. From Table 8.3, what is the average capacity factor for 1989 through 1996?
4. Calculate the specific output, kWh/m^2 in (a) 1985 for Enertech 44/60 and (b) 1990 for Enertech 44/40.
5. From Table 8.4 calculate for 7 months for Enertech 44/25: (a) kWh/m^2 and (b) capacity factor.
6. From Table 8.4 calculate for 1985: (a) kWh/m^2 and (b) capacity factor.
7. From Table 8.4 calculate kWh/m^2 for May and August 1984. Does specific output depend on the wind?

Information for problems 8–10. Today, Carter is not manufacturing wind turbines, and Vestas V27 is not in production.

Specifications	**Carter 300**	**Vestas V27**
Diameter, m	24	27
No. blades	2	3
Rated power, kW	300	225
Tower height, m	50	31.5
Installed cost (IC), 1990	$100,000	$225,000
Estimated annual energy, kWh	600,000	500,000
Weight specs, kg		
Rotor	1,340	2,900
Tower head (nacelle)	2,091	7,900
Tower	8,023 (includes gin pole)	12,000
Guy cables, winch	1,336	
Control box and panel	155	
Total	14,250	22,800

8. For the Carter 300, calculate (a) kWh/m^2, (b) $IC/kW, (c) kWh/kg, and (d) kWh/$IC.
9. For the Vestas V27, calculate (a) kWh/m^2, (b) $IC/kW, (c) kWh/kg, and (d) kWh/$IC.
10. Estimate the annual capacity factor for the Carter 300 and Vestas V27.
11. Go to the Vestas web page, www.vestas.com. (a) For the Vestas V52 (1.65 MW), estimate the annual kWh/m^2 for a good wind regime. (b) For the Vestas V90 (3 MW), estimate the annual kWh/m^2 for a good wind regime.
12. For the farm windmill, what is the approximate pump diameter if the water depth is 40 m. Approximately how much water could be pumped in a light wind?
13. For the farm windmill, what is the approximate pump diameter if the water depth is 20 m? Approximately how much water could be pumped in a light wind?
14. For the farm windmill, what is the approximate pump diameter if the water depth is 100 m? Approximately how much water could be pumped in a fair wind?
15. For the farm windmill (use Figure 8.14 for flow data), estimate water pumped for 1 month that has an average wind speed of 5 m/s. Use Rayleigh distribution (1 m/s bin width).
16. Check the Internet to see which companies sell wind–electric water pumping systems.
17. For the wind–electric water pumping system (use Figure 8.14 for flow data), estimate water pumped for 1 month that has an average wind speed of 5 m/s. Use Rayleigh distribution (1 m/s bin width).
18. For an annual average wind speed of 6 m/s, compare the predicted annual energy production for the Enertech 44 for the 25 kW and 60 kW wind generators. Use Figure 8.8 for power curves and use Rayleigh distribution (1 m/s bin width).
19. Electronic Wind Performance Reporting System is available online [5]. For the last year available, what is the statewide energy production for California? Which manufacturer had the largest installed capacity? Which manufacturer had the largest number of turbines installed?
20. By approximately what percent will bugs on blades reduce the power?
21. Select a wind farm that is close to your home town or city. What is the installed capacity? How much electricity did it produce last year? If values are not available, estimate from installed capacity and capacity factor.
22. Are there any village power systems in your country? If the answer is yes, determine if performance data are available for one system. What is the size of the system and annual energy produced?

23. Are there any wind-diesel systems in your country? If the answer is yes, determine if performance data are available for one system. What was the size of the system and annual energy produced?
24. List two types of boundary layer control for wind turbines. Briefly explain each.
25. Which type of wind turbine would perform best with heavy insect contamination on the blades? Why?

9 Siting

The crucial factor is the annual energy production from the wind turbine or wind farm (also called wind park or wind plant), and how the value of that energy compares to other sources of energy. Much of the data from meteorological stations in the world are of little use in predicting wind power potential and expected energy production from wind turbines.

9.1 SMALL WIND TURBINES

For small wind turbines, a measuring program may cost more than the wind turbine; therefore, other types of information are needed. As wind maps are developed for potential wind farms by countries, these maps can be used as guides to determine regions with enough wind for small wind turbines. Also, wind maps for countries and large regions obtained from numerical models have sufficient resolution for siting of small wind turbines. Since small wind turbines will be located close to the load, local topography will influence the decision on estimating wind speeds and siting. If the location is on exposed terrain, hills, or ridges, then the wind speeds would be higher than those in the valley. In complex terrain, some sites will be adequate for small wind turbines and other sites will be sheltered.

One of the factors in the settlement of the Great Plains of the United States was the farm windmill, which provided water for people and livestock. Therefore, if farm windmills are used or were used in the past in a region, then there is enough wind for small wind turbines in that region. Another possibility is to install met towers for reference data for a region. Generally, this would be done by regional or state institutions or governments, not by individuals interested in siting of small wind turbines.

Small wind turbines can be cost-effective for stand-alone systems using the general rule that the average wind speed for the lowest wind month should be 3 to 4 m/s. Also, general maps of wind power or wind energy potential for small wind turbines have been developed for large regions (Figure 9.1) [1]. These gross wind maps will be supplanted by national wind maps developed for determining wind energy potential for wind farms. Finally, if there are wind farms in the area, there is definitely enough wind for small wind turbines.

It is obvious that a small wind turbine should be located above (10 m if possible) obstructions and away from buildings and trees [2]. Towers for small wind turbines should be a minimum of 10 m and preferably 20 m, as higher towers generally capture more energy (Figure 9.2). Again, the trade-off is the extra energy versus the cost of a taller tower. Even towers of 35 m are sometimes used. As a general rule for avoiding most of the adverse effects of building wakes, the turbine should be located (1) upwind a distance of more than two times the height of the building, (2) downwind a minimum distance of ten times the building height, or (3) at least twice the building height aboveground if the turbine is immediately downwind of the building. The above rule is not foolproof because the size of the wake also depends upon the building's shape and orientation to the wind (Figure 9.3). Downwind from the building, power losses become small at a distance equal to fifteen times the building height. However, a small wind turbine cannot be located too far away from the load, as the cost of wiring will become prohibitive. Also, there will be more losses in the wires if you have DC rather than AC from the wind turbine to the load. In general, small wind turbines should not be mounted on occupied buildings because of possible problems of noise, vibration, and even turbulence. For the very small wind turbines, tower heights vary from stub poles on sailboats to short, 3 to 5 m towers, and some are even mounted on buildings. Paul Gipe has written numerous articles on all aspects of wind energy [3], and two of his books are for small wind systems [4, 5].

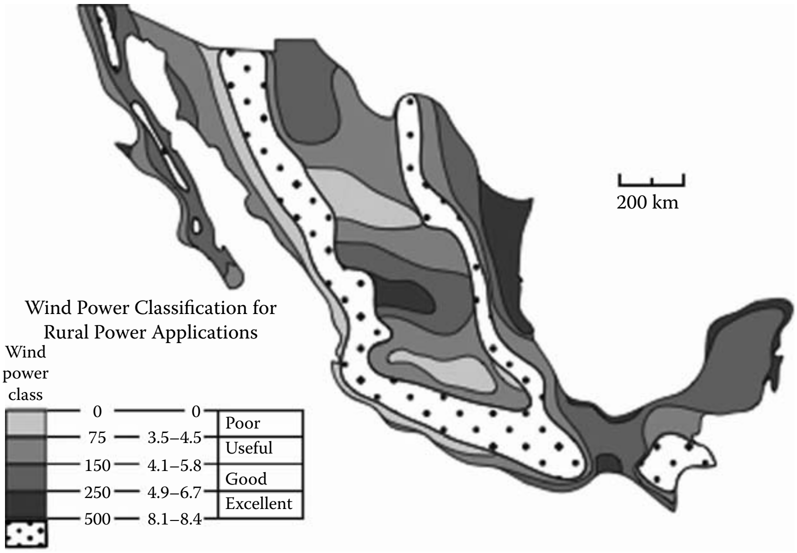

FIGURE 9.1 Wind power map for rural applications, Mexico. Notice difference in definition of wind power class and height is at 30 m.

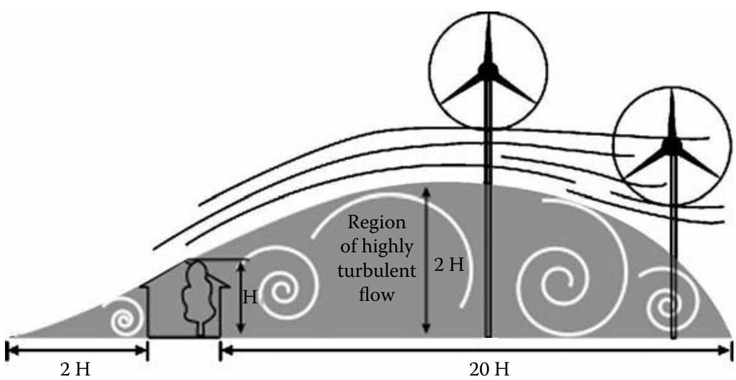

FIGURE 9.2 Height of small wind turbine close to obstacles of height H.

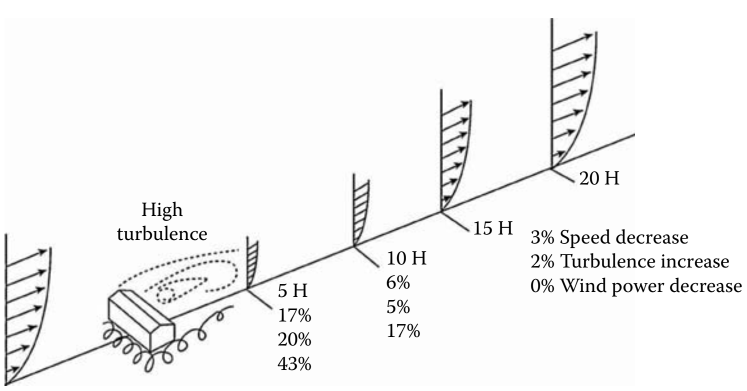

FIGURE 9.3 Estimates of speed and power decrease and turbulence increase for flow over a building [2]. Estimates shown are for building height H.

A unique concept is a wind cooperative of small wind turbines for farms, ranches, and public and private facilities in the Northwest United States [6]. Ten 10 kW wind turbines have been installed, and the map gives the location for each site. There are photos, comments from the owners, and details on wind turbines, wind resource, anticipated and actual performance, and interconnection.

Is there such a concept as wind rights if a neighbor erects a tall structure that obstructs the flow of wind to your turbine. From a visual standpoint, a wind turbine in every backyard in a residential neighborhood is much different than a PV panel on the roof of every home.

The American Wind Energy Association [7] and the Canadian Wind Energy Association [8] have sections for small wind turbines, which include information on siting. A guide for small wind turbines is available from the National Renewable Energy Laboratory (NREL) [9] with information on siting similar to the information presented above. The British Wind Energy Association section on small wind [10] includes information on a wind speed database and map (annual mean wind speed at 25 m height), small wind technologies, planning, and case studies. National wind energy associations in other countries probably have sections on small wind turbines.

There have been a number of designs by architects and inventors and even people selling wind systems (most not built or tested) to integrate wind turbines into the building structure in urban areas. The designs usually tout the increase of wind speed due to the building; however, in the real world, incorporating wind turbines into buildings is a difficult choice, due to noise, vibration, and safety concerns. In some concepts of installations on buildings, the wind turbines have to be mounted perpendicular to the predominant wind direction, as the wind turbines are fixed in yaw.

The estimated energy production is in the range of 1.7–5.0 TWh in the built environment (turbines in urban areas, turbines mounted on buildings, turbines integrated into buildings) in the United Kingdom [11]. The technical feasibility and various configurations are also discussed. There is an Internet site for urban wind [12] with downloads available: *European Urban Wind Turbine Catalogue*; *Urban Wind Turbines, Technology Review*, a companion text to EU *UWT Catalogue*; and urban wind turbine guideline for small wind turbines in the built environment and windy cities, and wind energy for the urban environment. The wind turbine guidelines include images of flow over buildings and example projects.

A newspaper in Clearwater, Florida, had a stacked Darrieus next to the building. It consisted of three Darrieus turbines, 4.5 m diameter, 6 m tall, 4 kW each (Figure 9.4). Fortis mounted three wind turbines (5 m diameter, at 2 kW rather than the nominal 5 kW) on a factory/office building. There was a small problem with vibration at high wind speeds due to the flexibility of the roof. The Aeroturbine has a helical rotor mounted in a 1.8 by 3 m frame, rated power of 1 kW [13]. A building in Chicago has eight units mounted horizontally on top of a building (Figure 9.5), while other buildings have units mounted vertically. Two 6 kW wind turbines were mounted on the roof of a civic center in the United Kingdom, which is described in a case study [14]. A different concept mounts a number of small wind turbines on the parapets [15] of urban and suburban buildings. The horizontal-axis wind turbine has a rated power of 1 kW mounted in modular housing (approximately 1.2 by 1.2 m). Fourteen wind turbines are on the corner of the Energy Adventure Aquarium building (Figure 9.6) in California, resulting in a kinetic sculpture.

The most spectacular structure with integrated large wind turbines is the Bahrain World Trade Center, where the two 240 m towers with sail silhouettes have three cross bridges that have wind turbines [16]. The wind turbines are 29 m diameter, 225 kW, and predicted to generate around 1,100–1,300 MWh/year, 11–15% of the energy needed by the buildings. The aerodynamic design of the towers funnels the prevailing onshore Gulf breeze into the path of the wind turbines.

9.1.1 Noise

Although zoning is an institutional issue, the regulations will affect the possibility of erecting a small wind turbine and, if possible, then the size of the wind turbine, tower height, how much space is needed around the tower, and the possibility of the effect of noise and even visual concerns of

FIGURE 9.4 Three stacked wind turbines (Darrieus), 4 kW each, next to building. Notice man on top. (Photo by Coy Harris, American Wind Power Center and Museum. With permission.)

FIGURE 9.5 Eight helical wind turbines, 1 kW, horizontal axis, on top of building, 8 kW total. (Photos by Kurt Holtz, Lucid Dream Productions. With permission.)

FIGURE 9.6 Wind turbines, 1 kW each, mounted on parapet of building. (Photo courtesy of AeroVironment. With permission.)

the neighbors. The noise from a small wind turbine is around the level of noise in an office or in a home. Noise from a small wind turbine is rarely a problem since the level drops by a factor of 4 at a distance of 15 m, and it is generally masked by background noise. A sound study with a 10 kW wind (wind speeds were 9–11 m/s) showed levels of 49–46 dBA for the turbine running and off at a distance of 15 m, and essentially no difference at a distance of 30 m and greater. However, if the wind turbine rotor is downwind, then there is a periodic sound every time the blade passes the tower, and even though the sound is the same level as the background sound, it can be annoying. In California, noise from a wind turbine must not exceed 60 dBA at the closest inhabited building.

9.1.2 Visual Impact

The State of Vermont has a scoring system for possible adverse visual impact of small wind turbines from two different vantage points [17]: private property (the neighbors' view) and public views (roads, recreation, and natural areas). For the neighbors' view the considerations are: (1) What is the position of the turbine in the view? (2) How far away is the turbine seen? (3) How prominent is the turbine? (4) Can the turbine be screened from view? For public views there are two additional considerations: (5) Is the turbine seen from an important scenic or natural area? (6) What is the duration of the view? Each is rated by a point system (Table 9.1), with a total of 12 points for the residential

TABLE 9.1
Criteria for Points for Visual Impact of Small Wind Turbines

	Neighbor View				Public View	
	1	2	3	4	5	6
Points	View Angle Degree	Distance m	Prominent	Screened	Vista	Duration sec
0	>90	>900	Below treetops	Complete	Degraded	0
1	0–45	450–900	At horizon line	Multiple trees	Common	<15
2	50–60	150–450	Above horizon line	Single tree, 1/2–2/3	Scenic	<30
3	60–90	<150	Above tallest mountain	No screening	Highly scenic	>60

TABLE 9.2
Rating of Visual Impact of Small Wind Turbines

	Score	
	Neighbor	**Public**
Negligible	0–3	0–3
Minimal	3–6	3–9
Moderate	6–9	9–14
Significant	9–12	14–18

viewpoint and 18 for the public viewpoint. If the score (Table 9.2) is below the significant range, the wind turbine is unlikely to have a visual impact unless it is close to and at the center of a scenic view. The score is only a general indicator for visual impact of small wind turbines. Wind turbines will be visible, at least from some viewpoints, as they will be above surrounding trees. In the Plains areas with few trees, small wind turbines will be noticeable from 1 to 3 km, the same as the trees around a farmhouse. Notice that there are comparable-height towers, such as cell phone towers, towers for lights at highway interchanges, radio towers, and the long rows of towers for utility transmission lines. The difference is that those towers do not have moving rotors.

9.2 WIND FARMS

For wind farms, long-term data are a necessity, and data should be collected on site for 2 to 3 years. Then the questions are: What is the long term annual variability? and How well can you predict the energy production for a wind farm? The siting of turbines over an area the size of a wind farm, about 5–20 km^2, is termed micrositing. Thus, the wind turbines should be located within the wind farm to maximize annual energy production, which gives the largest financial return. Array losses have to be considered in the siting process.

9.2.1 Long-Term Reference Stations

To determine if data from a historical site are adequate to describe the long-term wind resource at another site, the analysis should be done rigorously. Simon and Gates [18] recommend that the annual hourly linear correlation coefficient be at least 0.90 between the reference site and off-site data. Remember to take into account wind shear if the heights are different at the two locations. If the two sites are not similar in wind speed and direction trends and do not have similar topographic exposure, then they will probably not have that correlation value. Long-term reference stations should be considered in all locations in the world where there is wind power potential. These stations should continue to collect data even after a wind farm has been installed. Not only will this improve siting of wind farms, but it will provide reference sites for delineating the wind resource for single or distributed wind turbines in that region. As wind turbines have increased in size, the hub heights are higher, and because in most locations wind speed increases with height, there is a need for reference stations to collect data at least at 50 m, and if possible to 100 m.

9.2.2 Siting for Wind Farms

The number of met stations and the time period for data collection to predict the energy production for a wind farm vary depending on the terrain and the availability of long-term base data in the vicinity. In general, numerical models of wind flow will predict wind speeds to within 5% for relatively flat terrain and 10% for complex terrain, which means an error in energy of 15–30%. Therefore, a wind measurement program is imperative before a wind farm is installed. However, if a number of wind farms are already in the region, then 1 year of data collection might suffice.

For complex terrain, you may need one met station per three to five wind turbines. For wind turbines of 500 kW to megawatts, you may need a met station per one or two wind turbines in complex terrain. With more homogeneous terrain, as in the Plains, a primary tall met station and one to four smaller met stations may suffice. The tallest met station should be a representative location on the wind farm area, not the best point.

Contour maps are used for location of wind turbine pads and for roads. In general, the wind turbines will be located on the higher elevations within the wind farm area. Topozone has interactive topography maps (all different scales) online for the entire United States [19]. These maps are very useful in selection of met tower locations, micrositing, roads, and other physical aspects of the wind farm.

The key factors for array siting for the Zond wind farms [20] in Tehachapi Pass were an extensive anemometer data network, the addition of new stations during the planning period, a time frame of 1 year to refine the array plans, a project team approach to evaluate the merits of different siting strategies, and the use of initial operating results to refine the rest of the array. A large number of met stations were needed because the spatial variation of the wind resource over short distances in complex terrain was greater than expected. The energy output from 2 projects, 98 wind turbines and 342 wind turbines, was within 3% of the predicted value. This experience shows it is possible to estimate long-term production from a wind plant with acceptable accuracy for the financial community. One of the key factors is an extensive network of met towers.

In some older wind plants, the lowest producing wind turbines were relocated (these were small wind turbines). The money spent on micrositing is a small fraction of the project cost, but the value of the information gained is critical to accurately estimating the energy production. Many of the problems with low energy production are because of poor siting.

Wind turbines have become larger, with rotor diameters from 60 to 100 m and hub heights of 60 to 100 m. There are very little data at or above these heights; however, NREL had a program for tall tower data [21]. The problem is that any tall tower data collected by wind farm developers are proprietary.

Because of wind shear, wind turbines are located on the higher elevations for rolling terrain, on mesas, and on ridges in complex terrain. In the past, turbulence was considered a big problem for siting at the edges of mesas and ridges. However, with the taller towers, wind turbines are placed on the edges, which are perpendicular to the predominant wind direction. As an example, for wind turbines on mesas in Texas, the north edge of the mesa would have increased winds from northern storms in the winter due to the rise in elevation, and then in the summer with southern winds, there is room for expansion of the wake. Data on turbulence for these sites are proprietary, primarily because it affects operation and maintenance.

9.3 DIGITAL MAPS

Digital maps are useful as they give a general overview of the wind resource, confidence of the data, and other data (land use, transmission lines, etc.), which can easily be displayed on the same maps. NREL has created a higher-resolution digital wind map for the United States and is in the process of updating the maps by state using terrain enhancement and geographic information systems (GIS).

A very useful interactive tool, windNavigator, based on GoogleMaps®, is a wind resource map and data for the continental United States [22]. The map (2.5 km resolution) provides wind speeds at 60, 80, and 100 m and a pointer to give minimum and maximum mean annual wind speeds on a

200 m scale. Selectable areas at 200 m resolution (PDF or GIS data set) can be purchased. Satellite, hybrid, and terrain views are available for the world.

A similar interactive wind resource map (map, satellite, hybrid, and terrain views) and data for the world, FirstLook, has wind speeds at 20, 50, and 80 m [23], and presently wind data for the United States, Alaska, Canada, and Mexico are online. With FullView Assessment, resolution is at 90 m. In addition, a solar resource map is available. Remember, wind speed maps are useful for an indication of wind energy, but wind power maps are the next step.

9.4 GEOGRAPHIC INFORMATION SYSTEMS

A geographic information system is a computer system capable of holding and using data, which is spatially oriented. A GIS typically links different data sets, or a base set is displayed and overlays of other data sets are placed on the base set. Information is linked as it relates to the same geographical area. A GIS is an analysis tool, not simply a computer system for making maps.

There are two general methods of representing the data, raster and vector. Raster based means every pixel has a value, and vector based means that the data are represented mathematically—endpoints for lines and lines for polygons. Each pixel can represent an attribute, and the number of attributes depends on the number of bits: 16 to 256 colors or shades of gray. Therefore, pixels or vectors can have different attributes and are linked to a database, which can be queried. A GIS gives you the ability to associate information with a feature on a map and to create relationships that can determine the feasibility of various locations, for example, a hierarchical system for locating anemometer stations for wind prospecting.

An overlay is a new map with specific features, which is overlaid on the base map. Overlays are one form of database query functions. The overlay can be a raster or vector image, with the base map being a raster or vector image. The number of overlays is generally limited only by the amount of information that can be presented with clarity.

The main types of terrain data are the Digital Elevation Model (DEM) data and the Digital Line Graph (DLG) data. These are available at different scales, for example, the DLG at 1:2,000,000, 1:100,000, and 1:24,000. Depending on the scale, the DLG data contain highways, roads (even down to trails), lakes and streams, transmission lines (utility and gas), etc. The problem is that the data may be taken from fairly old maps and therefore be incomplete. The DEM data give the terrain height to 1 m on a latitude–longitude grid with a resolution of 3 arc seconds [pixel around 90 m by 90*cos(latitude) m]. NREL coupled the DEM database with software to produce shaded relief maps of 1° by 1°.

A technique of terrain enhancement [24] was used to identify windy areas in the Midwest. In the flat or rolling terrain found in most of the Midwest, the two most important factors influencing wind speed are terrain elevation and surface roughness. The wind map (normalized wind map from PNL digital map) was adjusted to an average elevation and average surface roughness in a circle (12 km radius) around that point. The U.S. Geological Service Terrain Elevation Data was the base map, which consisted of average elevations in 1 km^2 grid cells rounded to the nearest 6 m. Terrain exposure was determined by subtracting actual elevation from the average elevation for each 1 × 1 km grid cell. Then a power correction factor was calculated by

$$\frac{P}{P_a} = \frac{\left(\ln\left[\dfrac{H_h + E}{z_o}\right]\right)^3}{\left(\ln\left[\dfrac{H_h}{z_o}\right]\right)^3} \tag{9.1}$$

P_a = average power/area from normalized wind map
H_h = hub height, 50 m

E = exposure, m

z_o = roughness length; crop land 0.03 m, crop land/mixed woodland 0.1–0.3 m, forest 0.8–1.0 m

Care must be taken on use of P_a. Do you use the bottom or the middle of the wind class? Do you limit the number of wind class changes to one, especially for mountainous terrain?

9.5 WIND RESOURCE SCREENING

As an example, wind resource screening for the Texas Panhandle is presented [25, 26]. The DEM data (3 arc seconds resolution) along with DLG data were used. The original DEM data were in blocks of 1° by 1°. Data for utility transmission lines (69 kW and higher) were input by hand. Two GIS systems, IDRISI and PC ARC INFO, for personal computers were used. IDRISI has built-in functions that enhance its use for wind resource screening: slope, hill shading, aspect, and orthographic projection. A data sheet accompanies these functions, which shows bin size, max, min, etc.

The Panhandle of Texas is part of the Southern High Plains, with rolling hills in the East and above the Caprock, flat plains. The elevation rises from 450 m in the Southeast to 1,460 m in the Northwest. The Canadian River goes from west to east across the Panhandle. The other notable feature is Palo Duro Canyon. The graphs can be viewed in color or gray scale, with a number selectable up to 256. At 256 colors, a DEM map for all of the Texas Panhandle would display contours 4 m apart. The base map (Figure 9.7) is the DEM data for the Panhandle. Most of the images were created using sixteen values. The elevation data of the base map can be analyzed by the different commands in IDRISI. Instead of the whole area, subsets of the data can be analyzed in the same manner for more detail. The limitations on resolution are the cell size of the original data.

The Panhandle has a large wind energy potential since it has class 3 and 4 winds over the whole area. On the flat open plains, which describe much of the Panhandle, close to 100% of the area will be in the same wind power class. In this region, wind speed increases with height; therefore, modest relief may increase the wind power dramatically. Terrain exposure selects those areas, which are above and below the average elevation. A 15 km radius was used to determine an average elevation, then the maximum change from this average was 190 m (Figure 9.8). An orthographic projection with the overlay of terrain elevation shows more clearly the areas of higher elevation. On the basis of terrain exposure, a revised wind map was calculated. Some of the regions with positive exposure have been changed to a higher wind class by this process, and low areas have been changed to a lower wind class.

GIS was used to screen the wind resource in terms of the following criteria: wind power class, terrain type, vicinity of transmission line, slope, and aspect. Within the criteria, classes or levels can be selected to exclude or limit the area for wind plants. A map was generated for each of the following screening parameters:

- Wind class 3 and above
- Slope of 0–3°
- Aspect from 155° to 245° for area where slope is greater than 1°
- Multiples of 8 km from transmission line (69 kV and above)
- Excluded lands: parks, roads, urban, lakes, wildlife refugees

Then the maps are combined to show a map of the possible areas for wind farms by wind class. Within 8 km of transmission lines, the total area was 28,600 km^2, around 37% of the land in the Panhandle.

9.5.1 Estimated Wind Power for Texas, Pacific Northwest Labs

Pacific Northwest Labs (PNL) estimated the capturable wind power for Texas at 50 m height as 134,000 MW from class 3 and above winds, with 28,000 MW for class 4 winds. Class 4 winds are

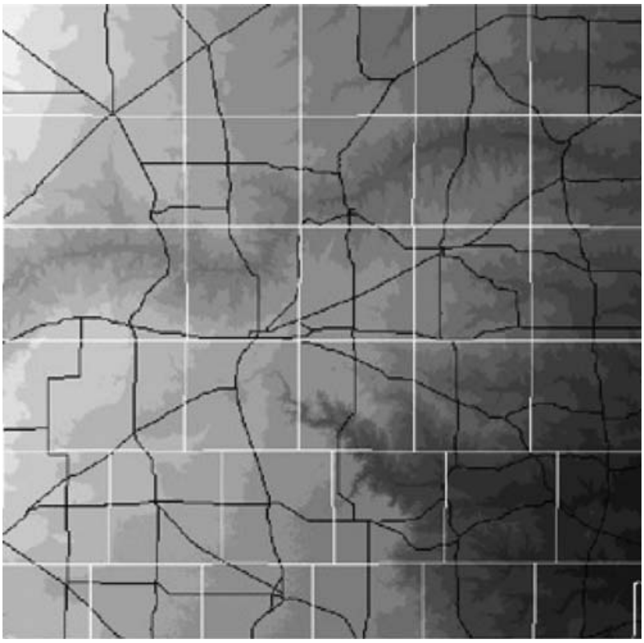

FIGURE 9.7 Digital elevation map (16 shades) of the Panhandle of Texas with county boundaries and major highways. Contour lines are 62 m apart.

FIGURE 9.8 Terrain exposure from the average for the Panhandle of Texas with major highways and transmission lines. Light areas have better exposure (range of 16 levels from –195 to +168 m).

located primarily in the Panhandle. The PNL estimate was made in the following manner. The total power intercepted over a given land area is a function of the number of wind turbines, the rotor swept area, and the available power in the wind. Environmentally sensitive land, urban areas, and terrain that is in valleys and canyons were excluded. The following formula is used to calculate the power intercepted by the rotor area of the wind turbines:

$$P_i = P_a A_t N \tag{9.2}$$

where P_a = average wind power potential, W/m^2; A_t = rotor area, π D^2/4; D = rotor diameter, *m*; and N = number of wind turbines.

The number of turbines that can be placed on the land area is

$$N = \frac{A_i}{S_r S_c} \tag{9.3}$$

where A_i = land area; S_r = spacing between turbine rows, D; and S_c = spacing within turbine row, D m^2. Note that $S_r S_c$ is the land area devoted to one turbine. In general, wind plants only remove 3–10% of the land, primarily for roads, from other productive uses. At some wind farms the roads are only 5 m wide, while at another wind farm with 3 MW wind turbines, the roads are over 10 m wide.

If the cost of land is high, then the land area for one wind turbine is smaller; however, the output from the wind plant will be reduced due to array effects. In California, some wind plants have turbine spacing of 2D within the rows and 5D to 7D to the next row. As a general rule, in the Plains area, 5–12 MW can be installed per square kilometer (spacing of 4D by 8D), and for the edge of bluffs and on ridges, 6–15 MW can be installed per linear kilometer (spacing of 2D to 3D, one row only). With closer array spacing the MW/km^2 would be larger; however, the array losses would also be larger.

The average intercepted power can be calculated from Equation 9.2, or the intercepted power per unit land area can be calculated from

$$\frac{P_i}{A_t} = \frac{\pi P_a}{4 S_r S_c} \tag{9.4}$$

Remember, this is the intercepted power, and capacity factors of 0.30 to 0.35 are used to estimate the capturable wind power.

9.5.2 Estimated Wind Power for Texas, Alternative Energy Institute

The same procedures of terrain enhancement and GIS were used to estimate the capturable wind power for Texas [27]. The selection criteria were wind class 3 or higher from revised wind map using terrain exposure, slope of 0–3°, excluded lands (urban, highways, federal and state parks, lakes, wildlife refuges, and federal wetlands), and within 15 km of transmission lines (115 kV and above).

The capturable annual power was calculated for the following conditions for the wind turbines: 50 m hub height, 10D by 10D spacing, 30% capacity factor, and no array losses (reasonable since the spacing is large). With these assumptions, the estimated annual capturable wind power was 157,000 MW (525,000 MW of wind turbines at 30% efficiency) with an annual energy production of 1,300 TWh. These results are somewhat larger than the estimates determined by PNL.

The estimates were further revised with data (at 40 and 50 m) from Alternative Energy Institute (AEI) met sites and private sites [28], which were then used to update the wind map (1 km pixel size) for Texas (Figure 9.9). The amount of class 3 and 5 lands was reduced from the previous estimate, while class 4

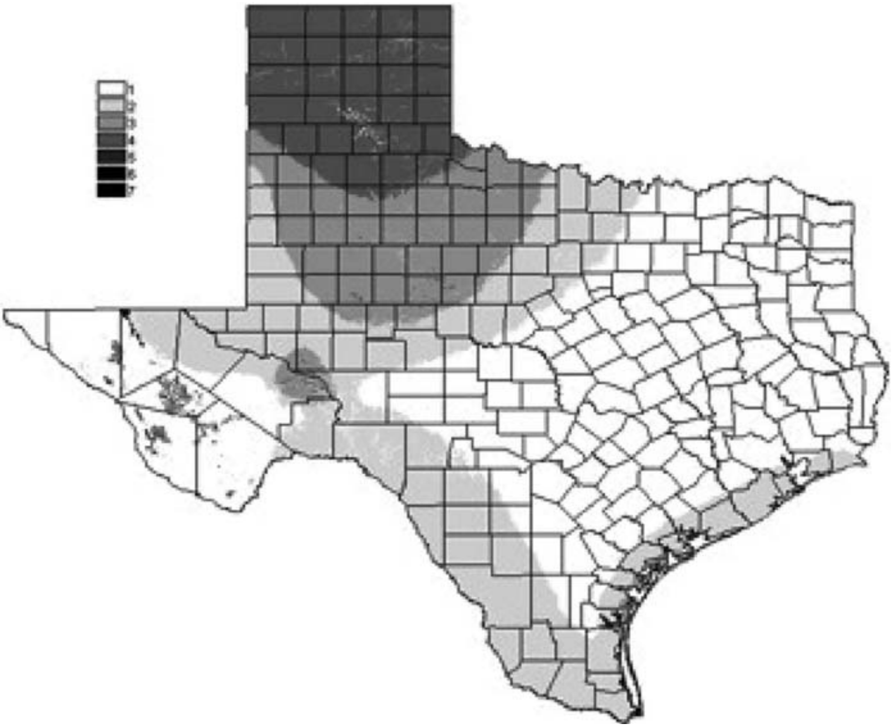

FIGURE 9.9 Wind power map for Texas, 1995.

lands increased. The selection parameters were the same, except for slope (areas with 0–10°) and located within 16 km of electrical transmission line, ≥69kV, for usable land for wind power (Figure 9.10).

The estimate for capturable wind power (Table 9.3) is also larger because a spacing of 7D by 9D was used and the capacity factor was 30% for class 3 lands and 35% for class 4 and above lands. The estimates show the large wind potential, even though this amount of capturable wind power, 172,000 MW, will never be installed when compared to the electrical generating capacity of Texas, 100,000 MW in 2008. Maps and estimates are available from the Alternative Energy Institute [29].

A number of wind farms have been built on mesas and terrain with exposure of edges or bluffs. In one area of West Texas (Pecos, Upton, and Crockett counties), 759 MW of wind farms has been installed on mesas. The major wind farms, close to 3,000 MW (installed from 2005 to 2008), are located from Abilene to Roscoe along Interstate Highway 10, and then northwest to Snyder along Highway 84. Some of these are on so-called mesas, with exposure on one side due to cliffs and bluffs.

The limit of proximity to transmission lines has now changed, as wind farms have been built within 40 km of major transmission lines. Also, the Texas Public Utility Commission is promoting new transmission lines to connect the Panhandle with the rest of the state. Without the constraint of proximity to transmission lines, the estimate for the amount of intercepted wind power is 850,000 MW with a capturable wind power around 270,000 MW. If offshore winds are included, then the estimate would be even larger.

9.5.3 Wind Power for the United States

Similar estimates have been made for the United States, regions and states. Winds of class 4 and above [30] with access to transmission lines are the most common criteria. The *State Wind*

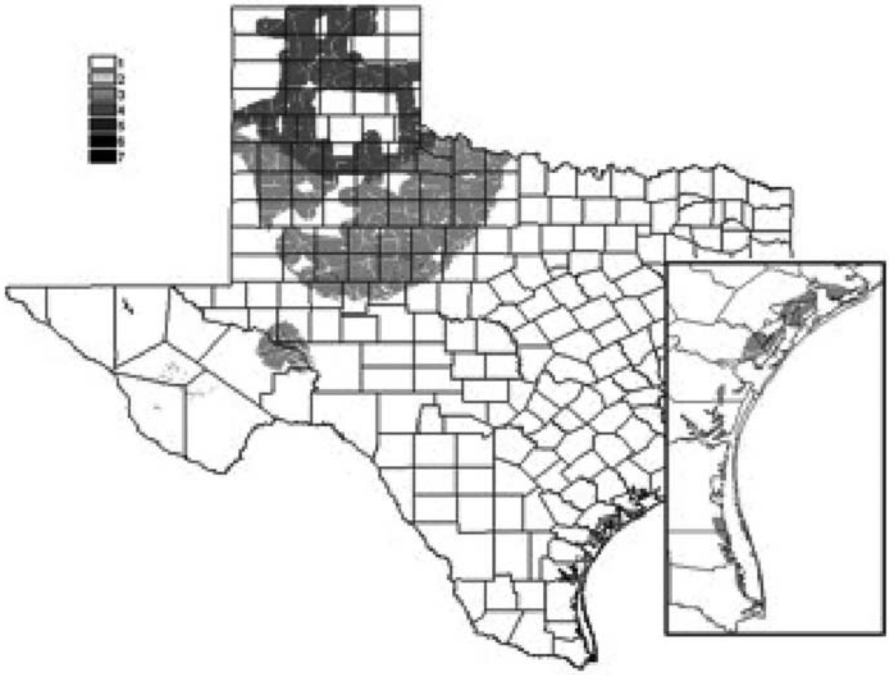

FIGURE 9.10 Land suitable for wind farms in Texas, 1995.

Working Group Handbook has articles and PowerPoint presentations by a number of different authors [31].

9.6 NUMERICAL MODELS

Numerical models for predicting winds are becoming more accurate and useful, especially for those areas of the world where surface wind data are scarce or unreliable. Models were primarily derived from numerical models for weather prediction [32]. Remember that a small difference in wind speed can make a large difference in energy. Therefore, in the final analysis, surface wind data are still needed for wind farms.

TABLE 9.3
Texas, Intercepted and Capturable Wind Power and Annual Energy Potential from Land That Satisfies the Screening Parameters

Wind Class	Area km²	Intercepted MW	Capturable Power MW	Energy TWh/year
3	69,299	302,365	90,170	795
4	41,391	232,196	81,269	712
5	42	288	101	1
6	54	471	165	1
7	2	22	8	
Total	110,788	535,342	172,252	1,509

MesoMap: The MesoMap system was developed specifically for near-surface wind forecasting. It is a modified version of the Mesocale Atmospheric Simulation System (MASS) weather model. MesoMap uses historical atmospheric data spanning 20 years and a fine grid (typically 1–5 km). MesoMap simulates sea breezes, mountain winds, low-level jets, changing wind shear due to solar heating of the earth's surface, the effects of temperature inversions, and other meteorological phenomena. MesoMap does not depend on surface wind measurements although surface measurements are desirable for calibration.

The model provides descriptive statistics at any height above ground, such as wind speed histograms, Weibull frequency parameters, turbulence and maximum gusts, maps of wind energy potential within specific geographical regions, and even the annual energy production of wind turbines at selected sites in the region.

WAsP: Wind Atlas Analysis and Application Program is software developed by Riso National Laboratory for predicting wind climate and power production from wind turbines. The predictions are based on wind data measured at stations in the region. The program includes a complex terrain flow model. WAsP was used for developing the European wind map (see Figure 4.3) and is used by many others across the world. Other models are available, so check the links listed below and the Internet.

9.7 MICROSITING

Wind maps, meteorological data from met towers, models, and other criteria are used for selection of the wind farm locations. Other considerations for the wind farm developer are the type of terrain (complex to plains); wind shear; wind direction; spacing of the wind turbines, which then depends on predominant wind direction and availability and cost of the land; and other items, such as roads, turbine, and substation. Terrain can be classified as complex, mesas, rolling, and plains. Passes may be primarily one type or a mixture. In general, spacing is given in terms of the diameter, D, of the wind turbine, so larger turbines will be farther apart.

As turbines have become larger, are wind shear data from 25 to 50 m sufficient to predict wind speeds at 70 to 100 m heights? The first answer is yes, for that site, although there is not a definitive answer at this point if the prediction is for another location in the same region.

In complex terrain, such as mountains and ridges, micrositing is very important, whereas in the flat plains, the primary consideration is spacing between turbines in a row and spacing between rows. On mesas, the highest wind speed is on the edge of the mesa facing the predominant wind direction, so there may be only one row of turbines. In rolling terrain such as hills, the wind turbines will be placed on the higher elevations.

In California, the high wind classes are due to the hot desert air rising and cooler air from the sea coming through the passes. There they have the complex terrain at Tehachapi Pass, rolling terrain of Altamont Pass (east of San Francisco), and both ridges and flat terrain at San Gorgonia Pass near Palm Springs. The winds in the passes are predominantly from the west, so the rows are primarily north–south. At San Gorgonia Pass some wind turbines were only 2D apart in the rows, and then 4D to 5D between rows because of the high cost for leasing the land for wind farms. With tight spacing, turbines could also be placed at different heights. As expected, the array losses are fairly large. Starting in 1998, the smaller-size turbines were being replaced with larger turbines.

The wind farm near White Deer, Texas, has eighty 1 MW wind turbines, which are 56 m diameter. The wind turbines have a spacing of 4D within the row and 8D between rows (Figure 9.11). North is at the top of the figure, and the lines indicate roads at 1 mile (1.6 km). Notice the buffer zone on the west, as that land was not under lease to the wind farm. Predominant winds are south-southwest during the spring and summer, and from the north in winter. As lower winds are in July and August, rows are situated perpendicular to those predominant winds. There are low spots due to playa lakes (only contain water after rain), so there are no wind turbines in those locations. Only the west side of the wind farm is visible in the photo, as there are more turbines to the east. Examples

FIGURE 9.11 West side of wind farm in the Plains, near White Deer, Texas. White lines are for roads, 2.5 km^2, 1 square mile. (Photo from Cielo Wind Power. With permission.)

of wind farms in other terrain are shown in Figures 9.12 to 9.14. A photo of an offshore wind farm is shown for comparison (Figure 9.15).

The amount of land taken out of production depends primarily on length and width of roads constructed on the wind farm. Values vary from 0.5 to 2 ha per wind turbine. If there are county roads, the wind farm developer will use less land; however, the developer will probably have to improve the county roads for the heavier traffic. If it is on a mountain ridge, the roads may be very expensive. The road from the bottom to the top for access to the Texas Wind Project at the Delaware Mountains cost $1 million in 1993.

There are the civil engineering aspects for wind farm site, such as location of assembly area, electrical substation, and roads (width and grade in complex terrain). Note that roads have to have wide turns for trucks hauling the long blades. In many cases a batch cement plant is on site, especially for complex terrain of ridges and mesas.

A general rule of thumb is that around 5–9 MW/km^2 can be installed on land that is suitable for wind farms. However, on ridgelines, at 2D to 3D spacing, the value would be around 8–12 MW/linear km. This assumes that the ridge is more or less perpendicular to the predominant wind flow. As wind turbines become larger, the megawatts per square or linear kilometer will increase due to

FIGURE 9.12 Wind farm in rolling terrain, Lake Benton, Minnesota. (Photo by Wade Weichmann. With permission.)

FIGURE 9.13 Wind farm on Southwest Mesa, near McCamey, Texas. Example of mesa with one row. (Photo from Cielo Wind Power. With permission.)

energy output increasing as the square of the radius. Notice that the landowner will lease blocks or areas of land, not just the places where turbines are located. It is interesting in the Texas Wind Power Project that land leased for the wind farm included all land at the 1,453 m contour and above (elevation of ridges is 1,830 m). The landowner is now trying to determine if any of the land below the contour has any wind potential.

Satellite and aerial images are used in micrositing and are available from different sources; some are free. Flash Earth (www.flashearth.com) has the option of switching between different sources, such as Google Maps, Microsoft VE, and others. The wind farms are fairly distinctive in the images, primarily because of the roads within the site and the area around each wind turbine. Be sure to zoom in enough to see the wind turbines, as oil fields show the same pattern, but the roads are not as wide. In some farming areas, round circles for irrigation sprinklers are very prominent; large circles

FIGURE 9.14 Wind farm in complex terrain, northwest Spain.

FIGURE 9.15 Nysted wind farm in the Baltic Sea, Denmark. (Photo from Siemens. With permission.)

are section sprinklers (1 square mile, 260 ha), and small circles are ¼-section sprinklers. Notice that the shadow of the wind turbines is more obvious than the wind turbines, and the angle of the shadow may be different from one part of the wind farm to an adjacent part, as the image was taken at a different date and time. Images from different sources will also be taken at different dates and times. New wind farms will not appear in the satellite images until they are updated, which could be more than a year.

Micrositing techniques of wind farm developers are proprietary. However, satellite images show the actual layout of wind farms, and from the images and topographic maps, a good idea can be obtained about the siting. If the type and model of wind turbine are known, then the spacing can be estimated from the image. The image of Trent Mesa, Texas (Figure 9.16), shows about half of the layout of the wind farm, which has 100 wind turbines, 66 m diameter, rated 1,500 kW.

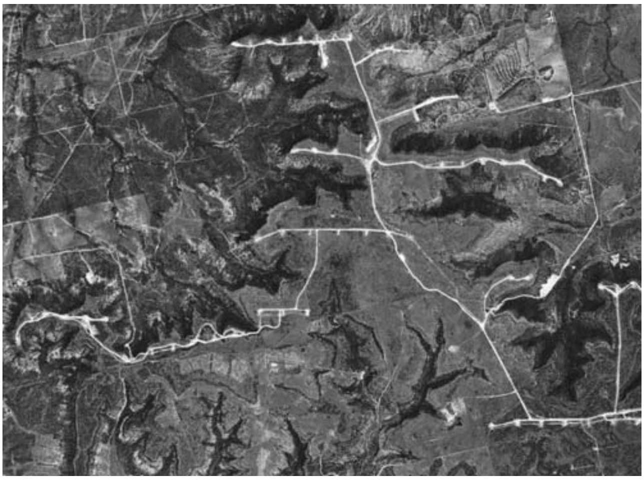

FIGURE 9.16 Satellite image of west side of Trent Mesa wind farm, Texas.

Economic and institutional issues also affect micrositing. A good example of all phases of a project is the Waubra wind farm (192 MW) in Australia [33], as the website has a description and photos from community relations, environmental to construction. A detailed site layout map is also shown.

9.8 OCEAN WINDS

Ocean wind observations (see Section 4.4) provide a complementary source of information for siting of offshore wind farms. The advantages of ocean wind maps are:

- Some satellite wind maps are public domain.
- All offer global coverage, which means really large areas without a large number of met towers.
- All are accessible in archives spanning several years.
- Accuracy is sufficient for wind resource screening.
- Ocean wind maps quantify spatial variations.
- Ocean wind maps are available in resolutions of 400 m, 1.6 m, and 0.25°.
- Software has been developed for their use.

The major problems with ocean winds are:

- Data are for 10 m height and values of wind shear are not known.
- Standard deviations are around 1.2–1.5 m/s on mean wind speed.
- Data are not available or not as reliable within 25 km of shore.

Ocean winds were used for wind resource estimation for Denmark [34]. Weibull parameters were calculated from the wind speed data to obtain a wind speed distribution, from which the wind energy production can be estimated.

The average wind speed for Padre Island, a barrier island off Corpus Christi, Texas, is 5.1 m/s at 10 m height, which is the same value for the ocean winds 25 km from the coast. Data from 10 to 40 m height indicated an annual average shear exponent of 0.19. A shear exponent of 0.15 was noted for a site 15 km off Cape Cod, Massachusetts [35]. Also, ocean winds, terrain, and predominant wind direction will indicate regions of wind potential for islands and near the shore. For example, ocean winds indicate an excellent wind resource for the islands of Aruba, Bonaire, and Curaçao off the northern coast of Venezuela.

9.9 SUMMARY

GIS provide a very flexible and powerful tool for terrain analysis relevant to wind energy prospecting. It can be used to reclassify the existing wind maps and to identify areas for meteorological measurements for possible wind farm sites. In addition, it can be used to quantify the wind power potential and, in conjunction with numerical models, to quantify the annual energy production.

Once a location is selected, then GIS and topomaps can be used in micrositing. The wind turbines should be located within the wind plant to maximize annual energy production. However, the 90 m resolution may not be detailed enough for micrositing in complex terrain. PNL used a technique of spline interpolation to fill in a finer grid from the 90 m data. Of course, if the DEM data at 10 m resolution are available, then the interpolation technique is not needed.

A number of numerical models for micrositing are available, and most run on a PC. More powerful programs for weather prediction and micrositing, which run on large computers or clusters of PCs, are also available. In general, these are commercial or the software package has to be purchased.

LINKS

Federal Wind Siting Information Center, www1.eere.energy.gov/windandhydro/federalwindsiting/.

D. M. Heimiller and S. R. Haymes, *Geographic Information Systems in Support of Wind Energy Activities at NREL*, NREL/CP-500-29164, 2001, available at www.osti.gov/bridge, or many of the other GIS publications in the NREL publications. More information on how the NREL maps are created, validated, etc.

Northwest mapping project, www.windmaps.org.

Regional Data and GIS Representation: Methods, Approaches and Issues—Scoping Workshop for GIS/Regionalization for EERE Models, www.nrel.gov/analysis/workshops/pdfs/brady_gis_workshop.pdf.

Trent Mesa Wind Project, www.trentmesa.com/default.htm.

Wind Powering America, www.eren.doe.gov/windpoweringamerica/where_is_wind.html.

Wind Resource Assessment Handbook, www.nrel.gov/docs/legosti/fy97/22223.pdf.

Information on software, models, etc.:

- MesoMap, www.awstruewind.com.
- 3TIER, www.3tiergroup.com/en/.
- EMD, WindPro, www.emd.dk/WindPRO/Frontpage.
- ReSoft, WindFarm, www.resoft.co.uk/English/index.htm.
- RETscreen, www.retscreen.net. Free software, decision-making tools.
- TRC, CAMET, and MM5 models, www.src.com/windenergy/windenergy_main.htm.
- WAsP, www.wasp.dk.
- WindFarmer, www.garradhassan.com/products/ghwindfarmer/.
- Wind Logics, www.windlogics.com/.

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8. Canadian Wind Energy Association. Small wind energy. www.smallwindenergy.ca/en/SmallWind.html.
9. *Small wind electric systems. A U.S. consumer's guide*. U.S. DOE, Renewable Energy and Energy Efficiency. www.nrel.gov/docs/fy07osti/42005.pdf.
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12. Wind Energy Integration in the Urban Environment. www.urbanwind.org.
13. Aerotecture International. www.aerotecture.com.
14. Urban Wind. Kirklees Council case study. www.urban-wind.org/admin/FCKeditor/import/File/Case_Study_UK1.pdf.
15. Aerovironment. Energy technology center: Architectural wind. www.avinc.com/Energy_Lab_Details.asp?Prodid=52.
16. Bahrain World Trade Center. www.bahrainwtc.com/index.htm.
17. Siting a wind turbine on your property, putting two good things together: Small wind technology and Vermont's scenic landscape. http://publicservice.vermont.gov/energy-efficiency/ee_files/wind/psb_wind_siting_handbook.pdf.
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31. Handbook available at Wind Powering America. www.eere.energy.gov/windandhydro/windpoweringamerica/pdfs/wpa/34600_wind_handbook.pdf.
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34. C. Jasager et al. Wind resources and wind farm wake effects offshore observed from satellite. Risoe National Laboratory, Wind Energy Department. www.risoe.dk/rispubl/art/2007_79_paper.pdf.
35. M. Swartz, D. Elliott, and G. Scott. 2007. Coastal and marine tall-tower data analysis. In *Proceedings, Windpower 2007*. CD.

GEOGRAPHIC INFORMATION SYSTEMS

Information is provided for PC versions of GIS: IDRISI and PC ARC/INFO. Mention of IDRISI and PC ARC/INFO does not imply any endorsement. Costs are in dollars (2008).

	IDRISI	PC ARC/INFO
Address	Clark Labs for Cartographic Clark University 950 Main St. Worchester, MA 01610-1477	Environment Systems Research 380 New York St. Redlands, CA 92373-9870
Telephone	508-793-7526	714-793-2863
Internet	www.clarklabs.org	www.esri.com/software/pcarc/
Academic/government	$675	Education discount
Community/private	$1,250	

PROBLEMS

1. A building is 20 by 15 m and 15 m tall. You want to install a 10 kW wind turbine. How tall of a tower and how far away from the building would you place it?
2. There are a number of trees (20 to 30 m in height) close to a house. You want to install a 10 kW wind turbine. What is the minimum height of the tower? What is the approximate cost of that tower?
3. Refer to Figure 9.3. The building is 15 m tall. What is the power reduction at 15 m height at a distance of 60 m downwind? At 150 m downwind? Would it be cheaper to use a taller tower or to move the location farther away from the building? Show all cost estimates.

4. Is there a small wind turbine in your region? If yes, what is the visual impact from the neighbor's view and from the public view? Use Tables 9.1 and 9.2 to estimate score.
5. Use Equation 9.1. Calculate the corrected power for a class 3 wind area if the terrain exposure is 80 m and area is grassland. Use the bottom and middle values for class 3.
6. Estimate the annual energy production for a 50 MW wind plant where the average wind power potential is 500 W/m^2 at 50 m height. Select the size of turbine from commercial turbines available today.
7. Do problem 6; however, now the land is high priced, so select close spacing and estimate array losses.
8. What size of land area do you need to lease for a 50 MW wind farm? Select the size of turbine from commercial turbines available today and the spacing. Remember, if your spacing between turbines is too close, you will have array losses. How may megawatts can you install per square kilometer?
9. The array spacing is 4D by 8D, for 3 MW wind turbines, 90 m diameter. How many can be placed in a square kilometer?
10. The row spacing is 2D for 3 MW wind turbines, 90 m diameter. How many can be placed per linear kilometer on a ridge?
11. Assume you have complex terrain. What size of land area do you need to lease for a 50 MW wind farm? You select the size of turbine from commercial turbines available today and the spacing. How may megawatts can you install per square kilometer?
12. In your opinion, what are some advantages and disadvantages of using vector or raster-based GIS in determining wind energy potential?
13. Check out two of the links on numerical models and see if they have any examples of wind maps. List website chosen, geographical region of wind map, and resolution of wind map.
14. For the White Deer wind farm (Figure 9.11), what is the land area allocated for each turbine? How many turbines can be placed in a square kilometer?
15. For the White Deer wind farm (Figure 9.11), if the roads are 7 m wide, estimate the amount of land taken out of production for the wind turbines within the square mile of Figure 9.11. Do not forget the space between each wind turbine.
16. Go to Flash Earth, www.flashearth.com, and search for White Deer, Texas (latitude, N 35°27'; longitude, W 101°10'). The wind farm is just to the northwest of the town. Zoom in to see the layout of the wind farm. Estimate approximate number of wind turbines per square mile for the wind farm. Remember, not all the land will have wind turbines on it within the area of wind farm.
17. Go to Flash Earth, www.flashearth.com, and search for the wind farms in San Gorginia Pass, California, just northwest of Palm Springs. Estimate the spacing for one of the densely packed wind farms.
18. How many met stations, at what height, and at what time period are needed for determining the wind potential for a 50 MW wind farm or larger? In general, terrain will not be completely flat. Also remember, wind turbines are getting larger, which means hub heights are larger. For your selection of number, height, instrumentation, and time period, estimate the costs.
19. Go to www.remss.com and look at QSCAT data for area off of Cape Cod and month of September 2007. Choose region "Atlantic, Tropical, North." What is the average wind speed and from what direction?
20. In the preliminary data collection for a wind farm, for how long should data be collected if:
    a. No regional data are available
    b. Good regional data are available.
    c. There are other wind farms in the area.
21. Go to www.topozone.com. Find quadrangle map that shows Mesa Redonda, New Mexico. It is in Quay County. What is the elevation of the mesa? You can see all of Mesa in

1:200,000 view. You will need 1:50,000 view to read elevation. Or go to www.newmexico.org/map/ or www.awstruewind.com (windNavigator) and use terrain map.

22. What is the general rule for MW/km^2 in plains and rolling hills? For MW/km for ridges and narrow mesas?
23. From Table 9.3, what is the estimated MW/km^2?
24. From Table 9.3, just using the general rule for km^2, what is the maximum MW of wind that could be installed? The maximum capturable power?
25. What is the annual wind speed at 100 m height on Mesa Redonda, New Mexico? Mesa Redonda is south of Tucumcari in eastern New Mexico. Use windNavigator [22].

10 Applications and Wind Industry

The main applications are the generation of electricity and water pumping (Table 10.1). Except for the installed capacity for wind farms, the other numbers are best estimates, as data are difficult to acquire. Applications for generation of electricity are divided into the following categories: utility-scale wind farms; small wind turbines, which include remote and stand-alone systems; distributed; wind-diesel; village power (generally hybrid systems); and telecommunications (high-reliability hybrid systems). Many village power systems use photovoltaic panels with battery storage, 1 to 3 days. There are wind hybrid systems and some wind power systems for village power. In some cases village power has diesel/gas for the backup. Stand-alone systems generally have batteries for storage.

There are wind-assist, where two power sources work in parallel to produce power on demand, and stand-alone systems. All wind turbines connected to the utility grid are wind-assist systems. In terms of size, wind turbines range from the utility-scale megawatt turbines for wind farms to small systems (≤100 kW) also connected to the grid to the 20–300 W remote units for sailboats and households, primarily in the developing world. Some people refer to these as micro wind turbines. Be careful of some vendors claiming that micro wind turbines will produce electricity cheaper than utility-scale wind turbines, as all you need to do is to connect a large number of them together.

10.1 UTILITY SCALE

The 94,000 MW installed at the end of 2007 produces an estimated 300 TWh/year. In Europe, the 1995 goal of 4,000 MW of wind by the year 2000 was way surpassed, and the later 2010 goal was set at 60,000 MW. In 2003 that was raised to a goal of 75,000 MW, and by 2007 there were already 57,000 MW installed, which generated 3.7% of the electrical demand. Now the European goal is 20% of electricity generated by renewables by 2020, of which 12–14% would be from wind. Of course, predictions are always risky, and the predicted megawatts change as projects and legislation are implemented and also changed. In Denmark, wind turbines supplied 21% of the electric consumption in 2007.

Offshore wind farms have been installed in Europe [1], with a capacity of 1,079 MW by the end of 2007. Examples are Horns Rev at 160 MW [2] and Nysted at 158 MW in Denmark. Offshore wind farms are being considered in the United States; however, there is substantial opposition to a wind farm off Cape Cod, Massachusetts. In the United States, there are four wind farms in Texas, which range in size from 523 to 736 MW, and John Deere is installing clusters of 10 MW wind farms. The 10 MW size allows for less regulation, but in clusters there are enough wind turbines to obtain economies of scale in installation.

In 2007 there were around 14,800 wind turbines installed in thirty-five countries in the world, with a capacity around 20,000 MW. This was a growth rate of 32% from the previous year (see Figure 1.12), and 43% were installed in Europe. Notice that the average size of wind turbines is now over 1 MW. The Global Wind Energy Council lists installed capacity in 2007 by region (Table 10.2) and each country within the region [3]. The United States was the largest market, followed by China and Spain. The growth of wind power in China was phenomenal (over double), as 3,304 MW was installed in 2007 [4], and the goal of 5,000 MW by 2010 was reached 3 years ahead of schedule. The domestic wind turbine industry in China accounted for 56% of the 2007 market, and two companies, Goldwind and Sinovel, accounted for 46% of the 3,304 MW, which also places them in the top ten suppliers in the world.

TABLE 10.1
Wind Industry Overview, Estimates (Data Given for 1995, 2002, and 2007 as a Comparison)

	1995	2002	2007
Utility scale, number	22,000	50,000	100,000
Installed capacity, MW	4,800	31,000	94,000
Production, kWh/year	$5 * 10^9$	$1 * 10^{11}$	$3 * 10^{11}$
Small systems, number	150,000	370,000	600,000
Installed capacity, MW	15	55	200–250
Wind-diesel, number			200
Village power, number	10–30	150–?	1,800
Telecommunication	20–50	150	200–?
Farm windmill,[a] number	300,000	305,000	310,000
Production/year	3,000	3,000	3,000

[a] Farm windmills are being replaced by electric pumps and PV pumps, and production primarily replaces 30- to 40-year-old windmills.

Three driving forces for installation of wind farms are economics, policy and incentives at the national and state levels, and the negative public perception of nuclear power, as some countries have even voted to shut down their nuclear power plants. Green power and reduction of pollution and emissions also assist in expanding the wind energy market.

European manufacturers dominate the market, and there has been continued consolidation of major manufacturers. The top six manufacturers have over 85% of the market, and then fifteen companies dominate the market with close to 98% share (Table 10.3). The United States has only one major manufacturer, and there has been the emergence of major manufacturers in China (Goldwind, Sinovel) and India (Suzlon). Notice with the large megawatt units that the number of units installed is around the same as the number of megawatts installed. Also notice that the production in 2007 of 22 GW is higher than the 20 GW installed as wind turbines were shipped but not commissioned by the end of the year. One global market projection is for 240,000 MW of wind power by 2012 [3], with much of the new installations in Asia.

10.2 SMALL WIND TURBINES

There is an overlap of small wind turbines with village power systems, as most of these wind turbines are less than 100 kW, and it is also the same for some of the distributed and wind-diesel systems. In

TABLE 10.2
World Installed Wind Capacity (MW) by Region for 2006 and 2007

	Total 2006	New 2007	Total 2007
Africa and Middle East	378	160	538
Asia	10,659	5,436	10,091
Europe	48,563	8,662	57,136
Latin America and Caribbean	807	30	537
North America	13,035	5,630	18,664
Pacific	1,000	158	1,158
World total	74,141	20,076	94,123

TABLE 10.3
Estimation of Global Installed Number and Capacity and Production for 2007 by Manufacturers of Large Wind Turbines

	By End of 2007		2007
Company	Total No.	Total GW	Production MW
Vestas	35,000	28.2	4,500
Enercon	12,273	13.7	2,480
Gamesa	10,000	13.0	3,000
GE Wind	8,400	11.3	3,280
Siemens	6,579	6.1	1,250
Nordex	3,269	3.9	600
Suzlon	3,000	3.0	1,870
Goldwind	2,882	2.4	830
Acciona	1,700	2.6	780
Mitsubishi	1,736	1.6	500
Ecotécnia	1,531	1.6	400
REpower	1,400	1.4	600
DeWind	550	0.5	
Fuhrländer	513	0.5	
Sinovel	453	0.6	680
Others		3.8	1,400
Total	89,786	94.2	22,180

Note: Much of the data were obtained from manufacturers' websites.

the United States and Europe, probably one-fourth or more of the small wind turbine capacity is grid connected. In China [5] and other developing countries, most are stand-alone systems for households, 50–300 W. So the numbers reported for production of small wind turbines will include all areas. A very rough estimate for global number of small wind turbines (50–100 kW) is 550,000 to 625,000 with a capacity of 200–250 MW (Table 10.4). The wide range is due to unknown accuracy of the production in China of 150,000 units in the 4 years 2004–2007 (most in the 300 W size).

There are approximately 100 manufacturers, with around 40 in Europe [6] and 30 in China. The largest production was in China, with 51,000 units in 2006, of which 16,000 were exported [7], primarily to other Asian countries. In the past, most of the Chinese production was 50–100 W wind turbines

TABLE 10.4
Small Wind Turbines in the World as of 2007

	No. Company	No. Produced
United States/Canada	13	106,000
Europe	38	72,000
Asia	35	425,000
Other	14	22,000
Total	100	625,000

Note: Total number of units produced by region; however, some are exported to other regions.

FIGURE 10.1 Small wind turbine, 50 W, remote household, Inner Mongolia, China. Note rope on tail for manual control, even though it has hinged tail for automatic furling.

for remote households (Figure 10.1). The small wind turbines provide enough electricity for a couple of lights, a radio, and a small black-and-white TV. The unknown in China is how much of the present production is for replacement of old wind turbines and how many are upgrades from the 50–100 W size units to 200–500 W and even 1 kW turbines. Marlec and Ampair in the United Kingdom and Southwest Windpower in the United States produce large numbers of micro wind turbines.

The United States is a leading producer of small wind turbines in the 300 W to 50 kW range. The total installed capacity in the United States is around 70 MW, with most of the units up to 1 kW being off-grid. In 2006, 6,800 units (capacity, 17.5 MW; average size, 2.5 kW) were sold in the United States, with 98% produced in the United States [8]. The export market for U.S. manufacturers in 2006 was 9,000 units (capacity, 18 MW; average size, 2 kW).

The National Wind Technology Center (NWTC), National Renewable Energy Laboratory (NREL), has a development program for small wind turbines and a small wind Turbine Verification Program [9]. The American Wind Energy Association has a small wind section, which includes Global Market Studies, 2005 and 2007, and U.S. Roadmap [10]. The Roadmap estimates that small wind could provide 3% of U.S. electrical demand by 2020.

10.3 DISTRIBUTED SYSTEMS

Distributed systems are the installation of wind turbines on the retail side of the electric meter for farms, ranches, agribusiness, small industries, and small-scale community wind for schools, public lighting, government buildings, and municipal services. As an example, in Lubbock, Texas, the American Wind Power Center and Museum installed a 660 kW unit, a cottonseed oil plant installed ten 1 MW units, and three school districts in nearby towns have installed eight 60 kW units.

By 2007, there were approximately 270 MW of community wind projects installed in the United States. In the United States the market for farm/industrial/business and community is estimated at 500 MW by 2010 and 3,900 MW by 2020 [11]. Distributed wind systems will have an impact especially on smaller utilities and electric cooperatives [12]. The international market is difficult to measure, as most of that market would be in village power and remote systems; however, for farm/industrial/business, the market is estimated at 400 MW by 2010 and 600 MW by 2020.

Distributed wind turbines for farmers, ranchers, and agribusinesses will be somewhat similar to the farm implement business. The barriers and possible incentives for distributed wind applications are:

1. Cost, not enough production to get economies of scale
   a. Favorable life cycle costs will not sell these wind turbines.
   b. Payback has to be 4 to 6 years.
   c. That means they have to compete almost directly with cost of electricity from utility, \$0.10–0.15/kWh.
2. No infrastructure
   a. Enough units have to be installed in a region for local business for sales and O&M. Within a 250 km radius, need \$1,000,000/year in sales. At \$50,000/unit that would be twenty units sold per year.
   b. For O&M need around 300 units installed in that area, 250 km radius.
   c. In time, distributed wind should be like the farm implement business. A large tractor costs over \$200,000.
3. Not enough selection of wind turbine sizes

   In 2008, Fuhrländer suspended production of its 30–600 kW units due to lack of supply of components and the big demand for utility-scale turbines.

   Suggested sizes for rural, grid connect:

   Residential: 10 kW
   Farm-ranch resident: 50 kW
   Agribusiness: 100, 250 kW
   Large agribusiness: 500–1,000 kW

   In a sense, they should be modular components. For example, Wind Eagle has a 30 or 50 kW unit, depending on wind regime. Again, once started, there will be a trend toward larger sizes.
4. For agribusiness, need to sell total package
   a. Wind turbine, electrical energy
   b. Demand side management
   c. Service
5. Incentives
   a. Able to use production tax credit.
   b. For irrigation market, wind class 3 and above, net energy billing on year basis for units up to 500 kW. The introduction of net energy billing of 50 kW (residential size wind turbines) in Texas resulted in essentially zero sales.
   c. Benefits for NOX and SOX: When carbon trading arrives, then distributed wind turbines need to be included.
   d. Installation of distributed wind turbines on rural electric cooperative grids.

There are projects classified as community wind [13], but they are not strictly distributed systems. Two or more farmers could purchase large wind turbines on a cooperative basis. In Minnesota, there are farmer-owned wind projects under 2 MW, with one or two large turbines, as there was a state production incentive of \$0.015/kWh for the first 10 years. Sixty-six farmers raised 30% of the \$3.6 million cost of four turbines (950 kW) for two projects. The remaining 70% was raised through local banks. A *Community Wind Development Handbook* [14] was developed on behalf of the Rural Minnesota

Energy Board. In Denmark, at the end of 2005, individuals or wind turbine cooperatives owned 83% of the 5,293 wind turbines. In terms of capacity, privately owned wind turbines had 77% of the capacity. The capacity percentage will probably decrease with the installation of more offshore wind farms.

10.4 WIND-DIESEL

For remote communities and rural industry the standard is diesel generators. Remote electric power is estimated at over 11 GW, with 150,000 diesel gensets, ranging in size from 5 to 1,000 kW. In Canada, there are more than 800 diesel gensets, with a combined installed rating of over 500 MW. In the State of Chubut, Argentina, they have village systems using diesel generators, which range from 75 kW in a small village to 1,250 kW for a large village. Because the systems are subsidized, from the state to the national level, it is difficult to determine the actual cost of electricity. In general, past costs were $0.20 to $0.50/kWh; however, it is now quite a bit higher, as oil is over $100/bbl.

Diesel generators are inexpensive to install; however, they are expensive to operate and maintain, and major maintenance is needed from every 2,000 to 20,000 hours, depending on the size of the diesel genset. Most small village systems only have electricity in the evening.

In Canada there are more than 300 remote communities with diesel-generated electricity, and coastal Alaska has around 90 villages, which have the potential for displacing diesel fuel with wind (see Section 8.6 for wind–diesel performance at Kotzebue, Alaska). Australia, Argentina, northeast Brazil, Chile, China, Indonesia, Philippines, coastal sub-Sahara Africa, and of course other countries with isolated villages and islands have the potential for wind–diesel systems. The design of wind–diesel systems plus modeling techniques and simulation is better now that operational experience at a number of sites is available.

Wind–diesel systems were developed and tested at Riso National Laboratory, Denmark; Netherlands Energy Research Center, Petten, Netherlands; Atlantic Wind Test Site, Prince Edward Island, Canada; National Renewable Energy Laboratory, United States; United Kingdom; and at other locations. Primary work was on developing wind–diesel systems for the retrofit market. This market would be for existing diesel generators in windy locations, which would be over 50% of the installed capacity. A wind biodiesel system is being tested at USDA-ARS, Bushland, Texas [15].

Wind–diesel [16, 17] is considered because of the high costs for generating power in isolated systems, and by 1986, more than a megawatt of wind turbines were installed with existing diesel systems. Today, a very rough estimate indicates there are around 200 wind–diesel systems, but the market is changing rapidly with the high cost of diesel fuel. Two manufacturers expect to install over 1,200 MW of wind at existing diesel plants in 2008–2009. Simulation models for wind–diesel systems are available.

There are two aspects: addition of wind turbines to existing diesel power plants as a fuel saver, and now integrated wind–diesel or wind hybrid systems for village power. Wind–diesel power systems can vary from simple designs in which wind turbines are connected directly to the diesel grid (Figure 10.2), with a minimum of additional features, to more complex systems [18]. Wind–diesel power systems have peak demands of 100 kW to a megawatt, based on AC bus configurations, and storage is needed for high penetration. However, there are a number of problems in integrating a wind turbine to an existing diesel genset: voltage and frequency control, frequent stop–starts of the diesel, utilization of surplus energy, and the use and operation of a new technology. These problems vary by the amount of penetration (Table 10.5). Wind turbines at low penetration can be added to existing diesel power for large communities without many problems, as it is primarily a fuel saver. One solution for high wind penetration is the use of flywheels or battery storage [19, 20].

There have probably been more than 200 wind–diesel projects from prototypes to operating systems. Reports on operational experiences from eleven wind–diesel installations are available from the 2004 workshop [21]. The U.S. Air Force installed four 225 kW wind turbines connected to two 1,900 kW diesel generators (average load, 2.2–2.4 MW) for a low-penetration system on Ascension Island [22]. Average penetration was 14–24%. Tower height was limited to 30 m due to

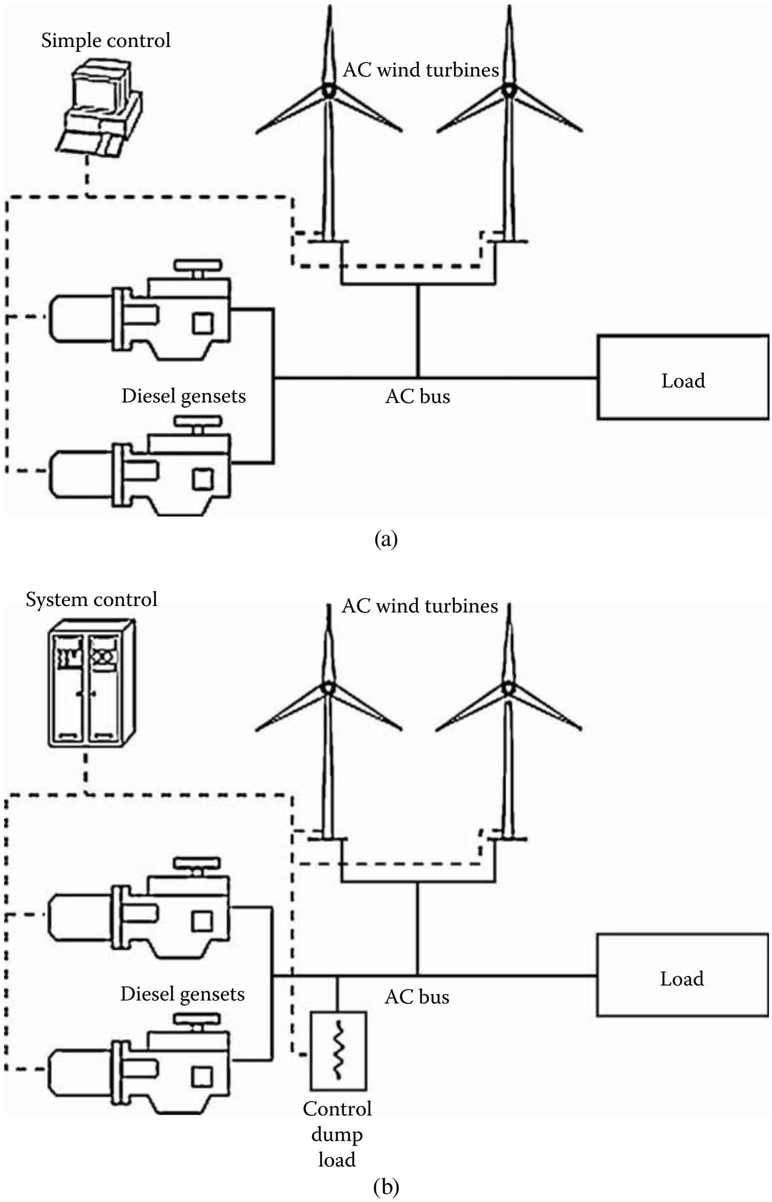

FIGURE 10.2 (a) Low-penetration diesel without storage. Diesel governor and voltage controls maintain system power quality. (b) Medium penetration with system control and dump load for high winds and medium diesel power. (c) High penetration with flywheel storage.

available crane capacity on the island. Then in 2003, two large wind turbines (900 kW), controllable electric boilers, and a synchronous condenser were installed that brought the average penetration to 43–64% [23]. Fuel consumption was reduced significantly, with a savings of approximately $1 million per year. Wind penetration ratios exceeding 40% usually have stability problems; however, reliable and stable power was delivered at 80% power penetration. Cape Verde had eleven wind–diesel systems, with energy penetration of 14% and power penetration of 35%, with some problems [24]. Three of the systems were not working in 2005. Wales, Alaska, had a high-penetration

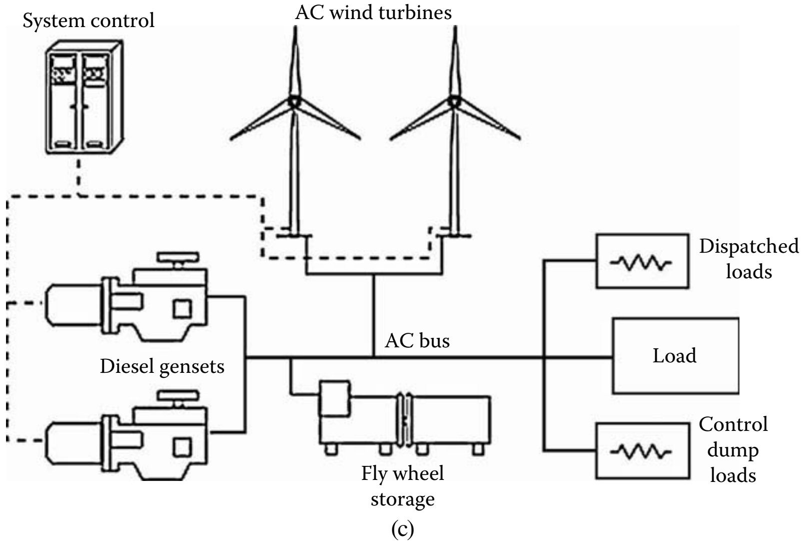

FIGURE 10.2 (*Continued*)

system (Figure 10.3) with battery storage [25, 26]. Wind turbines (3,250 kW) were added to the diesel system (four 1,200 kW) on King Island, between Tasmania and Australia, and wind power provided 18% of the electrical demand. In 2003, another 1,700 kW of wind power and a 200 kW battery and inverter system were added [27] to produce around 50% of the electrical demand. The large-flow vanadium redox battery reduces the variability of the wind energy.

Wind–diesel and wind hybrid systems are now available for village power, so the wind becomes an integral part of the original design [28]. A number of wind turbine manufacturers have wind–diesel or wind hybrid options [24]. These range from simple, no storage systems to complex, integrated systems with battery storage and dump loads.

Installation of wind-diesel systems and associated R&D has taken place for a number of years. There have been many configurations, but not too much consensus and replication. The technology is still not mature, and the village power market is not large enough. There is a lot of information from proceedings of wind-diesel workshops [21].

TABLE 10.5
Penetration (Class and Percent) for Wind-Diesel Systems

Class	Operating Characteristics	Peak Instantaneous	Annual Average
Low	Diesel runs full-time	<50%	<20%
	Wind power reduces net load on diesel		
	All wind energy goes to primary load		
	No supervisory control system		
Medium	Diesel runs full-time	50–100%	20–50%
	At high wind power levels, secondary loads dispatched to ensure sufficient diesel loading or wind generation is curtailed		
	Requires relatively simple control system	100–400%	50–150%
High	Diesels may be shut down during high wind availability		
	Auxiliary components required to regulate voltage and frequency		
	Requires sophisticated control systems		

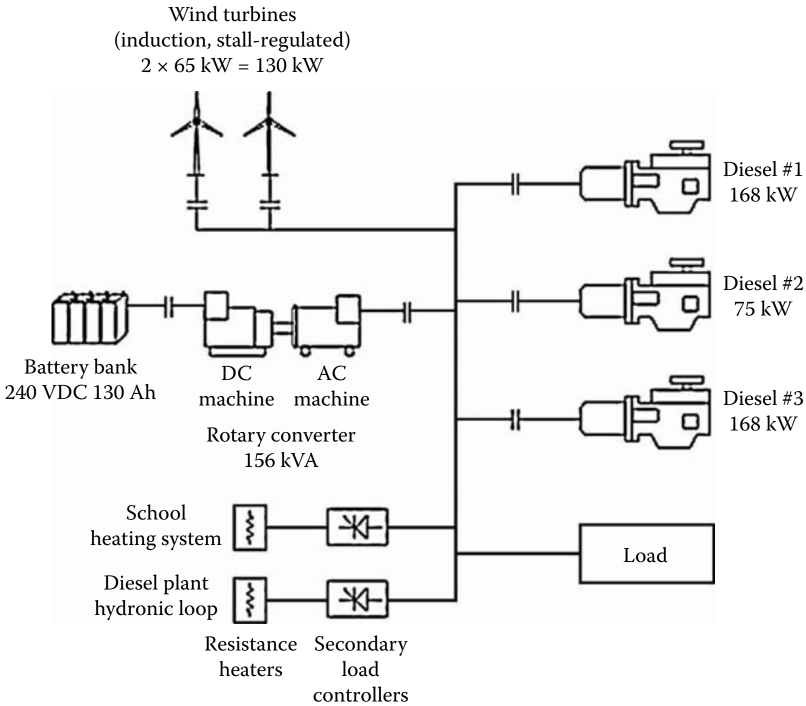

FIGURE 10.3 Diagram of high-penetration, wind–diesel system with battery storage, Wales, Alaska.

10.5 VILLAGE POWER

Around $1.6 * 10^9$ people do not have electric service because they are too far from transmission lines of conventional electric power plants. Extension of the grid is too expensive for most rural areas, and if extended, it has poor cost recovery. There is an effort to bring electricity to these villages using renewable energy (wind, PV, mini and micro hydro, biomass). Other components to supply reliable energy (limited) include controllers, batteries, and conventional diesel/gas generators. In windy areas, wind is the least-cost component of the renewable power supply.

Village power systems provide power to the community from a central power source, a mini grid. Village hybrid power systems [29] can range in size from small micro grids (<100 kWh/day, ~15 kWp) to larger communities (tens of MWh/day, hundreds of kWp). One or multiple wind turbines may be installed, 10–100 kW range. There are software programs for modeling hybrid systems [30, 31]. Notice the primary difference between village power and wind–diesel is in the size of the system, although there will be overlap.

There have been international conferences for village power, and NREL had a project database with 146 projects (1994–2000), of which 14 included wind. Global Village Energy Partnership provides information and publishes a newsletter [32]. Manufacturers' websites may show case studies; for example, Bergey Windpower has case studies of different types of installations that include village power [33].

The village renewable systems are the following types:

- Fuel saver system, addition of renewable energy system to existing diesel power plant (see Section 10.4)
- Renewable energy source, single or hybrid, with battery storage (Figure 10.4)

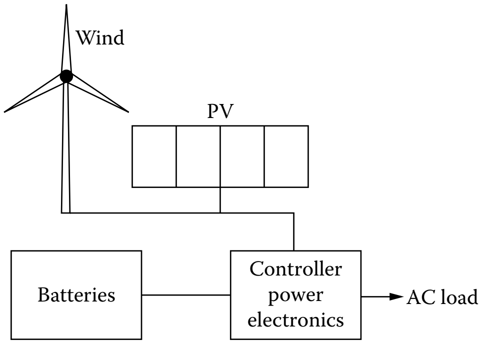

FIGURE 10.4 Diagram of hybrid wind/PV system with battery storage.

- Renewable energy source, single or hybrid, diesel/gas generator
- Renewable energy source, single or hybrid, diesel/gas generator with battery storage

The advantages of village power systems using renewable energy are:

- Provide AC or DC power for remote areas. For a system of any size, AC is the standard.
- Provide electricity for productive uses.
- Modular.
- No or small fuel costs.
- Lowest life cycle cost of electricity.
- May be owned and operated by local entities.

The disadvantages are:

- High initial capital cost compared to diesel generators
- More complex: sophisticated controllers, power conditioning, batteries
- High growth in demand—means there is not unlimited usage (load management, load limitation)
- Few suppliers, few systems installed, need high-volume production
- Infrastructure, who maintains (trained personnel), how much consumers pay for electricity

Institutional issues are more important than the technical issues, especially for demonstration projects. Many demonstration projects can become very political, and the social issues dominate over the technical issues. Institutional issues are:

- Planning, which includes locals before installation
- Cost, subsidies (who, how much), repairs paid when
- Ownership
- Operation and maintenance, training of operators
- Financing: world (multilaterals), other national aid agencies (lateral), and nongovernment organizations; national, state, local, and private organizations
- Tariff design, metering, ability and willingness to pay
- Load growth, education of users
- Quality of service
- Economic development versus social services (schools, clinics)
- Cultural response
- Institutional cooperation: local, state, national, electric utilities, financing

TABLE 10.6
Configuration of the Five Village Power Systems (Hybrid with Batteries) in Bulunkou Township, China (Wind Turbine Size, 10 kW Each)

	Bulunkou	Subashi N.	Subashi S.	Gaizi	Kahu Lake	Total
Wind	20 kW	20 kW	10 kW	20 kW	10 kW	80 kW
Solar	4 kW	4 kW	0	2 kW	0	10 kW
Diesel	30 kVA	30 kVA	15 kVA	30 kVA	15 kVA	120 kVA
Inverter	30 kVA	30 kVA	15 kVA	30 kVA	15 kVA	120 kVA
Battery bank	1,000 Ah	1,000 Ah	500 Ah	1,000 Ah	500 Ah	4,000 Ah
Mini grid length, m	1,200	750	3,600	590	350	6,490
Number of posts	18	12	69	85	5	189

10.5.1 China

There are around 1,800 renewable village power systems in the world (a very rough estimate), with over 1,250 in China. Around 100 renewable village power systems from 5 to 200 kW were installed in China by 2000; however, there were still over 21,000 villages and 7 million households without electric service [34, chap. 2]. Since then, China leads the world in installation of renewable village systems, of which 100 include wind. One example is the electrification of five villages in Bulunkou Township (Table 10.6) in Xinjiang Uigur Autonomous Region, China [34, chap. 5].

China started a Township Electrification Program in 2002, whose goal was to provide electricity to 1.3 million people in seven western provinces. The program called for 1,013 village power systems with a capacity over 18 MW: 292 small hydro, 689 PV, 57 PV/wind, and 6 wind systems (Table 10.7). Because the projects required some funding from the townships, not all the planned projects were installed. Notice the large difference in average size of the mini hydro versus PV and PV/wind systems, 780 kW versus 22 kW. In 2005, sixty-six of the PV/wind hybrid systems were

TABLE 10.7
Renewable Village Power Systems and Single Household Systems (SHS) from SDDX Program in Western Provinces of China

Province	PV/Wind	Cap kW	Mini hydro	Cap kW	SHS	Cap kW
Tibet	329	6,763	72	16,470		
Qinghai	112	2,715			6,800	136
Xinjiang	110	1,417	1	110	2,886	144
Corps	49	961			4,247	212
Inner-Mongolia	42	752			1,525	610
Gansu	23	995	8	35,190		
Sichuan	46	1,817	21	21,990		
Shaanxi	9	100	16	21,985		
Chongqing			3	4,840		
Yunnan			4	4,460		
Jiangxi			2	1,650		
Hunan	1	20	19	7,070		
Total	721	15,540	146	113,765	15,458	1,102

FIGURE 10.5 Fourteen of the 21 wind turbines, 10 kW each, at Mazongshan Township, Gansu Province, China. (Photo by Charlie Dou. With permission.)

visited to check on performance. A large hybrid village system (Figure 10.5) is in Gansu Province, which had a projected load of ~235 kW. Mazhongshan Township was 158 km from the nearest utility grid. The village power system consists of 210 kW wind power and 90 kW PV, which is divided into three groups. Each group includes seven 10 kW wind turbines, 30 kW PV, a battery bank of 240 V, 3,000 Ah, and a 100 kW DC–AC inverter, and the system provides electricity to one part of the township.

10.5.2 Case Study: Wind Village Power System

Huaerci [34] is a village in the mountainous area of eastern Xinjiang Province with 90 households, 360 inhabitants, with the primary economic activity being animal husbandry. The income per capita is well below the national poverty level. The distance to the nearest electricity grid is 110 km, and the roads are very bad. Lighting at night was provided by candles, and for children to do their homework, most families used two candles per night. The renewable resources are wind (annual mean wind speed, 8.3 m/s) and solar (annual average, 3,100 h).

The system configuration chosen was a single 10 kW wind turbine, a 55 kWh battery bank, and a 7.5 kW DC–AC inverter. The system produces around 50 kWh/day. The project was financed by a government-subsidized loan, 5 years at 3% interest.

The system provides 24 h power for the ninety households, two village offices, a school, and a TV transmitting station. All lightbulbs are energy saving, and since installation of the system, ten color TVs, thirty black-and-white TVs, and one CD player have been purchased. The peak residential load is about 5 kW, and energy consumption is around 300 kWh/month, with an additional 45 kWh/month for the institutional loads.

A Village Power Management Committee is composed of village officials, representatives of the villagers, and the deputy director of the border control stations. A tariff of 1.2 Yuan/kWh ($0.16/kWh) is charged to all customers. Most of the revenue will be used for maintenance costs, so there should be enough cash flow to replace the battery bank, but the village power system is not fully commercialized. There is a part-time operator. No productive loads are served to date due to limited system capacity.

Lessons learned are:

- Load analysis and prediction is important. Proper system configuration to match the load is a critical factor for system cost recovery.
- Six renewable energy village power systems have been developed in Barkol County. This provides a great opportunity to develop a multiple project management entity and to introduce a commercialized model to ensure sustainability.

- Productive loads should have been established at the beginning.
- A skillful technical operator should also provide some services to users and encourage wise use of electricity.

The large initial investment for renewable energy village power is beyond the financial resources of the local residents and local government.

Four villages in Barkol County have been powered by renewable energy since 1999. Each one is powered by a wind turbine system, and another two large villages are powered with a 30 kW wind system.

10.6 WATER PUMPING

The pumping of water and sailboats are the oldest and longest-term uses of wind power. The two common examples of mechanical water pumping are the historical Dutch windmill for pumping large volumes of water from a low lift and the farm windmill for pumping small volumes of water from a high lift [35–37].

For mechanical windmills or wind turbines the important considerations are the power in the wind and how that power can be transferred by the system. This means that the characteristics of the wind turbine (primarily the rotor) and the characteristics of the pump are combined in an operating system. The type of pump in many cases dictates the mode of operation of the rotor and how the rotational shaft power is transferred to pump power. Of course, the size of the system depends on the dynamic pumping head and the quantity of water to be pumped. For the farm windmill, the efficiency depends on the load matching of the rotor to a positive displacement type, in general a reciprocating pump (piston).

The American farm windmill (Figure 1.3) is still in widespread use around the world for pumping low volumes of water from wells or boreholes. It is estimated that there are around 80,000 operating in the Southern High Plains of the United States. World production is estimated at 3,000 per year. The American farm windmill is well designed for pumping small volumes of water for livestock and residences, and the design has not changed since the 1920s and 1930s. The only change has been in materials used for bearings and the use of plastic pumps and drop pipes.

The American farm windmill is characterized by a high-solidity rotor (also called a wheel) consisting of fifteen to eighteen blades (also called vanes), which are normally made in a slight curve (Figure 10.6). The large number of blades provides a high starting torque that is needed for operating the piston pump. Most units have back gearing (reduction in speed) that transfers the rotating motion of the rotor to a reciprocating motion for pumping water. All wind turbines have a way to reduce efficiency and not capture all the energy possible at high winds. On the farm windmill the rotor axis and yaw axis are offset to rotate (yaw) the rotor out of the wind. This is called furling. At low wind speeds, the tail and the spring bring the rotor perpendicular to the wind.

The rotor has a peak power coefficient (C_P) of about 30% at a tip speed ratio of around 0.8. The efficiency for a reciprocating displacement pump is essentially constant at 80% over the operating range of wind speeds. The overall annual efficiency (wind to water pumped) is around 5 to 6% (see Section 8.5).

In the 1970s and 1980s, different research groups and manufacturers attempted to improve the performance of the farm windmill [35, chap. 5] and reduce the cost. Many of these projects were designed to pump water in developing countries. Designers believed that the performance could be increased by the following changes:

1. Reduce the solidity (reduce the number of blades or area of blades), which means higher rotor rpm.
2. Change the characteristics of the pump by using variable stroke or variable volume to match the characteristics of the rotor.
3. Develop a windmill for the low wind regions of the tropics.
4. Counterbalance the weight of the rods, pump, and water column.

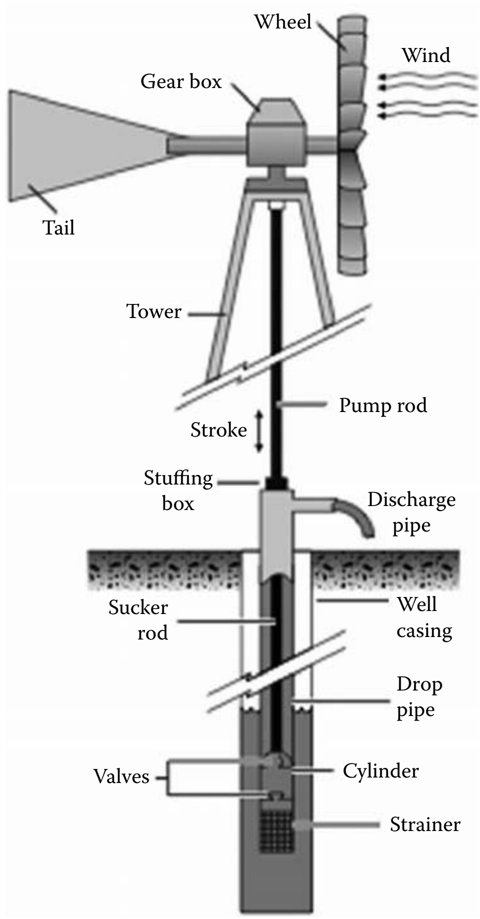

FIGURE 10.6 Schematic diagram of the American farm windmill.

The Agricultural Research Service, USDA, and the Alternative Energy Institute, WTAMU, have tested some of these concepts in their cooperative program on wind energy for rural applications [38]. A company in South Africa has a windmill with a rotating helix pump [39].

Costs can be reduced by using local materials, local light industry manufacturers, and new windmills designed for developing countries. One option is the use of the Savonius rotor for low-volume, shallow water. Another option is a wind turbine driving an air compressor and an airlift pump. However, the problem is still the same: the rotor is connected to a constant-torque device.

10.6.1 Design of Wind Water Pumping System

The requirements for the various applications differ in that water for livestock and residences is low volume with a storage tank, while villages require potable water with a storage tank for low or high volume, depending on the size of the village, and irrigation requires large volumes and generally does not need a storage tank. The steps to consider in designing or sizing a water pumping system are:

1. Water demand: livestock, residence, village, irrigation
2. Water resource: surface, well, volume available

TABLE 10.8
Livestock Water Requirement

Animal	Liter/Day
Cattle, beef	40–50
Cattle, dairy	60–75
Camels	40–90
Sheep and goats	8–10
Swine	10–20
Horses	40–50
Chickens (100)	8–15
Turkeys (100)	15–25
Evaporation	800–1,200

3. Hydraulic power: volume times dynamic head
4. Wind resource
5. Comparison of other power sources
6. Design considerations

The design process has other considerations in the final analysis: economics, operation and maintenance, institutional issues, equipment life, and future demand (addition or expansion of the system).

The average daily demand (m^3/day) is estimated for the month of high demand or the wind design month (month with lowest average wind speed). Also, the demand must take into account any growth during the design period, which should be at least 10 years. The water demand for livestock can be up to 90 L/day (Table 10.8). Evaporation from an open storage tank, especially in windy and dry areas, will require even more water. Also, animals will only travel a limited distance from the water source, so there needs to be one water source per 250 ha to harvest grassland. If the water supply and grassland are communal, then there is the distinct possibility that the growth in the size of the herds will result in overgrazing, especially close to the water supply.

The domestic water depends on number of people, usage, and type of service (Table 10.9). What is considered necessary in some countries or regions would be considered a luxury in others. In addition, people will consume more water during hot, dry periods. Local water consumption is the best guide; however, remember that usage per person will probably increase if water availability improves. Village water supply includes clinics, stores, schools, and other institutions. Growth in demand will depend primarily on water availability, growth in size of herds or flocks, and growth in population for villages. Again, the growth in population should be estimated from present local trends.

Water demand for irrigation (low or high volume) will depend on local conditions, season, crops, and evapotranspiration. These data are generally available from regional or national government agricultural agencies.

TABLE 10.9
Typical Water Consumption per Person

Service	Liter/Day
Stand post	40
Yard tap	75
Home connection	100
U.S. farm residence	125

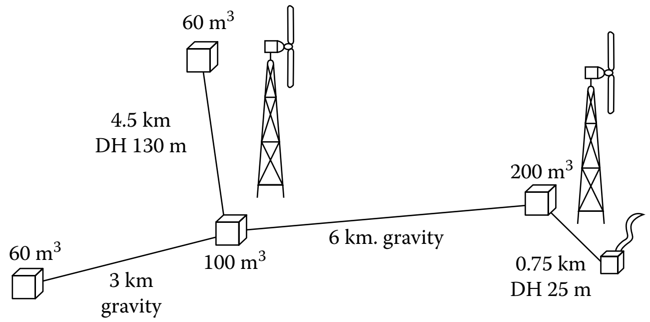

FIGURE 10.7 Layout of water supply for three villages, Naima, Morocco. DH = dynamic head.

10.6.2 Large Systems

Large systems have been considered for pumping water for irrigation and villages. These can be classified into wind-assist and remote, stand-alone systems. Wind-assist water pumping is where the wind turbine and another power source work in parallel to provide power on demand. Wind assist is essentially a fuel-saving mode of operation, since it does not require any changes in irrigation application. Wind assist can be further divided into indirect and direct connection. The advantages of the indirect connect are that the wind turbine does not need to be located at the well, and electricity can be returned to the grid when the wind turbine is producing more power than is needed by the load. A direct mechanical connection to the gear head has also been tested where the conventional power source is electric or diesel [40, 41]. The disadvantages of the mechanical connection are that the wind turbine has to be near the well, and the wind turbine can only be used when water is needed.

The wind–electric water pumping system is a major change from the farm windmill in two aspects: efficiency and volume of water. The annual efficiency is double that of the farm windmill, and because wind turbines are available in larger sizes (1–10 kW and 50 kW permanent magnet alternators), wind-electric systems can pump enough water for irrigation and villages. The wind–electric system consists of a wind turbine generator connected directly to a standard three-phase induction motor driving a centrifugal or submersible turbine pump. There is a good match between the wind turbine output and the centrifugal pump, because both have power proportional to rpm cubed. Another advantage of the wind–electric system is that the wind turbine can be located some distance from the well or pump.

An example is the two wind-electric systems (10 kW) that were installed in Naima, Morocco, in 1989 for supplying water for villages and animals [42]. The spring water is some distance from the villages. The first wind turbine pumps water from the collection tank to a large storage tank on top of the hill (Figure 10.7). There is gravity flow to two other storage tanks, and a second wind turbine to pump water to another village. The wind–electric systems replaced diesel pumping systems, which were inoperable. In 1997, an additional two 1.5 kW wind–electric water pumping systems were installed.

10.7 WIND INDUSTRY

After the oil crisis in 1973, the first step was the development of small wind turbines (defined as <100 kW). Most companies in the United States began by importing wind turbines, finding abandoned units to refurbish for personal use or to sell, and then designing and building systems similar to the wind chargers of the 1930s and 1940s (direct current, 0.1–4 kW, up to 5 m diameter). A number of home builders turned to the Savonius type because of its simplicity and ease of construction.

FIGURE 10.8 Top left, MOD-5B, Ohau, Hawaii. Top right, WTS, Medicine Bow, Wyoming. Top of MOD-2 is visible on lower right. Bottom, Westinghouse 600, Ohau, Hawaii. MOD-5B is visible on the right.

Electricity consumption had also increased over the small demand of the 1930s. There was a need for larger wind turbines, as 5 m diameter rotors could not meet the demands of farmers and ranchers. In addition, there were many more uses for electricity, which would require larger-size wind turbines.

Since the electric distribution system was almost everywhere in the United States, there was a market for wind turbines that were fully compatible with the utility system: 120, 240, or 480 V, alternating current (AC). Inverters with solid-state electronics were now available to connect direct current (DC) units and alternators to the utility line. Enertech and Carter were early proponents of induction generators, which could be connected directly to the utility grid.

The second step was the influx of federal funding for research through the Energy Research and Development Agency (ERDA) and later the Department of Energy (DOE). Federal support for wind energy began with $300,000 in 1973, and by 1980 had increased to $67 million. The federal program for development of wind turbines was geared to large units to connect to the utility grid (Figure 10.8). These units were to produce power in the range of $0.02–0.04/kWh. The program was managed by NASA–Lewis [43] starting with the MOD-0 (100 kW) and MOD-0A (200 kW) and progressing to megawatt-sized wind turbines. Five of the MOD-2s (Figure 10.9) were built, and the original design of the MOD-5 was reduced from 7,200 kW to 3,200 kW. All of these units had two blades.

During the 1980s, other large wind turbines were developed and installed in the United States and Europe (Table 10.10). The Hamilton Standard WTS-4, Wind Turbine Generator, Bendix-Schachle, and

FIGURE 10.9 MOD-2 wind turbines at Goodnoe Hills, Washington, near the Columbia River. Turbines were placed in a triangle for research on wake interference. (Photo from NASA-Lewis.)

TABLE 10.10
Large Wind Turbines, 500 kW and Greater, 1975–1990

Turbine	No.	Diameter	Rated kW	Year	Country
MOD-1	1	61	2,000	79	United States
MOD-2	5	91	2,500	82	United States
MOD-5B	1	88	3,200	86	United States
WWG-0600	15	43	600	85	United States
Mehrkam		4	2,000	80	United States
WTS-4	2	78	4,000	80	United States
Schachle-Bendix		25	3,000	80	United States
Alcoa		56 × 25	500		United States
VAWT 34m test bed		34 × 42	500	89	United States
HMZ		33	500	89	Belgium
DAF-Indal		24 × 37	500	77	Canada
Eolé		64 × 94	4,000	87	Canada
Nibe A		40	630	79	Denmark
Nibe B		40	630	80	Denmark
Tiareborg		60	2,000	88	Denmark
Tvind		54	2,000	78	Denmark
Windane		40	750	87	Denmark
M.A.N.		60	1,200	89	Germany
Monopteros		48	650	89	Germany
Stork-FDO		45	1,000	85	Netherlands
Windmaster		33	500	89	Netherlands
Newinco		34	500	89	Netherlands
Anisel. M.A.N.		60	1,200	89	Spain
Nausdden		75	2,000	82	Sweden
WTS-3		78	3,000	82	Sweden
WTS-75		75	2,000	83	Sweden
Howden		45	750	89	United Kingdom
Howden		55	1,000	89	United Kingdom
WEG LS1		60	3,000	88	United Kingdom

TABLE 10.11
Small Wind Energy Conversion Systems, Prototype Development Program Funded by U.S. Department of Energy

Contractor	Type	Size, m
1 kW at 8.9 m/s, high reliability, remote, $1,950,000		
Aerospace/Pinson	Giromill	4.6 × 5.5
Enertech	HAWT	4.9
North Wind Power	HAWT	4.9
4 kW at 7.2 m/s, $1,425,000		
North Wind Power	HAWT	9.1
Structural Composites	Dropped out at design stage	
TUMAC	Darrieus	9.1 × 11.5
8 kW at 8.9 m/s, $2,260,000		
Alcoa	Dropped out at design stage	
Grumman	HAWT	10
United Technologies	HAWT	9.8
Windworks	HAWT	10
15 kW at 8.9 m/s, $3,230,000		
Enertech	HAWT	13.6
United Technologies	HAWT	14
40 kW at 8.9 m/s, $4,450,000		
Kaman	HAWT	19.5
McDonnel-Douglas	Giromill	18 × 12.8

Alcoa units were developed primarily through private funds. However, a group of wind enthusiasts convinced federal officials to support a program for small wind energy conversion systems (SWECS). The SWECS prototype program awarded contracts in 1978 and 1979 (Table 10.11). By 1980 there were over fifty companies producing wind energy conversion systems (1–100 kW) in the United States. However, the installed capacity of SWECS was only around 3 MW from 1,700 units [44].

The third step was the passage of the National Energy Act of 1978. The section entitled Public Utility Regulatory Policy Act (PURPA) provided for connection of renewable power sources to the electric grid without penalty, and for payment to the producer for electricity sold to the utility company. The value of that electricity was determined by the avoided cost, which was implemented by the states.

10.7.1 Wind Industry, 1980–1990

The 5 years from 1980 to 1985 were the nascent stage of wind industry. The boom of wind farms in California drove the exponential growth of the wind industry from 3 to 900 MW. The California wind market was due to tax shelters (solar and investment tax credits), and avoided costs and standard contracts set by the California Energy Commission. As with many new industries, there were a lot of manufacturers. Only small wind turbines (<100 kW) were available commercially, and there were many problems with reliability. From 1980 to 1990, four features characterized the wind industry, which was synonymous with the wind farms in California: (1) rapid growth; (2) development of intermediate-sized wind turbines (100–600 kW) without government funding; (3) the aerospace companies in the United States dropped out, even those who received government funding for design and development; and (4) strong foreign competition, primarily from Europe. Foreign manufacturers, with Denmark leading the way, became an important factor. Vertical-axis wind turbines from Flowind and VAWTPower were installed in California wind farms, but the majority were horizontal-axis wind turbines.

The 5 years from 1986 to 1990 were primarily consolidation and shakeout within the industry. The tax credits ended in 1985; however, contracts from previous years meant wind turbines were still being installed in California, but not at the increased pace of the previous 5 years. There were less than ten U.S. manufacturers in 1990, and only one major manufacturer, U.S. Windpower.

U.S. federal R&D support for wind energy fell to a low of $8 million in 1988. However, the Europeans increased their support for wind energy during this period. Japanese companies, especially Mitsubishi, entered the world market and were determined to be a major manufacturer. Many of the earlier large-megawatt units were prototypes developed with government funding; however, by the end of the decade, the development was driven by the market, as those wind turbines increased in size from the 100 kW units.

Three hundred fifty million dollars, over half of the federal funding for wind energy from 1973 to 1990, was spent on the development of large wind turbines. This program was largely a failure because the program proceeded to the next stage without fully developing the wind turbines at the previous stage. Design of wind turbines was much more difficult than the engineers in the aerospace companies had anticipated, and the aerospace industry was only interested in cost plus government contracts, rather than developing a commercial product. All the Department of Energy prototypes were taken down due to failures or because O&M costs were too high.

10.7.2 Wind Industry, 1990–2000

World energy production in 1995 was estimated at 5 million MWh/year from over 22,000 wind turbines with an installed capacity of around 4,000 MW. The American Wind Energy Association set a very optimistic goal for the United States of 10,000 MW by the year 2000. This was not achieved, although there was a lot of activity in other states outside of California due to the new incentive of the production tax credit (PTC) for 1990–1995. The PTC was $0.015/kWh for 10 years, with an inflation factor for wind farms installed in later years. The PTC was extended a number of times; however, late extension meant hardly any installations during that year.

Sandia Labs managed the DOE program for VAWTs. A 34 m VAWT test bed, 500 kW, was tested at USDA-ARS, Bushland, Texas, from 1988 to 1998 (Figure 10.10). The DOE program, managed by the National Wind Technology Center, NREL, was changed to assistance and R&D for the U.S. industry to meet the foreign competition through the Advanced Wind Turbine Program [45–47]. Also in the United States, there was the EPRI/DOE Wind Turbine Performance Verification Program, which was to provide a bridge from utility-grade development programs to commercial purchases. The 1995 goal of the U.S. Department of Energy Advanced Wind Turbine Program was to develop wind turbines for class 3 wind regimes (5–5.5 m/s average at 10 m height), which would produce electricity at $0.03–0.04/kWh, with O&M costs of $0.005/kWh. Another DOE R&D project goal was for cost of energy from wind of $0.025/kWh or less at sites with 6.7 m/s winds by 2002.

Government regulations and incentives in Europe, especially in Germany, resulted in rapid expansion of industry and installation of wind turbines. There was more consolidation, and some manufacturing shifted from Denmark.

The manufacturers of two-blade, light-weight machines went out of business, for example, Carter. However, prototypes are still being used in testing, and Vergnet in France is selling a commercial machine. There were not any vertical-axis wind turbines being produced for the wind farm market. This period was characterized by:

1. Continued rapid growth of the wind industry. Size of wind turbines increased from 200 kW to megawatt size. Countries outside the United States and Europe installed wind farms, with 1,220 MW installed in India by the end of 2000.
2. European manufacturers dominated the market for large wind turbines.
3. Offshore wind farms were installed in Europe.

FIGURE 10.10 Vertical-axis wind turbine, 34-m test bed at Research Center, USDA-ARS, Bushland, Texas, USA. VAWT rated at 500 kW, peak power 625 kW. (Photo from USDA-ARS. With permission.)

4. Development of large wind turbines with no gearboxes.
5. Only one manufacturer of large wind turbines in the United States. Kenetech went out of business, leaving only one manufacturer of large turbines, Zond. Zond was then purchased by Enron and renamed Enron Wind.

The Utility Wind Integration Group in the United States published a number of brochures [48] on all aspects of the wind industry. This information is primarily for planners in utilities and policy makers in state governments.

10.7.3 Wind Industry, 2000–2010

Wind turbines are now a part of the planning process for new electric plants in many countries. Europe continues to lead in installed capacity, development of multimegawatt turbines, and manufacturing. Global producers of equipment for electric power plants, General Electric (Enron), United States, and Siemens (Bonus), Germany, became manufacturers by purchasing wind turbine companies. Vestas, which absorbed NEG-Micon, is still the leading manufacturer of large wind turbines. For large machines, the three-blade, full-span, variable-pitch, upwind machines now dominate the market.

The most economical size of wind turbines has not been determined, as the trend has been larger machines for the wind farm market. However, in many locations, especially islands and other remote locations in the world, the infrastructure is the limitation for installation of megawatt wind turbines, for example, cranes. The larger wind turbines are now being developed for offshore.

In the United States, with the production tax credit and the Renewable Portfolio Standard in Texas, there was a resurgence of wind farm installations. In 2006, Texas (Figure 10.11) surpassed California in installed capacity, and a number of other states have passed Renewable Portfolio Standards. Since no wind turbines from the DOE program became major players in the commercial market, by 2006 the research project was changed to assist manufacturers, through the program area of the Low Speed Wind Technology Project [49]. The cost-shared research and development projects with industry included a 2.5 MW wind turbine, Clipper Windpower; a modular power

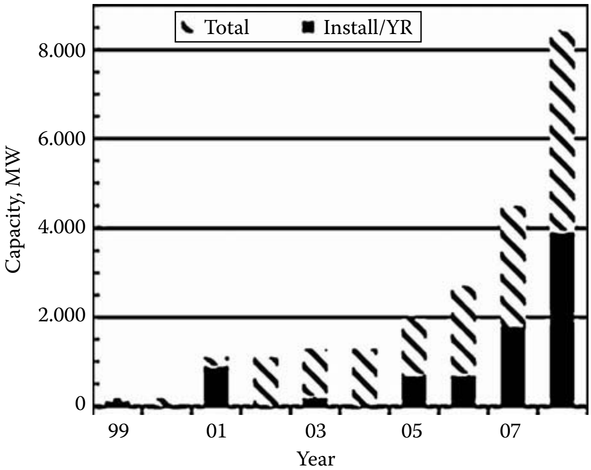

FIGURE 10.11 Wind farm capacity in Texas, number installed/year and cumulative. Capacity installed in 2008 was estimated at 3,900 MW.

electronics package that can be scaled from small to megawatt wind turbines; a 1.5 MW direct-drive generator, Northern Power Systems; a prototype multimegawatt low-wind-speed turbine, General Electric; and others.

Another emerging market is village electrification in developing countries. It is cheaper to have village power than to extend transmission lines. The primary source of energy will be renewable energy: solar, wind, hydro, and biomass. Many of these will be hybrid systems with batteries and diesel for firm power. Large lending institutions, such as the World Bank and national government aid programs, now realize there is an alternative to large-scale projects for producing power. Also, there are more manufacturers of small wind turbines, and manufacturers in the United States and China expanded their production.

Landowners now harvest the wind much as they harvest the sun for food and fiber. Since financing for large wind power plants requires millions of dollars, the landowner usually leases the land and receives a royalty from the energy produced by the wind turbines, similar to the oil and gas industry. The difference is that the wind resource can be fully determined before large amounts of money are invested, and even more important, the resource will not run out.

10.8 COMMENTS

Beside the emerging markets of distributed systems and village power, there are two other factors, which will increase the market: green power and reduction of pollution. People can purchase green power at a premium, and a lot of that power generation is from one to a few wind turbines (Figure 10.12) or from wind farms. There are a number of urban areas, which are in nonattainment for clean air, and one way to reduce pollution is by production of electricity from renewable energy.

The reduction of carbon dioxide emissions per the Kyoto Treaty is part of many nations' regulations. As trading in CO_2 becomes regulated in the United States, electricity produced by wind turbines will become more valuable. Then wind energy will be the most cost-competitive power source on the market.

There are some other wind applications of interest in terms of commercial systems and prototype testing. These are the production of hydrogen, compressed air storage, pumped hydro, a stand-alone electric-electric system for making ice, and desalination. There are also wind hybrid systems for telecommunications and remote military installations. Many of these sites are only accessible by helicopter, so fuel costs are high.

FIGURE 10.12 Two Vestas, V47, 660 kW on ridge of Hueco Mountains, east of EI Paso, Texas. Electricity sold under the green power program. Notice the car at the base of the turbine on the right. (Photo from Cielo Wind Power. With permission.)

A full-scale wind hydrogen energy plant [50] and testing facility began operation in 2007 on the island of Lolland, Denmark. During some periods wind power produces 50% more energy than is needed. The project will store the excess wind power as hydrogen for use in residential and industrial facilities.

An ultraviolet water purifier powered by renewable energy was tested by USDA-ARS and AEI [51]. A controller was developed and five configurations were tested, two with PV (100 W), two by wind (500 W), and one by hybrid wind/PV. The PV-only system is more efficient and cost-effective than the wind-only system. However, the wind/PV system is more reliable in terms of power. The system purified 16,000 L/day, which is enough potable water for around 4,000 people at an estimated equipment cost of around $5,000. In Afghanistan, water is purified by using ozone produced from electricity from a wind/PV hybrid system. The technology is a small system, which used around 160 W to produce 2 g of ozone per hour. Treatment is on a batch basis of 500 L to produce 2,000–4,000 L/day. The system is powered by a 1 kW wind turbine, 280 W of PV, a small battery bank, and an inverter.

LINKS

American Wind Energy Association, www.awea.org.

Danish Wind Turbine Manufacturers Association, www.windpower.org/core.htm. Lots of information in guided tour.

DOE Wind Energy Program, www1.eere.energy.gov/windandhydro.

Global Wind Energy Council, www.gwec.net org.

National Wind Coordinating Committee, www.nationalwind.org.

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PROBLEMS

1. What is a wind-assist power system?
2. Go to the *Windpower Monthly* website. Then go to Windicator. Which country in the world has the largest installed capacity of wind power? How much? What is the installed capacity in China? Another place to obtain information is the Global Wind Energy Council, www.gwec.net.
3. Estimate the wind installed capacity 5 years in the future for the world, for your country.
4. Estimate the capacity of offshore wind farms in the world today.
5. Are there any small wind turbines in your region? If yes, find out how many are rated power, stand-alone, or grid connected.
6. Are there any wind distributed or community systems in your region? If yes, for one project, provide number of turbines and rated power. If no, find information on the Internet for one system.
7. Should distributed wind systems receive incentives? If yes, in your opinion, what incentive?
8. What is the main difference between low and high penetration for wind–diesel systems?
9. Go to the National Wind Technology Center, NREL, website. What R&D programs do they have?
10. Go to the National Wind Technology Center, NREL, website. What non-R&D programs do they have?
11. Find an example of a village project that is not in the text. What type and size systems were installed?
12. In your opinion, what are the major advantages and disadvantages for renewable village power?
13. Why are wind–electric water pumping systems installed rather than the proven farm windmill?
14. Compare the annual efficiency for the farm windmill to a wind–electric system.
15. What factors contributed to the initial wind farm boom in California?
16. Which manufacturer is the largest supplier of megawatt wind turbines?
17. Go to two or three manufacturers' websites and find out what is their largest commercial wind turbine. State diameter, rated power, and tallest tower.
18. Does the utility from which you buy electricity have wind farms on its transmission lines? If yes, for one wind farm find out the number of turbines and rated power.
19. What are some applications of small wind turbines? Bergey Windpower has examples of applications, or use an example from the text.
20. In your opinion, why are there not more manufacturers of large wind turbines in the United States.
21. Find two example projects of wind–diesel on the Internet. State specifications of the systems.

11 Institutional

The interconnection of wind turbines to utility grids, regulations on installation and operation, and environmental concerns are the main institutional issues. The National Energy Act of 1978 in the United States was a response to the energy crisis caused by the oil embargo. The main purpose was to encourage conservation of energy and the efficient use of energy resources. The Public Utility Regulatory Policies Act (PURPA) covers small power producers and qualifying facilities (independent power producers), which are up to 80 MW [1, 2]. Sections 201 and 210 of PURPA encourage the use of renewable energy. The main aspects of PURPA are:

- Utilities must offer to buy energy and capacity from small power producers at the marginal rate (avoided cost) the utility would pay to produce the same energy.
- Utilities must sell power to these small power producers at nondiscriminatory rates. Qualifying facilities are entitled to simultaneously purchase and sell. They have the right to sell all their energy to the utility and purchase all the energy needed.
- Qualifying facilities are exempt from most federal and state regulations that apply to utilities.

Public utility commissions, utilities, independent power producers, and the courts determined the implementation of PURPA. Determination of avoided costs was the main point of contention between small power producers, independent power producers, and utilities.

The National Energy Strategy Bill of 1992 included the provision of wheeling power over utility transmission lines. The Federal Energy Regulatory Commission (FERC) can order the owner of transmission lines to wheel power at costs determined by FERC. The utilities are allowed to recover all legitimate, verifiable economic costs incurred in connection with the transmission services and necessary associated services, including, but not limited to, an appropriate share, as transmission will be needed from any of the costs of any enlargement of transmission facilities. From the standpoint of wind power, this legislation is very important of the major source of wind energy in the Great Plains, to the major load centers. In 1997, FERC opened transmission access.

The deregulation of the electric utility industry by the states has changed the competition for renewable energy. Deregulation essentially means the integrated electric utility companies are split into three areas: generation of power, transmission, and distribution. Also consumers can buy from different power producers. The other aspects for increased use of renewable energy are green power and reduction of pollution and emissions from fossil fuel plants that generate electricity.

Cavallo [3] argued that wind energy could become a high-capacity system by wheeling power from the Great Plains to California, or from the Texas Panhandle to Dallas–Fort Worth. He conducted a paper study of a 2 GW wind farm in Kansas, which could have a capacity factor of 60%. The first large wind plant (initially 40 MW, expansion to 80 MW) in Texas was in the western part of the state, and power was wheeled to the Lower Colorado River Authority area in central Texas.

11.1 AVOIDED COSTS

Avoided costs were established by the public utility regulatory body in each state. The Federal Energy Regulatory Commission defines avoided cost as the incremental or marginal cost to an electric utility of energy or capacity, which the utility would have to generate or purchase from another source if it did not buy power from the qualifying facility. Avoided cost reflects the cost from new power plants, not the average cost from plants already installed. The avoided cost includes not only present but also future costs.

However, many utilities said they did not need any new generation; therefore, avoided costs were only the fuel adjustment cost. Utilities may set a standard purchase rate for qualifying facilities under 100 kW capacity. Contact your public regulatory body for more information on small power production. In the 1980s, the California Public Utilities Commission (PUC; now CEC) set the avoided costs and types of contracts for qualifying facilities [4]. Standard Offer 4 set the avoided costs for a period of 10 years, while Standard Offer 1 was variable, depending on the cost of fuel. One of the reasons wind farms started in California was the high avoided costs set by the PUC.

The fuel adjustment cost for Southwestern Public Service in the Texas Panhandle in January 1994 was $0.02/kWh. The company was consolidated with a company in Colorado and Minnesota, now called Xcel Energy, and in 2008 the avoided cost is still the fuel adjustment cost. However, it has risen to around $0.05/kWh due to the increase in the price of natural gas. Therefore, some utilities now consider wind as a hedge against future volatility of natural gas costs and are actively seeking wind farms.

11.2 UTILITY CONCERNS

For a few wind turbines on a large utility grid there would be no problems with the amount of power. It would be considered as a negative load, a conservation device that is the same as turning off a load. For large penetration, 20% and greater, other factors such as the variability of the wind and dispatching become important. The utilities are concerned with safety and power quality due to any wind turbines on their grid.

11.2.1 Safety

Safety is a primary consideration. This includes energizing a dead utility line, grounding of equipment, and lightning. This issue has been resolved, as large numbers of wind turbines have been connected safely to the utility line. Induction generators have to be energized by the utility line, so when there is a fault on the line they do not operate. Inverters have sensors for loss of load to disconnect them from the utility line.

Of course, safety in installation and operation is of concern, as with any other industrial enterprise. High voltages, rotating blades and machinery, large weights, and working at heights of 50 to 100 m make for a hazardous workplace. Safety is the first consideration for working around wind turbines. Never climb a met tower or a turbine tower if you are the only person at the site. Although the large wind turbines have taller towers, it is easier to climb inside a tubular tower than on a truss or met tower, especially in inclement weather.

There is a summary and full list of wind turbine accidents up to March 31, 2008, which includes accident type, turbine, date, and location [5]. The summary notes 482 accidents that include 49 fatalities, with the most common cause being falls from turbines. Thirty-five of the fatalities were industry workers and fourteen were public fatalities, of which three were from road accidents attributed to driver distraction. Surprisingly, four people were killed when an airplane crashed into a wind turbine during a fog. The largest number of accidents was from blade failure, and the second most common accident was from fire. It is clearly understood that the data, especially early data, are not comprehensive.

For example, AEI and USDA have tested over sixty prototype wind turbines with a number of failures, from lost blades to complete destruction, which are not in the database. The longest distance for a blade failure was 56 m from a small wind turbine, 4 kW, which is quite a bit shorter than the documented 400 m distance noted in the summary. However, the top of a forklift hit a high-voltage line while moving a rebar cage for a wind turbine foundation, and the worker, Patrick Acker, holding the cage was electrocuted; that fatality is in the database.

Another source reports a mortality rate of 0.4 deaths/TWh for the mid-1990s, which dropped to 0.15 deaths/TWh by the end of 2000 [6]. Of course, some of the deaths are associated with the transport of wind turbines. A database is available. Those numbers for the mortality rate for the wind industry need to be compared to those of other energy industries, such as coal.

11.2.2 Power Quality

Power quality refers to harmonics, power factor, and voltage and frequency control. A number of wind turbines on the end of a feeder line could require extra equipment to maintain quality of power. Utility companies have to supply reactive power for induction generators, and in general, capacitors on the wind turbine or at the wind farm substation are required to maintain the power factor.

11.2.3 Connection to the Utility

The utility should be informed at the earliest possible stage of the intention to connect a wind turbine to its system. Information for the utility should include:

- Specifications of the wind turbine
- Schematic (block diagram) of the electrical system
- Description of machine controls when there is loss of load (utility power)

Even though there may be net energy billing, the utility may require a meter that measures energy flow in both directions.

Liability for damage is another concern of utilities. The utilities would like to be insured against all damage due to the wind turbine operation. Of course, the small power producer would like to be insured against damage to the wind turbine as a result of utility operation; however, that is impossible to obtain. Insurance should be available as part of your homeowner policy or as part of your business policy. Some electric cooperatives were requiring proof of a $500,000 liability policy for connection of a wind turbine to their system.

For wind farms, an interconnection study from the utility will cost from $30,000 to $100,000. This study determines the effect of the wind farm on the transmission lines and existing generators. Guides for utility-scale wind turbines are available [7].

An example of onerous regulation for small wind turbines comes from the State of Washington, where the Department of Labor and Industries refuses to sign off on small wind systems without an Underwriters Laboratory (UL) listing on every component. Washington will now require a few specially registered electrical engineering firms to certify even existing wind systems that are not UL listed (all) at a cost of around $2,000. This action on the part of Labor and Industries inspectors has brought small wind sales to a halt in Washington.

11.2.4 Ancillary Costs

Wind farms, especially as they become a larger percentage of the generation capacity on the grid, pose other costs for the utility. The variability of wind can increase operating costs, such as committing unneeded generation, scheduling unneeded generation, allocating extra load-following capability, violating system performance criteria, and increasing cycling operation on other generators. Estimates of these costs are $0.001–0.005/kWh [8] or even up to 0.0185/kWh. The wind integration impact becomes more significant at higher wind penetration into the grid.

In 2008, the Montana Public Service Commission set a rate up to $0.00565/MWh for integrated wind power into the Northwestern Energy utility from the Two Dot wind farm. The integration rate is then subtracted from the amount Northwestern Energy would pay the wind farm for power, which would reduce the utility payment for wind-generated electricity to as low as $44.25/MWh.

11.3 REGULATIONS ON INSTALLATION AND OPERATION

Permits are required in residential areas for construction, and even in rural areas in some states. The major zoning issues are tower height, setbacks, noise, aesthetics, environmental impact, and safety. The probability of failure, such as a thrown blade, is the most common objection. However, risks are accepted from other areas, such as cars, utility lines (electric and gas), etc. Signs, trees, and even utility poles have failed in high winds or under conditions of icing.

Tower access needs to be controlled, as does access to the high voltage. One factor that can never be dismissed is that anything that interferes with TV will be unacceptable to the public. When the metal blades on the MOD-0A interfered with TV reception on Block Island, Rhode Island, the DOE had to install cable for the residents. Most locations do not have specific zoning regulations for wind turbines. Before installing a small wind turbine, be prepared to educate public boards and your neighbors [9–13].

11.4 ENVIRONMENT

The main environmental issues are visual impact, noise, birds, and bats. The visual impact can be detrimental, especially in locations that are close to scenic areas or parks. It is the same story: people are in favor of renewable energy, but "not in my backyard." The turbines should be drab colors, not highly reflective, and the rotors should be rotating in the same direction.

Some people are adamantly opposed to wind farms, most are neutral, and the rest are in favor. For those opposed, generally the visual impact is the most important concern [14]. The photo gallery of Stopillwind has before and after photos of wind farms. The ones most in favor of wind farms receive an economic return from the wind farm, whether directly or indirectly. The wind farm developer needs to do community education as soon as the project is official. Economic development in rural areas is very powerful from a political standpoint.

Noise measurements have shown in general that wind turbines are below the ambient noise; however, the repetitive nose from the blades stands out, and one would not want a residence in the middle of a wind farm. The whine from gearboxes on some units is also noticeable. However, with larger wind turbines at higher hub heights and new airfoils, the noise has been much reduced. The farmers who live close to the wind turbines at the White Deer, Texas, wind farm (eighty 1 MW turbines) report that noise is not a problem.

The rotor area for a 90 m diameter wind turbine is over 6,000 m^2, the rpm is around 10 revolutions/min, and the velocity of the blades is different from the root to the tip. Large wind turbines have a slower rpm than small wind turbines; however, the tip speed ratios are similar, so either blade has a large enough velocity to kill a bird. So factors for the question of mortality of birds by wind turbines are fatalities, bird species, season, the threat to the population, and possible forms of mitigation [15]. Collision rates per turbine per year vary from 0.01 to 23; the latter was for a coastal site in Belgium, which included gulls, terns, and ducks. Other coastal sites in northwest Europe had yearly average collision rates ranging from 0.01 to 1.2 birds per turbine. None of these examples has been associated with significant population decline. Flocks of geese and ducks entering an offshore wind farm decrease by a factor of 4.5. At night, more migrating flocks entered the wind farm; however, they increased their distance from the wind turbines. Overall, less than 1% of the ducks and geese flew close enough to the turbines to be at any risk of collision [16].

In general, migratory birds fly well above the heights of wind turbines [17]; however, overcast and ground clouds may lower the flight paths. Two large wind farms near the coast, south of Corpus

Christi, Texas, have a radar for monitoring migration of birds, and wind turbines are shut down if they pose a threat to the birds.

Avian mortality became an issue in Altamont Pass as wind turbines killed some raptors. Transmission line poles had caps put on them to keep the birds from using them as a perch, thereby extending their wings between the lines and being electrocuted. Xcel Energy, a utility company, agreed to evaluate 90,000 miles of transmission lines in twelve states to fix any equipment likely to kill birds.

The two primary areas of concern are (1) possible litigation resulting from the killing of even one bird if it is protected by the Migratory Bird Treaty Act or the Endangered Species Act, and (2) the effect of avian mortality on populations. A number of projects [18] have been funded since 1994 to find out the effect of rotating blades on raptors, and if there are methods to make them stand out to birds: color, noise, etc. Another possibility is that the trust towers make natural perches, since there are no trees in the area. One wind farm stipulated tubular towers as a precaution, and most large turbines now have tubular towers. NWTC, NREL, has a section on avian studies [19].

Another area that experienced problems was in southern Spain [20]. Tarifa is a temporary roosting area for migratory birds to and from Africa. Biologists believe the problem of avian mortality at the site is partly due to aerodynamics as the soaring birds travel the air currents that propel them up the ridges where the wind turbines are located. The large birds do not have the maneuverability of the smaller birds.

From the example in Spain, it is obvious that some locations will be off limits to wind farms. For example, a wind farm could not be located next to a wildlife refugee for an endangered species of bird, such as the whooping crane. Even though thousands of birds are killed by communication towers, buildings [21], hunters, and even cars, the Sierra Club and other environmental groups will become adversaries if there is a problem. Of the hundreds of millions of birds killed annually in the United States, how many are killed by wind turbines? After bats became a problem in West Virginia, guidelines became available for both bird and bat impacts [22, 23]. Wildlife/wind interaction publications are available from the National Wind Coordinating Collaborative—one that is a guidance document on preconstruction utilization counts to make predictions and postconstruction fatality studies [24].

As expected, fatality rates for birds vary by the biological characteristics of the specific wind farm and the surrounding area. In Altamont Pass, California, raptors had the highest fatality rates. Outside of California, studies at twelve wind projects have estimated fatality rates from 0.63/turbine/year to over 10/turbine/year at a fragmented mountain forest site in Tennessee. Bat fatality rates are estimated from a low of 1.5/turbine/year for most of the United States to a high of 46/turbine/year in the eastern United States [25].

There will be land areas that are excluded because of environmental considerations, national and state parks, wetlands, and some wildlife refugees. Environmental impact statements will have to be done as the Environmental Protection Agency has jurisdiction over many aspects of proposed location of a wind farm. In addition, some states and even counties have regulations concerning the environment, which will have to be met before a wind turbine or a wind farm can be installed. First, check with local officials before you install your wind turbine.

The National Wind Coordinating Collaborative (NWCC) members are from utilities, state legislatures, state utility commissions, consumer advocacy offices, wind equipment suppliers and developers, green power marketers, environmental organizations, and state and federal agencies. Permitting publications are available from NWCC [24].

The issues of regulatory framework, environment, and impact analysis and mitigation are covered in the AWEA *Siting Handbook* [26]. The information is for projects of 5 MW and greater; however, it is still useful for smaller projects. Early in the siting process, the developer should conduct a critical analysis of the environmental issues; required permits, licenses, and regulatory approvals; threatened or endangered species or habitat; avian and bat species; identification of wetlands and other protected areas; and location of known archeological and historical resources. A constraints map is a useful tool for depicting environmental and land use constraints.

Regulations, from federal to local, play a part in any project. Federal permitting requirements for wind energy projects are environmental to Federal Aviation Administration. There is coordination at the federal level for regulations through the Federal Interagency Wind Siting Collaboration [27]. The U.S. Fish and Wildlife Service has an advisory committee and a Wind Turbine Siting Working Group [28] to develop guidelines. The purpose is to help protect wildlife resources, streamline site selection, and assist in avoiding postconstruction environmental concerns. A check on archeological sites is generally imperative at the planning stages for wind farms. Regulations on archeology differ by state, and in some states private land is excluded. However, the developer would be wise to have a preliminary check on archeology sites.

The regulatory process for siting a wind project varies widely by state. One state may have a simple review process before a single agency, while other states may have a complex, time-consuming process involving multiple agencies and even multiple levels of government. NREL in collaboration with the National Association of Counties created a guide for county commissioners [29]. Sometimes there seem to be competing regulations from different agencies, and the number of agencies can be large. Industry maintains that regulations are now a major portion of their cost of doing business. In many cases, industry says it cannot meet proposed regulations because it is uneconomical.

After the critical analysis of environmental issues, a more detailed analysis should address possible impacts and measures to mitigate those impacts. Biological concerns are habitat loss, alteration or fragmentation of habitat, bird and bat collisions with wind turbines, electrocution of raptors, and affect on vegetation. Mitigation of the impacts has to be monitored after the project is operational. Water, especially wetlands, soil erosion, and water quality have to be considered. The clearing of scrub brush for roads, tower pad sites, and even for laying underground wires is welcomed by ranchers; however, the cleared areas, such as shoulders of the roads, have to be seeded and monitored for growth and erosion.

The visual impact for wind farms is quite different from that of small wind turbines because of the number of and taller towers, as they will be visible from 20 km. In the Plains they are visible from all angles (Figures 11.1 and 11.2), with only the curvature of the earth limiting the distance. In mountainous areas, the wind turbines will be in lines on the ridges, but in general they are not visible from all angles because most of the roads are in the valley and the view is blocked. It is the moving rotors that make wind turbines more visible. The requirements to install lights on towers over 60 m make them conspicuous at night, especially when the flashing red lights are synchronized to outline the wind farm. Shadow flicker happens and the high impact is generally located within approximately 300 m of the turbine. In a pasture with no trees in the summer time, a rancher noticed that yearling calves at the New Mexico Wind Energy Center were lined up in the shadows of the tower of the wind turbines and moved to keep in the shade as the tower shadow moved.

FIGURE 11.1 Visual impact of different size wind turbines at different distances. Photo taken in late afternoon looking south. Foreground: 3.2 km to one turbine, diameter = 90 m, 3 MW, tower height = 80 m. Middle at left: 4.4 km to eight turbines, diameter = 64 m, 1.25 MW, tower height = 72 m. Background: 9.5 km to first row, 14.5 km to back row, wind farm with thirty-eight turbines, diameter = 88 m. 2.1 MW, tower height = 80 m.

FIGURE 11.2 Visual impact of wind farm; near edge is 11 km, far edge is 17 km. Photo taken in late afternoon, looking east. Wind turbines, diameter = 56 m, 1 MW, tower height = 60 m.

The noise from large wind turbines is much less than in the past, and in general the permitted levels at property boundaries are established by most states and localities. The most prominent noises are the passage of the wind turbine blades and from components, primarily gearboxes.

One area that is often overlooked is the amount of traffic, from the large trucks hauling the wind turbines and the cranes to the project to the numerous pickups, both during construction and afterwards. Routes from source and delivery ports become important, and invariably local roads have to be improved. For mesas and complex terrain, most of the ranchers like the new roads, especially since the roads are maintained by the wind farm.

The large amount of activity and people during the construction phase and the amount of space and equipment are sometimes surprising to rural communities. During the construction phase, the developer will interfere with the normal operations; for example, cattle guards will have to be installed as opening and closing gates take too much time. Livestock may be injured or killed, and damages will be paid. Finally, solid and hazardous wastes during construction and also during operation have to be managed.

For protection against liability, a developer may perform a screening assessment or an environmental site assessment prior to acquisition of the property. The American Society for Testing and Materials has screening tools and standards for environmental site assessment [30].

11.5 POLITICS

As with any endeavor, politics enters the situation. To make a change in behavior, especially when the competition is an entrenched industry, you need incentives, penalties, and education. Someone estimated that the amount of each type of energy used is in direct proportion to the amount of subsidies for that type of energy. Subsidies are in the form of taxes, tax breaks, and regulations, all of which generally require legislation. What every entity (industry) wants are incentives for themselves and penalties for their competitors. In addition, they want the government to fund R&D and even commercialization.

Incentives are usually in the form of tax breaks, or can be in terms of subsidies, mandates, and regulations. Public utility commissions are now demanding that utilities use integrated resource planning, which means they have to consider renewables and conservation in the planning process. Can utilities make money for kilowatt-hours saved? Who is supposed to take the risk, the consumers or the shareholders? Three Mile Island and the nuclear utility industry are good examples of politics, from the local to the national level. The Price Anderson Act, a federal law, limited the amount of liability from a nuclear accident. Without that legislation, the nuclear industry could not have sold plants to utilities.

Penalties are generally in the form of taxes and regulations. Environmental groups in the United States have already indicated that utility planners will be held accountable for the risk of a carbon tax if they plan on new coal plants. In other words, their opinion is that the shareholders and not the consumers should take the risk.

Education is public awareness of the possibilities or options, a realistic cost/benefit comparison over the lifetime of the energy systems. Remember, you cannot fool mother nature and you will pay one way or another.

Politics will continue to influence which and how many different energy sources are subsidized. Present policies include a tax or limitation on greenhouse gas emissions, rebates on equipment or incentives for electrical energy produced from renewable energy, Renewable Portfolio Standards, set prices for renewable energy, and tax credits.

11.6 INCENTIVES

Energy subsidies have serious effects, generally in favor of conventional fossil fuels and established energy producers. Subsidies for renewable energy between 1974 and 2000 amounted to over $20 billion worldwide. This compares with the $300 billion per year to conventional energy sources, not even taking into account expenditures for infrastructure, safeguards, and military actions [31]. The privatization of the electric industry along with the restructuring into generation, transmission, and distribution has opened some doors for renewable energy.

11.6.1 United States

The major impetus to the wind industry was due to the federal tax credits, the National Energy Act of 1978, and the avoided costs set by the California Public Utilities Commission. The federal tax credits for wind turbines were available from 1980 to 1985. For small systems for personal use, the tax credits were 40% of the cost, up to a maximum of $4,000. For a business, the tax credits were 25% off the bottom line. During this period, tax shelters for California wind farms were the primary method of financing.

A part of the National Energy Strategy Act of 1992 provided a $0.015/kWh incentive for production of electricity by wind energy. An investor can claim the production tax credit (PTC) under Section 45 of the IRS Code [32]. The provisions are:

- The investor owns the wind facility, which is placed in service during the period December 31, 1993 to July 1, 1999.
- The investor produces the electricity at the wind facility.
- The investor sells the electricity to an unrelated party.

The credit applies to production through the first 10 years of operation. The credit is intended to serve not only as a price incentive, but also as a price support. The credit is phased out as the average national price exceeds $0.08/kWh, based on the average price paid during the previous year for contracts entered into after 1989. Both values will be adjusted for inflation. The credit can be carried back for 3 years and carried forward for 15 years to offset taxes on income in the other years. The PTC was extended several times, now through 2009.

There was a provision of direct payment, Renewable Energy Production Incentive, to public utilities, co-ops, and Indian tribes, which is equivalent to the PTC. The problem is that Congress has to fund it every year, the amount of funds may be less than requested, and wind projects have to compete with other renewable projects.

The federal government continues to support wind energy through the Department of Energy budget for Energy Efficiency and Renewable Energy [33]. As always, the budget for renewable energy is less than the budget for nuclear energy. In 1973, the amount for wind was $300,000, and that increased steadily to $67 million in 1980. During Reagan's term, that was reduced every year, and in 1988 the amount budgeted was $8 million. Since then there have been increases and the budget for wind for FY 2008 was $49.5 million. A major part of the funding has gone toward development of large horizontal-axis wind turbines.

The tone or direction is set by the administration, which changes with the president. The early direction was R&D plus demonstration projects, which was supposed to lead to commercialization. During the Reagan years, *commercialization* was a bad word and private industry was supposed to commercialize wind turbines. Federal funding was for generic R&D, such as aerodynamics, wind characteristics, etc. Funding increased slightly during the Bush term, as the advanced technology program was initiated. This program was to recapture part of the market acquired by foreign wind turbines.

Under Clinton there was renewed interest in renewable energy and the direction was commercialization. The Climate Change Action Plan moved DOE from focusing primarily on technology development to playing an active role in renewable energy commercialization. This initiative was backed up with $72 million for FY 1995 ($18 million for wind) and a total of $432 million through the year 2000. DOE was looking primarily to wind for the emissions reductions from renewables, since it is the most economical at this time.

Under George W. Bush, the national energy plan first focused on increased production of oil and gas. With pressure from Congress, conservation, energy efficiency, and renewables are now part of the package. However, an increase in fuel efficiency for the automotive industry, CAFE standards, did not pass until the last year of the G. W. Bush presidency.

When there is money available, then every federal lab and university wants part of it, and there is a proliferation of new institutes and consulting groups. The wind money in the early years was divided among the following programs:

Large HAWTs (>100 kW)	NASA–Lewis
Small wind turbines (<100 kW)	Rocky Flats, Rockwell International
Vertical-axis wind turbines	Sandia Labs
Wind characteristics	Battelle Pacific Northwest Laboratory
Innovation wind turbines	Solar Energy Research Institute
Agricultural applications	U.S. Department of Agriculture

The innovative program and the agricultural program were terminated after a few years.

The Wind Energy Research Center at Rocky Flats was in charge of the small wind systems program. The Rocky Flats location was chosen because of politics, too much publicity on environmental problems at the plutonium facility. Early in the program they purchased units for testing and then started a field evaluation program [34]. The field evaluation program was to install two units in every state and the territories, definitely a political plus. After forty units were installed, this program was abandoned due to costs, and the wind turbines from the small wind industry were not ready.

The small wind machine program was transferred to the Solar Energy Research Institute (SERI). In addition, NASA–Lewis retired from the large HAWT program, transferring what was left to SERI. The president designated SERI as the National Renewable Energy Laboratory (NREL), on an equal footing with the other national labs that had their beginnings from the development of nuclear weapons, high-energy physics, or both. The expected progression was that NREL would absorb all the other programs associated with renewable energy, although Sandia Labs continued with the VAWT program. As always, there was and is a bit of political infighting. Today, the National Wind Technology Center, NREL, performs R&D and administers most programs concerning wind energy.

A 1999 initiative was Wind Powering America [35], whose goals were to meet 5% of U.S. energy needs with wind energy by 2020 (i.e., 80,000 MW installed); to double the number of states that have more than 20 MW of wind capacity to sixteen by 2005, and triple it to twenty-four by 2010; and to increase wind's contribution to federal electricity use to 5% by 2010. Subsequently, the secretary accelerated the DOE 5%

commitment to 2005. Achieving the 80,000 MW goal would result in over a $100 billion investment and $1.5 billion of rural economic development (where the wind resources are the greatest).

11.6.1.1 State Incentives

States are also competing for renewable energy as a way to offset importation of energy and as a way to create jobs. The Database of State Incentives for Renewable Energy (DSIRE) is a comprehensive source of information on state, local, utility, and selected federal incentives that promote renewable energy [36]. Overview maps tables are available by type of incentive and policies.

Minnesota passed legislation requiring Northern States Power (now part of Xcel Energy) to acquire 425 MW of wind power by the year 2002 in exchange for permission from the state legislature to store waste from its Prairie Island nuclear facility in dry casks outside the plant. With the success of the Renewable Portfolio Standard in Texas, by 2008, twenty-six states had passed RPSs and another six states had passed renewable energy goals.

Texas passed legislation that the Lower Colorado River Authority could acquire renewable energy from plants located on state lands outside of its service territory. This paved the way for a 35 MW wind farm (1995) in the Delaware Mountains in the Trans-Pecos region, with an extension for another 200 MW, of which 40 MW has been installed.

Some states have mandated deregulation of the electric utility industry. Besides giving the consumers choice of producers, most of the states have a system benefits charge (SBC), which lets utilities recover stranded costs of power plants, primarily for nuclear plants. In some states, part of the SBC is set aside for renewable energy. For example, in California, funds from SBC are available to offset part of the cost for small wind systems.

The wind farm boom in Texas was fueled by the production tax credit and a Renewable Portfolio Standard (RPS), enacted in 1999, which was part of electric restructuring. The mandate was for 2,000 MW of new renewables by 2009 in the following amounts, by 2-year steps:

Year	MW
2003	400
2005	450
2007	550
2009	600
Total	2,000

Because so much wind power was installed (Figure 10.11), the RPS was increased in 2005 to 5,880 MW by 2015 (again by 2-year steps), with a goal of 10,000 MW by 2025. There was a mandate of 500 MW from other renewables in that RFP. For the 2015 mandate, the amount that can be produced by wind will be surpassed in 2008, as wind farm capacity will be an estimated 8,000 MW (Figure 10.12), and if the federal production tax credit is extended, then the goal of 10,000 MW will be easily be surpassed within another 2 to 3 years.

Another aspect of the electric restructuring in Texas is that electric retailers have to acquire renewable energy credits (1 REC = 1 MWh) from renewable energy produced in Texas or face penalties of up to $50/MWh. Anybody may participate in the REC market: traders, environmental organizations, individuals, etc. The market opened in January 2002, and early prices were around $5/REC. In 2008 the RECs were selling for $5–8. The RECs are good for the year created and bankable for 2 years.

As always, industries seek tax breaks at every level. States and local entities give tax breaks for economic development, and wind farm developers would like a property tax break or abatement on installed costs, as that is the major cost. Conventional power producers can deduct the cost of fuel, whereas for renewable energy there are not deductions since the fuel is free. Tax abatements have become common with a payment in lieu of taxes for schools.

11.6.1.2 Green Power

Green power is a voluntary consumer decision to purchase electricity supplied from renewable energy sources or to contribute funds for the utility to invest in renewable energy development. Green power is an option in some states' policy, and also has been driven by responses of utilities to customer surveys and town meetings. Green power is available to retail or wholesale customers in twenty-two states [37].

In the early 1990s, a small number of U.S. utilities began offering green power options to their customers. The consumer had to pay a premium, which was around $3/month for a 100 kWh block. This represented a powerful market support mechanism for renewable energy development, which was mainly wind energy. More than half of all U.S. electricity customers have an option to purchase green power from more than 750 utilities, or about 25% of utilities nationally [38]. It is interesting that some utilities have lowered the rate premium on green power as traditional fossil fuel costs have increased. As green power becomes cheaper than regular power, will those consumers who purchased green power pay below the regular rate? NREL ranks the utility green power programs annually [39].

11.6.1.3 Net Metering

If the renewable energy system produces more energy than is needed on site, the utility meter runs backward, and if the load on site is greater, then the meter runs forward. Then the bill is determined at the end of the time period, which is generally 1 month. If the renewable energy system produced more energy over the billing period than was used on site, the utility company pays the avoided cost. Most of the states have net metering, which ranges from 10 to 1,000 kW, with most in the 10 to 100 kW range [40].

In general, net metering did not increase the sale of wind turbines because the small wind turbines, 10–50 kW, are not cost-competitive with retail electricity. Larger-sized wind turbines can be cost-competitive for users with large loads, where all the electricity is used on site. Because the value set for the avoided cost is generally only equal to the fuel adjustment cost, you want to use that energy on site, as that displaces energy at the retail rate. Also, if the time period could be set longer than 1 month, net metering would be more useful to the producer. This is especially true for irrigation, where the large demand is in the summer, and that is the period of low winds for most of the United States.

Of course, utility companies do not like net metering because it increases the billing problem, and the utilities say that one group of customers is subsidizing another group of customers. With electric restructuring, utilities are worried that large customers will find cheaper electricity, and then rates will rise for residential customers. Does that mean that many residential customers are subsidized today?

11.6.2 Other Countries

Several European countries started wind energy programs in the 1980s, with most emphasizing megawatt wind turbines; however, these had little success. The manufacturers in Denmark produced small to larger units in steps and acquired around 50% of the early U.S. market, and 66% of Europe's installed capacity in 1991. Today, European manufacturers have captured the major share of the world market for wind farms.

There were different policy options for renewable energy in the European Union (EU) [41, 42]. The effectiveness and efficiency of current and future support for renewable energy for producing electricity were analyzed [43]. Free trade in renewables in the EU market is complicated by the fact that renewables are supported by mandates or fixed prices at different levels by country and even state. This support could be regarded as a substitute for a pollution tax on fossil fuels.

Promotion of wind energy in Europe was based on two models: (1) price support for kilowatt-hour production and (2) quota or capacity based (Table 11.1). Quota is similar to a Renewable Portfolio Standard. In general, the minimum base price has resulted in the most installations [44].

TABLE 11.1
Models of Compensation in Europe (€ 2003)

Country	Minimum Price €/kWh
Netherlands	9.2
Germany	6.6–8.8
France	8.4
Portugal	8.1
Austria	7.8
Spain	6.4
Greece	6.4
	Quota
Italy	13.0
United Kingdom	9.8

In Denmark the Windmill Law requires electric utilities to purchase energy from private wind turbine owners at 85% of the consumer price of electricity plus ecotax relief of about \$0.09/kWh. Electric utilities receive about \$0.015/kWh subsidy for wind power. The development of wind power was tied to the Energy 21 goal of reducing CO_2 emissions by 20% by 2005.

Germany accounted for half the European market after 1995. Germany adopted the Electricity Feed Law (EFL) in 1990 as an instrument for climate protection, saving fossil fuels, and promoting renewable energy. The law obliged utilities to buy any renewable energy from independent power producers at a minimum price defined by the government, which is based on the average revenue of all electricity sales in Germany. The initial value in 1991 was €0.16/kWh. The EFL was modified in 1998, which set a regional cap of 5% for renewable electricity. Since the Renewable Energy Sources Act was enacted, the electricity generation in Germany from renewable energy almost doubled from 6% in 2000 to 13% in 2007 [45]. Most of that is generated by wind.

Earlier programs for promoting wind (100 MW and expansion to 250 MW program) received kWh support. Because so much wind was installed, in 2004 it was changed to €0.085/kWh for 5 years and then €0.055/kWh for the next 15 years. There was a decrease of 2.5% per year, which meant in 2010 the price would be €0.079/kWh for 5 years and then €0.05/kWh for 15 years. Some states in Germany also gave a 50% investment grant in the late 1980s and early 1990s. Special low-interest loans for environmental conservation measures were also available for financing wind projects. These factors contributed to the massive growth of wind in the 1990s in Germany, which ranks number one in the world in installed capacity.

India ranks fifth in the world in installed capacity due to a favorable fiscal/policy environment. In the last 10 years, wind power development in India has been promoted through R&D, demonstration projects and programs supported by government subsidies, fiscal incentives, and liberalized foreign investment procedures.

Central government: Income tax holiday, accelerated depreciation, duty-free import, energy capital/interest subsidies.

State governments: Buyback, power wheeling and banking, sales tax concession, electricity tax exemption, demand cut concession offered to industrial consumers who establish renewable power generation units, and capital subsidy. Tamil Nadu and several other state electric boards purchase wind energy at about \$0.064/kWh.

11.7 EXTERNALITIES

Externalities are defined as social or external costs and benefits, which are attributable to an activity that is not borne by the parties involved in that activity. Externalities are not paid by the producers or consumers and are not included in the market price, although someone at sometime will pay for or be affected by them.

Social benefits, generally called subsidies, are paid by someone else and accrue to a group. An example is the Rural Electrification Act, which brought electricity to rural United States. An example of a positive externality (social benefit) is the benefit everyone gets from cleaner air from installation of wind farms. On the other side, a good example of a negative externality is the use of coal in China, as every city of 100,000 and over has terrible smog, due to use of coal for heating, cooking, industry, and production of electricity. In 20 years, there will be a large public health cost for today's children.

External costs can be divided into the following categories:

- Hidden costs borne by governments, including subsidies and R&D programs.
- Costs associated with pollution: health and environment damage, such as acid rain, destruction of the ozone, unclean air, and lost productivity. An example is CO_2 emissions [45], and even though global warming is disputed by many in industry and some scientists, it may have far-reaching effects.

Mechanisms for including externalities into the market are:

Government regulation: This historical approach has led to inefficient and monopolistic industries, inflexible and highly resistant to change. The current vogue is for deregulation and privatization of energy industries. However, if external costs are not included, short-term interests prevail. Regulations can require a mix or minimum use of energy sources with lowest life cycle costs, which include externalities.

Pollution taxes: Governments can impose taxes on the amount of pollution a company generates. European countries have such taxes. Another possibility is to give renewable energy credits for producing clean power. Pollution taxes and avoidance of pollution have the merit of simplicity, and have only a marginal effect on energy costs, but they are not a true integration of external costs into market prices. The taxpayer pays, not the consumer. The pollution tax could be assessed in the consumer bill; therefore, it is paid based on how much is used.

Integrated resource planning (IRP): This model combines the elements of a competitive market with long-term environmental responsibility. An IRP mandate from the government would require the selection of new generating capacity to include all factors, not just short-term economic ones.

Subsidies for R&D and production.

Many studies on externalities have been conducted. The European Union's six-volume *ExternE: Externalities of Energy* is probably one of the most systematic and detailed studies to evaluate the external costs associated with a range of different fuel cycles [46]. In their estimates, external costs for production of electricity by coal can be as high as \$0.10/kWh, and for nuclear power, \$0.04/kWh.

Since 1995, companies in the United States have been trading sulfur dioxide (SOX) and nitrogen oxide (NOX) emissions, which are precursors of acid rain and contributors to ground-level ozone and smog. Essentially, industries trade in units called allowances, which can be bought, sold, or banked for future use. Carbon dioxide trading [47] is not included in the United States; however, some states are now passing laws to reduce CO_2 production, and when the next president takes office, it is very probable that there will be national regulations on CO_2 emissions. Wind generator systems reduce CO_2 emissions by almost 10 tons/MWh (Table 11.2) when displacing coal generation [48].

TABLE 11.2
Emissions (Metric Tons) from Electric Power Sector in United States, 2005

	Carbon Dioxide		Sulfur Dioxide		Nitrogen Oxides	
	kg/kWh	tons 10^6	kg/kWh	tons 10^6	kg/kWh	tons 10^6
Coal	0.97	1,938	0.006	9.1	0.0034	3.5
Natural gas	0.42	340			0.0008	0.2
Oil	0.63	101	0.05	0.4	0.001	0.1
Total		2,340		9.5		3.8

The largest emitters of carbon dioxide are the United States and China [49]. In Europe, CO_2 emission reductions are worth $40/ton in some countries.

11.8 TRANSMISSION

A major problem for wind farm development is that many load centers are far away from the wind resource, and wind farm projects can be brought online much faster than new transmission lines can be constructed. A number of large transmission projects have been proposed in the United States [50, 51]. For major wind farm development in the Great Plains, new transmission lines will have to be constructed [52–56]. A large transmission investment of $\$13*10^9$ would increase a retail bill of $100 by about $1.

For those states with electric restructuring, transmission is now a separate company and the question is jurisdiction (who pays for new lines), and if curtailment is needed, who is curtailed and the priority of curtailment. Curtailment happens when the wind farms are producing more power than the transmission lines can carry; therefore, some or all of the wind turbines in a wind farm have to be shut down. In the McCamey area of West Texas, curtailment of output from wind farms is a problem. Even with new transmission lines, more wind farm development in that area will be limited by transmission capacity. Since the jurisdiction of the Electric Reliability Council of Texas (ERCOT) does not include the windy areas of the Panhandle, there are proposals to build transmission lines from the Panhandle to major load areas in ERCOT. Competitive Renewable Energy Zones were selected across Texas and different scenarios are being proposed for major transmission lines [57]. Some wind companies have already proposed to build the transmission lines, and developers are tying up land in the Panhandle for wind leases. In 2008 T. Boone Pickens, noted oil man, purchased 667 GE wind turbines for the first phase (1,000 MW) of a proposed 4,000 MW wind farm in the Panhandle.

In the European Union, transmission is also a major issue [58]. The electricity markets are not competitive for four reasons: lack of cross-border transmission links; existence of dominant, integrated power companies; biased grid operators; and low liquidity in wholesale electricity markets [59]. The conclusion is that a significant amount of wind power is determined more by economics and regulations than by technical or practical constraints.

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PROBLEMS

1. What type of incentives should there be for renewable energy, particularly wind energy? Give a brief explanation for your choices.
2. For energy production from a wind facility, what is the avoided cost that the utility would pay?
3. What are ancillary costs?
4. List two environmental issues for installing a large wind farm in your area.
5. How much support should the U.S. government provide for wind energy? Why?
6. What type of projects should the federal government support? (Some examples are R&D, prototype, demonstration, turbine verification, and commercialization projects.)
7. Should state and local governments provide incentives for wind energy? If yes, list your choices and explain why.
8. What type of education would be most effective for promoting renewable energy? At what level and to whom?
9. What are the major environmental concerns if a renewable energy system is planned for your area?
10. List three externalities for electricity from coal power plants.
11. How many states in the United States have net energy metering of 100 kW or greater?
12. What is the longest period for net energy billing?
13. What incentives are there for residential size wind systems in your state?
14. Does your electric utility offer green power. If yes, what is it? If no, briefly describe the green power program of Austin Energy, Austin, Texas.
15. Go to www.dsireusa.org. How many states have Renewable Portfolio Standards? How many states have a rebate program for purchasing wind systems?
16. What are present market values of renewable energy credits in Texas?
17. Should there be a pollution tax for electricity produced by fossil fuels? If yes, how much per metric ton?
18. Calculate the carbon dioxide that wind displaced for the world. Use kilograms per kilowatt-hour from coal power electric plants for comparison. Use 35% capacity factor for wind plants in estimating annual energy production.
19. Calculate the carbon dioxide that wind displaced for EU and for the United States. Use kilograms per kilowatt-hour from coal power electric plants for comparison. Use 35% capacity factor for wind plants in estimating annual energy production.
20. What is the cost per kilometer for building a major transmission line, 300 kV or larger?
21. Compare the fatality rates for birds and bats from wind turbines.
22. What is the leading cause of death in the wind industry? What are the leading causes of wind turbine accidents?

12 Economics

The most critical factors in determining whether it is financially worthwhile to install wind turbines are the initial cost of the installation and the annual energy production. In determining economic feasibility, wind energy must compete with the energy available from competing technologies. If the system produces electrical energy for the grid, the price for which the electrical energy can be sold is also critical. Today, wind farms are essentially competitive with all new power plants, even combined-cycle natural gas turbines, as fuel prices have increased with oil over \$100/bbl. To increase market penetration of wind systems, the return from the energy generated must exceed all costs in a reasonable time.

Of course, all values for electricity produced by wind turbines depend on the wind resource, so there is a range of values. Installed costs for wind farms had declined to \$1,000/kW by 2003, which translates to a value of electricity produced of \$0.04–0.06/kWh. Operation and maintenance (O&M) costs for wind farms were around \$0.01/kWh. In the United States contracts for selling electricity from wind farms were signed in 1995 for \$0.04/kWh, and in 2002 for less than \$0.03/kWh. Since then the prices of steel, cement, and copper have increased, and the installed costs in 2008 are estimated at \$1,800–2,000/kW, which translates to a value of electricity of \$0.07–0.09/kWh. None of the earlier dollar values have been corrected for inflation.

Therefore, the U.S. Department of Energy's (DOE) goals for wind turbines for wind farms to produce electricity at \$0.03/kWh for class 6 lands (6.7 m/s annual average at 10 m height) by 2004 and \$0.03/kWh for class 4 lands (5.8 m/s annual average at 10 m height) by 2010 cannot be met. These values include O&M at \$0.005/kWh. However, the cost of electricity from new power plants using fossil fuels will also increase, so electricity from wind farms is still competitive.

Systems of 1 kW are not cost-effective when connected in parallel to the utility grid, even for single residences; however, people will purchase them for other reasons. Residences connected to the utility grid need 5–10 kW machines, and farms, ranches, and businesses need a minimum size of 25 kW (around 10 m diameter) or larger. In general, installed costs for small wind turbines up to 50 kW are around \$2,500–\$5,000/kW, which translates to a value of electricity produced of around \$0.12–0.30/kWh.

The size of the wind turbine for residences, farms, ranches, and rural applications depends on the amount and price of electricity from the grid, if net metering is available and local infrastructure. The kilowatt-hour consumed can be obtained from the monthly electric bill or by calling the local utility to obtain the monthly use. To maximize the return on the wind system, most of the energy should be used on site, because that energy is worth the retail rate. However, net energy billing allows for larger-sized systems, as the system can be sized for producing all the energy needed on site within the billing period.

As stated in the previous chapter, economics is intertwined with incentives and penalties, so actual life cycle costs [1] are hard to determine, especially when externalities of pollution and government support for R&D for competing energy sources are not included.

12.1 FACTORS AFFECTING ECONOMICS

The following list includes most of the factors that should be considered when purchasing a small wind energy conversion system for home, business, or farm or ranch.

1. Load (power) and energy
   Energy: Calculate by month or by day for small systems
2. Cost of energy from competing energy sources to meet need

3. Initial installed cost
   Purchase price, shipping costs, installation costs (foundation, utility intertie, labor, etc.), cost of land (if needed)
4. Production of energy
   Type(s) and size(s) of wind turbines
      Warranty, company (reputation, past history, number of years in business, future prospects), reliability, availability
   Wind resource
      Variations within a year, variations between years
5. Selling price of energy produced or unit worth of energy and anticipated energy cost changes (escalation) of competing sources
6. Operation and maintenance costs
   General operation, ease of service, emergency services and repairs, insurance, infrastructure (are service personnel available locally?)
7. Cost of money (interest rate, fixed or variable)
8. Inflation (estimated for future years)
9. Legal fees (negotiation of contracts, titles, easements, permits)
10. Depreciation if system is a business expense
11. Any national or state incentives

12.2 GENERAL COMMENTS

The general uncertainty regarding future energy costs, dependence on imported oil, reduction of pollution and emissions, and to some extent availability, has provided the driving force for the development of renewable sources. The prediction of energy costs escalation is a hazardous endeavor, as the cost of energy is driven primarily by the cost of oil. Oil was $15–25/barrel in the 1990s, and predictions in the late 1990s were for a gradual increase to $30/barrel by the year 2020. However, oil reached $30/bbl in 2003 and then soared to $130/bbl in 2008. Price increases have not been and will not be uniform, in terms of either time or geography. At the point in time where demand exceeds production, there will be another increase in the price of oil. Some experts predict that the peak of world oil production will occur in this decade, while others predict it will be from 2016 or even into 2040. The most important factors are the estimated total reserves and what is the amount recoverable. As price increases, it becomes economic to recover more from existing reservoirs and to produce oil in more difficult reservoirs: polar, deep sea, tar sands, and even oil shale.

Every effort should be made to benefit from all incentives for installing a wind turbine, mainly national and state incentives. The cost of land is a real cost, even to those using their own land. This cost is often obscured because it occurs as unidentified lost income. Wind turbines occupy space and will reduce the amount of land available for farming or ranching. For wind farms, the amount of land taken out of production can run from 0.5 to 1.5 ha/turbine.

Wind turbine availability is important in determining the quantity of energy produced. For optimum return, the machine must be kept in operation as much of the time as possible, consistent with safety considerations. Background information on machine performance, including failures, should be sought out and used to estimate the downtime. Availability for earlier machines was low; however, recent figures reached 98%. The distribution of this energy throughout the year can affect the value of the energy. If most of the energy comes during a time of increased demand on the utility system, or during the time energy is needed on the site, then that energy is clearly of more value.

Wind turbines can produce electricity for consumption on or near the site, to sell to a utility, or both. The higher the selling price, the more economically feasible the project becomes. In general, where there are one or a few wind turbines, the owner will use part of the energy and sell the excess to the utility. The electricity used on site displaces electricity at the retail rate. For those states that have net energy billing (in general, size is limited to small wind turbines), even the energy fed back to the utility is worth the retail rate. If more energy was produced than was used during the billing period, then that energy is sold for avoided cost. For locations where the retail rate is higher than the avoided cost paid for excess energy fed back to the utility, economic feasibility improves with increasing on-site consumption. The price paid by the utility is either negotiated with the utility, set by law, or decided by a public regulatory agency.

EXAMPLE 12.1

A wind turbine produces 2,000 kWh in a month. There are two meters: one measures energy purchased from the utility company (3,000 kWh), and the second measures energy fed back to the grid (1,200 kWh). The energy displaced by the wind turbine is 800 kWh (2,000 – 1,200). Retail rate (from grid) is $0.08/kWh. The value of the excess energy sold to the grid (avoided cost set by the state) is $0.04/kWh.

Bill if Use Two Meters	kWh	$/kWh	$
Meter 1	3,000	0.08	240
Meter 2	1,200	0.04	–48
Month charge for second meter			15
		Total	207
	Net billing, one meter runs forward and backward		
Meter	1,800	0.08	144

Clearly net billing is preferable, because all the energy produced by the wind turbine is worth the retail rate, up to the point where the meter reads no difference from the previous month.

The costs of routine operation and maintenance for individuals represent the time and parts costs. Until system reliability and durability are better known for long time periods, the costs of repairs will be difficult to estimate. It is important that the owner has a clear understanding of the manufacturer's warranty and that the manufacturer has a good reputation. Estimates should be made on costs of repairing the most probable failures. Insurance costs may be complicated by companies that are uncertain about the risks involved in a comparatively new technology. However, the risks are less than those associated with operating a car.

Inflation will have its principal impact on expenses incurred over the lifetime of the product. The costs of operation and maintenance, and especially the unanticipated repairs, fall into this category. On the other hand, cheaper dollars would be used to repay borrowed money (for fixed-rate loans).

12.3 ECONOMIC ANALYSIS

Economic analyses, both simple and complicated, provide guidelines. Simple calculations should be made first. Commonly calculated quantities are (1) simple payback, (2) cost of energy (COE), and (3) cash flow.

A wind turbine is economically feasible only if its overall earnings exceed its overall costs within a time period up to the lifetime of the system. The time at which earnings equal cost is called the payback time. The relatively large initial cost means that this period could be a number of years, and in some cases earnings may never exceed the costs. Of course, a short payback is preferred, and a payback of 5 to 7 years is acceptable. Longer paybacks should be viewed with caution.

How do you calculate the overall earnings or value of energy? If you did not have any source of energy for lights, radio, and maybe a TV, a cost of $0.50–$1.00/kWh may be acceptable for the benefits received. Many people are willing to pay more for green power because they know it produces less pollution. Past green power premiums were around \$0.03/kWh for a 100 kWh block. And finally, a few people want to be completely independent from the utility grid, no matter what the cost.

12.3.1 Simple Payback

A simple payback calculation can provide a preliminary judgment of economic feasibility. The difference is usually around 3–7 % between borrowing money for a system and lost interest if you have enough money to pay for the system. In 2003 and again in 2008, the lost interest rate was very low. The easiest calculation is cost of the system divided by cost displaced per year, and assuming that operation and maintenance is minimal and will be done by the owner.

$$SP = IC/(AKWH * \$/kWh) \tag{12.1}$$

where SP = simple payback, years; IC = initial cost of installation, \$; AKWH = annual energy production, kWh/year; and \$/kWh = price of energy displaced.

EXAMPLE 12.2

You purchase a 300 W wind turbine for battery charging. Installed cost = \$850, produces 220 kWh/year at \$0.50/kWh (the estimated cost for remote electricity).

$$SP = \$900/(220 \text{ kWh/year} * 0.50 \text{ \$/kWh})$$
$$SP = 900/110 = 8 \text{ years}$$

The next calculation would include the value of money, borrowed or lost interest, and annual operation and maintenance costs:

$$SP = \frac{IC}{\left(AKWH * \frac{\$}{KWH} - IC * FCR - AOM\right)} \tag{12.2}$$

where FCR = fixed charge rate, per year, and AOM = annual operation and maintenance cost, \$/year.

EXAMPLE 12.3

You purchase a 3.5 kW wind turbine with inverter to connect to the grid, IC = \$14,000, produces 6,000 kWh/year. You are losing interest at 4% on the installed cost. Retail rate of electricity is \$0.11/kWh. Assume AOM = \$50/year.

$$SP = 14{,}000/(6{,}000 * 0.11 - 14{,}000 * 0.04) = 14{,}000/(660 - 560) = 140 \text{ years}$$

You would think twice before purchasing this system on an economic basis. And no O&M was included.

The FCR could be the interest paid on a loan or the value of interest that would have been received from displaced money from savings. An average value for a number of years (5) will have to be assumed for \$/kWh for electricity displaced, as future costs of electricity from the utility company may be difficult to estimate. In general, electric rates do not fluctuate much and do not increase rapidly. The one change with deregulation is that the fuel adjustment cost can change quickly.

EXAMPLE 12.4

You purchase a 50 kW wind turbine, IC = \$120,000, produces 120,000 kWh/year, AOM = 0.01 * IC = \$1,200/year, FCR = 0.07. Retail rate of electricity is \$0.11/kWh.

$$SP = 120{,}000/(120{,}000 * 0.11 - 120{,}000 * 0.07 - 1{,}200) = 120{,}000/(13{,}200 - 8400 - 1200)$$
$$SP = 33 \text{ years}$$

Equation 12.2 involves several assumptions: the same kilowatt-hours are produced each year, the value of the electricity is constant, and there is no inflation. More sophisticated analysis would include details such as escalating fuel costs of conventional electricity and depreciation. In general, these factors might reduce the payback.

12.3.2 Cost of Energy

The cost of energy (value of the energy produced by the wind turbine) gives a levelized value over the life of the system (assumed to be 20 to 25 years). The cost of energy (COE) is primarily driven by the installed cost and the annual energy production.

$$COE = (IC * FCR + AOM)/AKWH \tag{12.3}$$

The COE is one measure of economic feasibility, and is compared to the price of electricity from other sources (primarily the utility company) or the price for which wind-generated energy can be sold. If purchasing a wind turbine for displacing electricity on site, the COE should be compared with an estimated average cost of electricity from the utility company over the next 10 years. The cost of energy for small systems is higher than for wind farms, with some economies of scale for larger size of small wind turbines (Table 12.1). In general, the AOM is around \$0.005/kWh. In Equation 12.3, major replacement costs are included in the annual operation and maintenance costs.

EXAMPLE 12.5

Use same input data as Example 12.4, except FCR = 0.08 and AOM = 3% * IC.

$$COE = (120{,}000 * 0.08 + 3600)/120{,}000 = \$0.11/\text{kWh}$$

A sensitivity analysis (Figure 12.1) shows how the different factors in Equation 12.3 affect the cost of energy. The most important factors are installed cost and annual energy production.

The cost of energy formula from Electric Power Research Institute (EPRI), tag-supply method [2], is similar to Equation 12.3. There is the addition of levelized replacement costs (major repairs)

TABLE 12.1
Range of Cost of Energy for Small Systems, Wind Class 4 to 2 (Capacity Factors 35–25%)

System, kW	\$/kWh
1	0.20–0.30
10	0.18–0.23
50	0.10–0.18

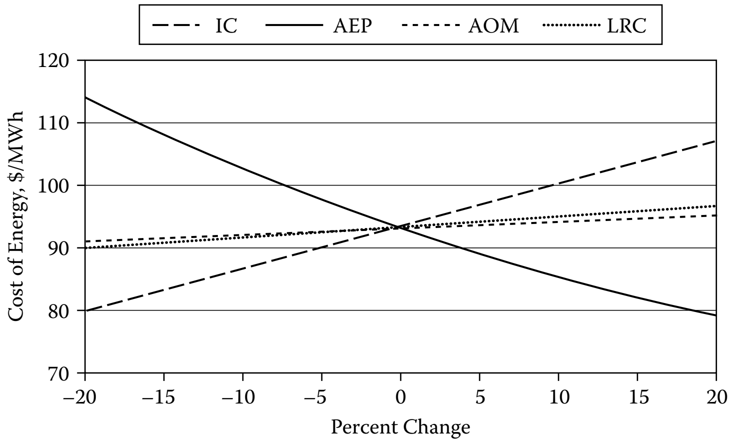

FIGURE 12.1 Sensitivity analysis for cost of energy for wind turbine.

and fuel costs for conventional power plants. Since the cost of fuel for wind energy is zero, that term will be left out:

$$\mathrm{COE} = \frac{(\mathrm{IC} * \mathrm{FCR}) + \mathrm{LRC} + \mathrm{AOM}}{\mathrm{AEP}} \tag{12.4}$$

where LRC = levelized replacement cost ($/year) and AEP = net annual energy production (MWh or kWh/year).

The COE can be calculated for $/kWh or $/MWh, and the last term could be separate as AOM/AEP, $/kWh or $/MWh. With histogram data and power curves to calculate annual energy production, the cost of energy can be calculated. A first estimate for levelized replacement costs could be 4–5% of the installed cost.

EXAMPLE 12.6

Wind turbine, 1 MW, IC = $1,600,000, FCR = 0.07, AEP = 3,000 MWh/year, LRC = $80,000/year, AOM = $8/MWh = $0.008/kWh.

$$\mathrm{COE} = \frac{(1{,}600{,}000 * 0.08) + 80{,}000}{3000} + 8 = \$77/\mathrm{MWh} = \$0.077/\mathrm{kWh}$$

That cost of energy needs to be compared to all expected net income from the wind farm, which includes any incentives, depreciation, and expected rate of return.

Levelized replacement cost distributes the costs for major overhauls and replacements over the life of the system. For example, in a village power system, storage batteries will need to be replaced every 5 to 7 years. The levelized replacement cost can be calculated with the following information. Again, it is an estimate for future replacement costs based on today's costs of components.

1. Year in which the replace is required, *n*
2. Replacement cost, including parts, supplies, and labor, RC
3. Present value of each year's replacement cost, PV

The present value for replacement costs is given by

$$\mathrm{PV}(n) = \mathrm{PV}(n) * \mathrm{RC}(n) \tag{12.5}$$

where PVF(n) = present value factor for year $n = (1 + I)^{-n}$; I = discount rate = 0.07, and RC(n) = replacement cost in year n.

The levelized replacement cost is the sum of the present values multiplied by the capital recovery factor (CRF):

$$\mathrm{LRC} = \mathrm{CRF} * \sum_{n=1}^{20} \mathrm{PV}(n) \tag{12.6}$$

where CRF = 0.093.

EXAMPLE 12.7

Calculation of levelized replacement cost for 50 kW turbine. Work done in a spreadsheet.

LRC Calculation

Component	Year, *n*	RC(*n*)	*I*	PVF(*n*)	PV(*n*)
Bearings	10	6,500	0.07	0.508	3,304
Blades	10	5,000	0.07	0.508	2,542
Subtotal					5,846
LRC, $/year		**544**			

Now the COE = (120,000 * 0.08 + 544)/120,000 = 0.01 = $0.095/kWh. This value can be compared with the value in Example 12.5. The problem is the determination of major repairs, year, and replacement cost.

12.3.3 Value of Energy

Another formula [3] for estimating the value of energy is

$$\frac{f_o}{c} \geq \frac{(1+r)^L \alpha r L}{\left[(1+\alpha)^L\right]\left[(1+r)^L - 1\right]} \tag{12.7}$$

where f_o = value of energy saved per year, $; c = initial installed cost, $; L = years to payback; α = fuel inflation rate; and r = interest rate.

Because there is not a factor for operation and maintenance, the interest rate should be increased by 1–2%. Equation 12.7 can be solved by iteration by using different values of L to calculate the right-hand side and then comparing that to the left-hand side of the equation. As interest rates increase, payback times increase; as fuel inflation factors increase and cost of electricity increases, payback times decrease.

12.4 LIFE CYCLE COSTS

A life cycle cost (LCC) analysis gives the total cost of the system, including all expenses incurred over the life of the system and salvage value, if any [1, 4, 5]. There are two reasons to do an LCC analysis: (1) to compare different power options, and (2) to determine the most cost-effective system designs. The competing options to small renewable energy systems are batteries or small diesel generators. For these applications the initial cost of the system, the infrastructure to operate and maintain the system, and the price people pay for the energy are the main concerns. However, even if small renewable systems are the only option, a life cycle cost analysis can be helpful for comparing costs of different designs or determining whether a hybrid system would be a cost-effective option. An LCC analysis allows the designer to study the effect of using different components with different reliabilities and lifetimes. For instance, a less expensive battery might be expected to last 4 years, while a more expensive battery might last 7 years. Which battery is the best buy? This type of question can be answered with an LCC analysis.

$$\mathrm{LCC} = \mathrm{IC} + M_{PV} + E_{PV} + R_{PV} - S_{PV} \tag{12.8}$$

where LCC = life cycle cost, IC = initial cost of installation, M_{PV} = sum of all yearly O&M costs, E_{PV} = energy cost, sum of all yearly fuel costs, R_{PV} = sum of all yearly replacement costs, and S_{PV} = salvage value, net worth at end of final year, 20% for mechanical equipment.

Future costs must be discounted because of the time value of money, so the present worth is calculated for costs for each year. Life spans for wind turbines are assumed to be 20 to 25 years; however, replacement costs for components need to be calculated. Present worth factors are given in tables or can be calculated. Life cycle costs are the best way of making purchasing decisions. On this basis, many renewable energy systems are economical.

The financial evaluation can be done on a yearly basis to obtain cash flow, break-even point, and payback time. A cash flow analysis will be different in each situation. Cash flow for a business will be different from a residential application because of depreciation and tax implications. The payback time is easily seen, if the data are graphed.

EXAMPLE 12.8

Residential application with rebate, IC = \$25,000, down payment = \$7,000, loan = \$18,000 at 10% (payment = \$4,000/year), O&M = 2.5% * IC = \$500/year, energy production = 50,000 kWh/year (75% consumed directly, displacing 8 cents/kWh electricity, and 25% sold to the utility at 4 cents/kWh, with utility escalation at 3%/year). Cash flow done in a spreadsheet.

Year	0–1	2	3	4	5	6	7	8	9
Down payment	7,000								
Principal left	18,000	15,800	13,380	10,718	7,790	4,569	1,026	0	
Principal paid	2,200	2,420	2,662	2,928	3,221	3,543	3,897	1,128	
Interest	1,800	1,580	1,338	1,071.8	778.98	457	103	0	
O&M	500	500	500	500	500	500	500	500	500
Insurance	50	50	50	50	50	60	60	60	60
Property tax	70	70	70	70	70	70	70	70	70
Costs	7,620	4,620	4,620	4,620	4,620	4,630	4,630	1,758	630
Value energy used	3,000	3,090	3,183	3,278	3,377	3,478	3,582	3,690	3,800
Value energy sold	500	515	530	546	563	580	597	615	633
Rebate	4,000								
Income	7,500	3,605	3,713	3,825	3,939	4,057	4,179	4,305	4,434
Cash flow	–120	–1,015	–907	–795	–681	–573	–451	2,546	3,804
Cumulative		–1,135	–1,922	–1,702	–1,476	–1,253	–1,023	2,096	6,350

In this analysis the payback time is in year 8. There are a number of assumptions about the future in such an analysis. A more detailed analysis would include inflation and increases on costs for operation and maintenance as the equipment becomes older.

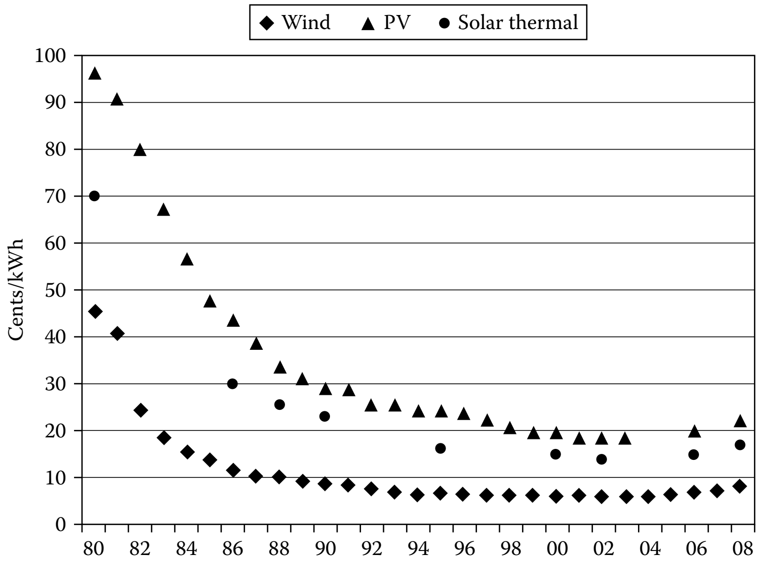

FIGURE 12.2 Cost of energy for generation of electricity: wind, photovoltaic, and solar thermal ($ 2008).

A cash flow analysis for a business with $0.02/kWh tax credit on electric production and depreciation of the installed costs would give a different answer. Also, all operating expenses are a business expense. The economic utilization factor is calculated from the ratio of the costs of electricity used at the site to that of the electricity sold to the utility.

The core of the RETScreen tools [6] consists of a standardized and integrated renewable energy project analysis software that can be used to evaluate the energy production, life cycle costs, and greenhouse gas emission reductions for the following renewable energy technologies: wind, small hydro, PV, passive solar heating, solar air heating, solar water heating, biomass heating, and ground-source heat pumps. The Hybrid2 software package [7] includes economic analysis. The cost of energy for wind, photovaltic, and solar thermal have decreased dramatically since 1980 (Figure 12.2).

12.5 PRESENT WORTH AND LEVELIZED COSTS

Money increases or decreases with time, depending on interest rates for borrowing or saving and inflation. Many people assume energy costs in the future will increase faster than inflation. The same mechanism of determining future value of a given amount of money can be used to move money backward in time. If each cost and benefit over the lifetime of the system were brought back to the present and then summed, the present worth can be determined:

$$PW = \frac{(\text{cost total for year } S) - (\text{financial benefit total for year } S)}{\left(1+d\right)^{M}} \tag{12.9}$$

where cost total = negative cash flow, S = specific year in the wind system lifetime, M = years from the present to year S, and d = discount rate.

The discount rate determines how the money increases or decreases with time. Therefore, the proper discount rate for any life cycle cost calculation must be chosen with care. Sometimes the cost of capital (interest paid to the bank, or alternately, lost opportunity cost) is appropriate. Possibly the rate of return on a given investment perceived as desirable by an individual may be used as the discount rate. Adoption of unrealistically high discount rates can lead to unrealistic life cycle costs. The cost of capital can be calculated from

$$CC = \frac{1 + \text{loan interest rate}}{1 + \text{inflation rate}} - 1$$

If the total dollars are spread uniformly over the lifetime of the system, this operation is called levelizing.

$$\text{annualized cost} = \frac{PW\ d\ (1+d)^P}{(1+d)^P - 1} \qquad (12.10)$$

where P = number of years in the lifetime.

One further step has been utilized in assessing renewable energy systems versus other sources of energy such as electricity. This is the calculation of the annualized cost of energy from each alternative. The annualized cost calculated from Equation 12.8 is divided by the net annual energy production of that alternative source;

$$\text{COE} = \text{annualized cost/AEP}$$

It is important that annualized costs of energy calculated for renewable energy systems are compared to annualized costs of energy from the other sources. Direct comparison of annualized cost of energy to current cost of energy is not rational. Costs of energy calculated in the above manner provide a better basis for the selection of the sources of energy.

RETFinance is an internet-based cost of electricity model [8] that simulates a 20-year nominal dollar cash flow for a variety of renewable energy power projects. It is difficult to compare cost and COE for different years without taking into account the effects of inflation. There are a number of sites on the Web for calculating inflation from past years to the present [9]. As an example, installed costs for wind farms in 2003 were $1,000/kW, which is equivalent to $1,160/kW in 2008. Of course, the amount of inflation in the future is a guess.

12.6 EXTERNALITIES

Externalities are now playing a role in integrated resource planning (IRP), as future costs for pollution, carbon dioxide, etc., are added to the life cycle costs. Values for externalities range from zero (past and present value assigned by many utilities) to as high as $0.10/kWh for steam plants fired with dirty coal. Again, values are being assigned by legislation and regulation (public utility commissions).

As always, there is and will be litigation by both sides. The Lignite Energy Council petitioned the Minnesota Public Utilities Commission to reconsider its interim externality values. The council represents major producers of lignite, investor-owned utilities, rural electric cooperatives, and others. They focused their protest on values assigned to CO_2 emissions, as their position was that there was an acknowledged lack of reliable science that CO_2 emissions are harmful to society. In Europe, different values have been assigned to CO_2 emissions, which makes wind energy more cost-competitive.

Wind turbines have three main beneficial externalities: local source of energy, the generation of electricity does not require water, and they do not emit greenhouse gasses. In Texas, fossil fuel power plants use 1,670 L/MWh [10], so the 4,500 MW of wind power in Texas (2007) will save water, $23 * 10^6$ m^3/year. An average of 700 kg of CO_2/MWh is emitted from coal and natural gas power plants. That 4,500 MW of wind in Texas will reduce CO_2 emissions by $9 * 10^6$ metric tons per year. The present value for CO_2 trading in Europe is $30/metric ton, which is equivalent to $20/MWh, and to around $30/MWh if replacing coal plants.

12.7 WIND PROJECT DEVELOPMENT

The three most important considerations for development of wind farms are:

1. Land with good to excellent wind resource
2. Contract to sell electricity produced
3. Access to transmission lines (proximity and carrying capacity)

The American Wind Energy Association [11, 12] and Wind Powering America [13] also have information on project development. The project development list covers many areas; however, it was placed in economics, as that is the final decision on a project. Much of the information was from Disgen [14].

PROJECT DEVELOPMENT

1. Site selection
   1.1. Evidence of significant wind resource
   1.2. Preferably privately owned remote land
   1.3. Proximity to transmission lines ⇒ 69 kV (up to 25 miles for good site and ⇒ 135 kV). Note possibility of future transmission lines.
   1.4. Reasonable road access
   1.5. Few environmental concerns
   1.6. Receptive community
2. Land
   2.1. Term: Expected life of the turbine (early, 20–30 years, 10-year option; later, 30–50 years, multiple 10-year options)
   2.2. Rights: Wind rights, ingress/egress rights, transmission right-of-way for wind farm
   2.3. Owner compensation: Percentage of revenue, per turbine, or combination
   2.4 Assignable: Financing requirement
   2.5 Indemnification
   2.6 Reclamation provision
   2.7 Bond to remove wind turbines at end of project
   2.8 Wind energy easements, legal issues
3. Wind resource assessment
   3.1. Lease, $/acre, 1–5 years, or flat fee
   3.2. Corollary data: Wind maps (national, state, other), NWS data, other
   3.3. Install meteorological tower(s), hub height or at least 50 m
   3.4. Collect 10 min or an hour of wind speed and direction data, 1–2 years, minimum 1 year
   3.5. Quality report on meteorology
   3.6. Output projections for several turbine types
   3.7. Landowner receives data, meteorology report, and output projections if developer does not exercise option for installation of project.
4. Environmental
   4.1. Cursory review for endangered species
   4.2. Biological resources
      4.2.1. Wildlife habitat
      4.2.2. Loss of vegetation

- 4.3. Avian studies
  - 4.3.1. Raptors
  - 4.3.2. Migratory birds
  - 4.3.3. Review with interested parties: Audubon, federal, state, local
  - 4.3.4. Required studies and reports
- 4.4. Bats
- 4.5. Archeological sites
- 4.6. Noise
- 4.7. Visual
- 4.8. Soil erosion and water quality
- 4.9. Solid and hazardous wastes
- 4.10. Active compliance monitoring

5. Economic modeling
   - 5.1. Output projections (see Section 3.6)
   - 5.2. Turbine costs
   - 5.3. Turbine installation
   - 5.4. Roads, substations, transmission
   - 5.5. Communication and control
   - 5.6. Taxes: Sales, income, property (depreciation schedule), tax abatement
   - 5.7. O&M estimates
   - 5.8. Finance assumptions: Production tax credit, accelerated depreciation, equity rate of return, incentives (local, state), debt rate and term (coverage ratios), debt/equity ratio
   - 5.9. Other: Insurance, legal
6. Interconnection studies
   - 6.1. Interconnection request, electric reliability council
   - 6.2. Capacity limitation
   - 6.3. Load flow analysis
   - 6.4. Voltage controls
   - 6.5. System protection
7. Permits
   - 7.1. Local, state, federal
   - 7.2. Public involvement at early stage
   - 7.3. Public land, private land
     - 7.3.1. Land use permit
     - 7.3.2. Building permit
8. Sale of energy/power
   - 8.1. Energy/power purchase agreement
     - 8.1.1. Long-term contract with utility
     - 8.1.2. Green power market
     - 8.1.3. Market, avoided cost
     - 8.1.4. Renewable energy credits
     - 8.1.5. Future income, emission trading
   - 8.2. Kilowatt hour: Real or nominal levelized
   - 8.3. Capacity: Kilowatts
   - 8.4. Term
   - 8.5. Credit-worthy buyer
   - 8.6. Facility sales agreement
   - 8.7. Turnkey price, complete project
9. Financing
   - 9.1. Source of equity; rate of return, 15–18%
   - 9.2. Source of debt

9.3. Market rates
9.4. Term of debt
9.5. Assignable documents
9.6. Third-party due diligence
10. Turbine purchase
10.1. Power curve (output projection)
10.2. Turbine cost
10.3. Turnkey construction cost
10.4. Warranties, equipment and maintenance
10.5. Construction financing
10.6. Past history of manufacturer
10.7. Availability of turbines, date
11. Construction (turnkey)
11.1. Roads
11.2. Water and gravel
11.3. Turbine foundations (excavation, concrete)
11.4. Interconnection to utility (substations, transformers, wire)
11.5. Turbine assembly and erection (cranes)
11.6. Commissioning
11.7. Environmental restoration
11.7.1. Reduce road width?
11.7.2. Grass
11.7.3. Control of noxious weeds
11.7.4. Assembly area
12. Maintenance
12.1. Fixed cost per turbine per year
12.2. Availability warranties
12.3. Penalties for nonperformance
12.4. Types of costs
12.5. Labor
12.6. Management
12.7. Insurance, taxes
12.8. Maintenance equipment: cranes, vehicles, other
12.9. Parts on hand
12.10. Nonrecurring costs, major repairs
12.11. Roads, maintenance and access for landowner

The following example shows the main points of a contract signed by the Permanent University Fund, State of Texas, for a Woodward Mountain wind farm (32 MW) near McCamey (year 2000).

Area: 602 ha (1,487 acres); period, 20 years, with option to terminate early
Installation bonus: $2,000/MW + security deposit
Royalty: 4% years 1–10, 6% years 11–20, minimum annual royalty projected income stream
Turbine: 48, Vesta V47, 660 kW
RECs: Royalty paid if any value realized
Removal bond: Mutual agreement
Hunting: Company indemnified
University audits, independent outside auditor
Meter calibration required every 3 years
Curtailment shared by all landowners

TABLE 12.2
Representative Lease for Wind Farm

Resource	1–3 year
Flat fee	$10,000
$/acre/year	$1–4
Contract	30 year
Option	2 (10 year)
Construction, road, etc.	$3–4/month
Flat fee	$4,000/MW
Income/year	4%
Royalty Per turbine (minimum)	$4,000/MW
Escalation	0.5% every 5 years

For wind farms, the landowner may receive one or more offers, and the leases (Table 12.2) will differ by region, wind resource, and access to transmission. Some landowners are forming associations for dealing with wind farm developers. In the United States, wind turbines can be installed on land currently under the Conservation Reserve Program (CRP); however, there may be a penalty or reimbursement, which is decided by the CRP district.

Other considerations for the landowner are: Who certifies the energy meter? And when? If there is future revenue from pollution credits, the landowner should share in that return. In countries where the national or state governments control the land, the question concerns present occupants, who and when receives payment (once or annual), and how much is paid for land removed from previous use.

The construction phase of a wind farm project will take from 6 months to a year, while the total development time from selection of land to commission may take up to 6 years (Table 12.3). Wind farms can be installed much faster than transmission lines can be built. Besides the production tax credits, a limiting factor that began in 2008 was that the demand for wind turbines was larger than production, which means lead times for delivery are 2 to 3 years after purchase orders.

12.7.1 Costs

The installed costs have increased from around $1.2 million/MW in 2003 to $1.6–2 million in 2008 (both in $ 2008), because of the increase in the price of steel, copper, and cement. Also, the price

TABLE 12.3
Representative Wind Farm Project Timeline

Site Evaluation	Permitting and Negotiation	Construction, Commission
Identify site, conduct preliminary evaluation, secure land options 5–8 months	Permits, land use, transmission Negotiate power purchase agreement, interconnect 12–36 months	Construction 4–12 months
Install anemometers, collect and analyze data 12–24+ months	Turbine purchase agreement 12–36 months	Commission 1–2 months
←	Developer (36–72 months)	→
	←	Turbine supplier (24–36 months)

TABLE 12.4
Percent Component Costs for Wind Farm Installation

	%
Turbine	74–82
Foundation	1–6
Electric	1–9
Connection to the grid	2–9
Finance	1–5
Land	1–3
Roads	1–5
Consultants	1–3

is higher because the world demand for wind turbines is higher than production. A comparison of the estimated components of the cost of energy shows, as expected, that capital cost is the major component [15], and the primary installed cost is for the wind turbine (Table 12.4). The installed cost for offshore wind farms is around 1.5 times that for wind farms on land.

12.7.2 Benefits

Wind farms represent rural economic development with the primary benefit of long-term stable income (no fluctuations compared to commodity prices) to the landowner. Representative numbers are for a wind farm (30 MW or greater) using capacity factors of 30% in wind class 3 and 35% in wind class 4. A 50 MW wind farm would require 1,200 ha (1 ha = 2.5 acres), which can include ten to thirty landowners. Around 1–3% of the land is removed from production, primarily for roads. The return on land removed from previous use is around $10,000–16,000/ha/year, a much greater return per hectare than farming or ranching. In contrast to oil and gas leases, the return to the landowner is less from wind farms; however, there is the big advantage of a nondepletable resource.

The rural economic development also includes construction and then operation. During construction there will be 100–200 jobs for 4–8 months, around 1 man-year per MW. The administration and operation and maintenance of wind farms results in ten to fourteen full- time jobs per 100 MW. This shows why state legislatures and local entities are now promoting wind power, and also promoting the manufacturing of turbines and components in their state.

The Colorado Green Wind Power Project near Lamar, Colorado, is an example. Construction started in the summer of 2003. The 162 MW project consists of 108 GE wind turbines (1.5 MW) on a lease of 4,450 ha from fourteen landowners. The footprint from the wind farm is about 2% of the land. During construction there were 200 to 300 jobs, and after completion, there were around 15 local jobs. The wind farm pays around $2 million per year in property taxes. After construction, the project was purchased for $212 million by Shell Wind and PPM Energy from GE Wind.

12.7.3 Sale of Electricity

The crunch number for a project is the sale price of electricity generated by the wind farm. For some older contracts for wind farms in Texas, the sale price was below $0.025/kWh for a 15-year contract. The only way this could happen was with the production tax credit, accelerated depreciation, tax abatements, and renewable energy credits (RECs). For wind farms being installed today in the United States, the production tax credit is still the main driver. Sale contracts are higher, and some wind farms are selling electricity in the wholesale or merchant market. One selling price is the avoided cost, which is mandatory, and the minimum value that should be paid to the wind farm is the fuel adjustment cost of the utility.

The COE is estimated for a 50 MW wind farm in the Panhandle of Texas, class 4 winds. The wind turbines are rated at 1 MW and are on 70 m towers. The installed cost ($ 2007) is around $1,600/kW, and from Example 12.6, the COE is $77/MWh. So with a production tax credit of $20/MWh, the wind farm developer would need to obtain around $55/MWh. Other factors, such as accelerated depreciation, would assist in the return.

The value to the landowner can be estimated as

$$AEP = 50 * 3 * 106 \text{ kWh/year} = 1.5 * 108 \text{ kWh/year}$$

The $0.55/MWh (landowners will not receive any of the PTC) generates $8 million/year at 4% royalty = $320,000/year.

At $4,000/MW, the minimum would be $200,000/year.

At 0.5 ha per turbine taken out of production, 20 ha are lost. The value at 4% royalty = $16,000/ha/year. This is much more than a farmer or rancher can make from crops and livestock.

The wind farm will also pay property taxes; however, in many cases wind farms try to obtain tax abatements for some time period for the economic development. Instead, the wind farm will pay in lieu of taxes, primarily for schools.

The megawatt hours generated, income, and the rate paid to the wind farm by yearly quarters can be obtained from the Federal Energy Regulatory Commission (http://eqrdds.ferc.gov/eqr2/frame-summary-report.asp). The capacity factor can be calculated from the megawatt-hours generated and the installed capacity of the wind farm. Also, the type of sale can be obtained from the rate: power purchase agreement at fixed rate, power purchase agreement with peak and off-peak values, or if it is market, it gives the high and low value plus the average. As an example, for 2008 Q1, the Wildorado Wind Ranch received $5.4 million for 178,000 MWh from a power purchase agreement of $30.77/MWh. Since the wind farm has an installed capacity of 161 MW, the capacity factor for that quarter was 49.6%.

12.8 HYBRID SYSTEMS

When wind is added to an existing diesel generation plant, the cost of the turbine and controls is compared to the dollars saved on diesel fuel. In 2004 for villages (under 1,000 people) in Alska, Village Electric Cooperative powered by diesel gensets, the average price was $0.38/kWh, broken down as follows:

	2004 Percent	2008 Percent
Fuel	46	77
Operation and maintenance	21	9
Renewal and replacement	19	8
General and administration	14	6

Since then, the cost of diesel has increased significantly and the percent cost of fuel and electricity ($0.55/kWh) has increased accordingly. This is the reason for the renewed interest in wind turbines. For villages in Nunavik, Canada, served by Hydro Quebec, diesel fuel represented 54% of the operation cost and, as above, that percent will increase.

FIGURE 12.3 Hybrid (wind/PV/diesel) renewable village power system for Subashi, Xinjiang Province, China. (Photo by Charlie Dou. With permission.)

At Ascension Island, the simple payback was estimated to be 7 years for the addition of two 900 kW wind turbines in a high-penetration system. This saves an additional 2,400,000 L of diesel per year, and for diesel at $1.50/L that would be $3,600,000/year, and so the simple payback would be around 3 years. Most wind–diesel systems will not be this dramatic. High-penetration systems will also save on diesel maintenance, since the diesel gensets will not operate as many hours.

The three 100 kW wind turbines produce around 675,000 kWh/year as part of a wind–diesel plant at Toksook Bay, Alaska. The wind turbines displace 196,000 L of diesel per year, and if the cost of diesel at bulk price is $1.50/L, or even more, that produces a savings of $300,000 per year. If the installed cost for the wind turbines was around $1,500,000, then the simple payback would be 5 years. In May 2008, bid price for bulk diesel in remote Alaska was as high as $1.90/L.

At St. Paul Island, Alaska, the installed cost was $905,000 ($ 1999) for a wind–diesel system [16] that provided power to an industrial complex (no grid). The high-penetration, no–storage system consisted of one wind turbine, 225 kW, and two 150 kW diesel generators. The cost of energy from the system was $0.15/kWh, compared to diesel grid costs of $0.43/kWh ($ 2004). Since then, two more wind turbines have been added to support economic development and to generate enough power for residential consumption.

Costs for renewable village power systems vary widely, as most systems are components from different suppliers and manufacturers, and of course are located in remote locations. The best example is China's SDDX project (2002–2005), which consisted of 721 PV, wind, and PV/wind renewable village power systems (15,540 kW), 292 small hydro stations (113,765 kW), and 15,458 small single-household units (1,103 kW) with an installed capacity of 130,408 kW (see Table 10.7). The total investment was $4.7 * 10^9$ Yuan (~$570 million), or an average of $4,370/kW [17, chap. 6].

The cost was $178,000 for one village hybrid system (Figure 12.3) in a remote region of China ($ 2003). This included everything from power generation to the mini grid transmission lines. The configuration is two 10 kW wind turbines, 4 kW PV, 30 kVA diesel, 1,000 Ah battery bank, and a 38 kVA DC–AC inverter. At 54 kW the installed cost was $3,300/kW, which is very reasonable for a remote location. The renewable part of the system produces around 150 kWh per day. The unknowns in calculating the cost of energy are percent of the energy supplied by the diesel generator, cost of diesel fuel, levelized replacement costs, and operation and maintenance. A known major cost is that the battery bank will be replaced every 5 to 7 years.

Small hybrid systems are available, which usually can be set up as modular systems.

Company	Size kW	Wind kW	PV kW	Battery kWh	Inverter kW	Energy kWh/year	$
Bergey	10.1	7.5	2.6	84	6	12,000	57,000
Bergey	1.2	1.0	0.18	10.6	1.5	1,200	7,800
Southwest	1.3	0.40	0.88			750	

Most manufacturers do not supply prices on their websites. Notice that shipping and installation to remote locations will increase the cost, sometimes to double the cost of the energy components. From the initial cost and energy production the cost of energy can be estimated.

For village power, which source do you choose: wind, photovoltaic, or hybrid wind/PV? For the hybrid system, a life cycle cost analysis would determine the ratio of wind to PV. The advantages of PV are no mechanical moving parts and everything is at ground level. For comparison, suppose the local resources for both wind and solar are good, and a 20 kW system is needed for village power. The capacity factor for wind is 25%, and for solar it is 4 h/day at peak power, 80% sunshine. The estimated yearly production for wind is 43,000 kWh and for PV is 6,000 kWh. Also, installed cost for wind is cheaper than installed cost for PV, so the reasons for choosing wind power are obvious. That is also the reason that hybrid systems have more wind than PV power, five or more times greater.

12.8 SUMMARY

Wind farms are the cheapest renewable energy source for generating electricity, as the cost of energy (COE) from wind turbines has decreased from over $0.50/kWh in the 1970s to 0.06/kWh in 2003 (Figure 12.4). The numbers in Figure 12.2 represent cost of energy for a class 6 wind resource, and then starting in 1995, the numbers were shifted to represent class 5 and class 4 winds; therefore, the range is at least 0.02/kWh [18]. Notice that the COE projections for 2005 and later are already wrong, primarily because of the increased cost of materials and oil. Since 2003 the COE for wind

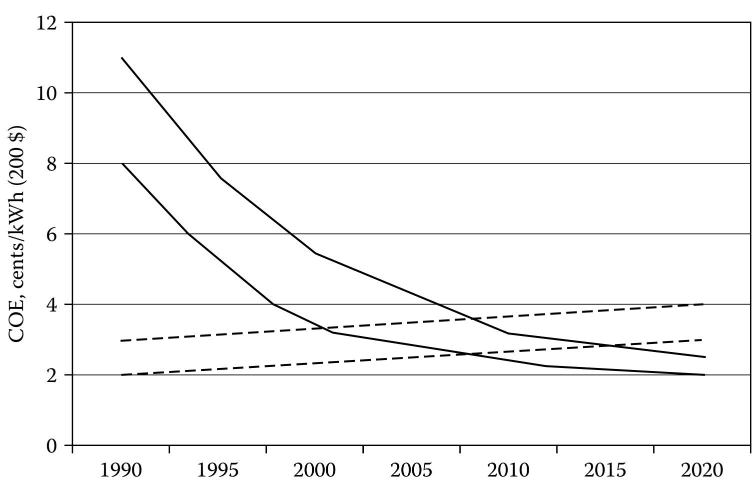

FIGURE 12.4 Cost of electricity from wind turbines and projected future costs. Solid lines for high and medium wind regimes; dashed lines, bulk power generation. Values from NREL graph.

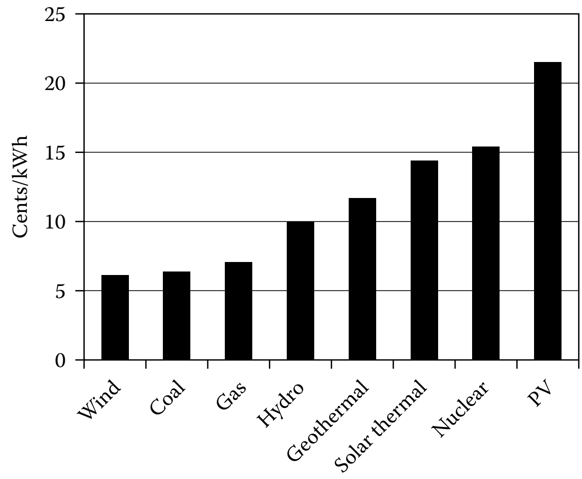

FIGURE 12.5 Estimated cost of energy for new power plants for generation of electricity.

farms has risen to \$0.07–0.09/kWh in 2008. New power generation from other energy sources will have similar cost increases for the same reasons.

Wind is also cheaper than other renewable sources of energy for producing electricity (Figure 12.5) and is competitive with new fossil fuel plants. Wind is even cheaper than combined-cycle gas turbines with natural gas at \$6/mcf. The wind farm business is much like the oil and gas business, except it is much easier to prospect for wind energy and the resource is nondepletable. As externalities are added to fossil fuel costs, wind energy becomes the cheapest energy for generation of electricity. Of course, wind cannot provide all the electricity because of the variability of the resource. If cheap storage becomes available, that changes the market for all the different types of new power plants.

From economics, mandates (legislation or regulation), or on a voluntary basis, there will be more use of renewable energy. Traditional energy sources have an advantage in that fuel costs are not taxed, while for renewable energy the fuel costs are free. The problem is the high initial costs for renewable energy, and most people would rather pay as they go for the fuel.

In 2008, small wind turbines, 10 kW and smaller, in general, are not cost-competitive with electricity from the grid. However, if life cycle costs are used or if rebates are available, then they are competitive in many situations.

Green pricing is now available from many utilities. The premium was around \$0.03/kWh for a block of 100 kWh/month; however, rate premiums continue to drop. In the United States, 2007 utility green power sales exceeded $4.5 * 10^9$ kWh, about a 20% increase from the previous year. Approximately 600,000 customers are participating in utility programs for green power.

Another major driving force for renewable energy is economic development and jobs at the local or state level. That is because renewable energy is local: it does not have to be shipped from another state or country.

The capacity of existing transmission lines and the curtailment of wind farms are major problems. The other major problem is that the wind resource is generally quite distance from major loads and new transmission lines will have to be built. The questions with deregulation are: Who will finance the construction and who will overcome the right-of-way problems?

The values of externalities range from zero (past and present value assigned by many utilities) to as high as \$0.10/kWh for steam plants fired with dirty coal. Again, values are being assigned by legislation and regulation (public utility commissions). As always, there is and will be litigation by both sides on external costs and who should pay for them.

12.9 FUTURE

As stated earlier, predictions about the future are risky; however, here they are:

1. At some point in time there will be a distributed wind market, very similar to the farm implement business today. A farmer, rancher, or agribusiness owner will go to the bank and obtain a loan for a wind turbine (size range from 25 to 1,000 kW). He will expect a payback of 5–7 years, and it will make money for him for the next 15 years. The nice thing about money from wind-generated energy, value of energy displaced (retail rates) and the avoided cost for electricity, is that it will not fluctuate like other agriculture commodities.
2. Major transmission lines will be built from the windy plains areas in the United States to load centers. Within 10 years, wind power will compete with fuel adjustment cost without production tax credits, primarily due to value received for the reduction of carbon dioxide emissions.
3. There will be trading in carbon dioxide in the United States, much as there is now trading in NOX and SOX. At that point in time, wind energy becomes the cheapest source of electricity. Why is Shell Oil now buying wind farms? In my opinion, it is the same as European countries buying forests in South America to reduce carbon dioxide emissions. A wind farm, La Venta II (83 MW), in Oaxaca, Mexico, displaces 205,380 tons/year of carbon dioxide, and the CO_2 credit for the first 7 years goes to the Spanish Carbon Fund, which helped finance the project. The value of wind energy would increase by $0.0.03–04/kWh if the avoided CO_2 is worth $30/ton.
4. Cooperative wind plants, from one to ten units, will become common. Because of the economies of scale, groups of farmers will form cooperatives to buy larger-sized wind turbines.

As stated in Chapter 2, the world faces a tremendous energy problem, and a number of people have sounded the warning and suggested solutions [19, 20]. The first priority is conservation and energy efficiency, and the second is the increased use of renewable energy. Wind has now become part of national energy policies, which is reflected in the large growth rate in wind capacity across the world.

LINKS

European Wind Energy Association, www.ewea.org/index.php?id=201. Economics of wind energy.
National Renewable Energy Lab, www.nrel.gov/analysis. Energy analysis.
National Renewable Energy Lab, www.nrel.gov/wind/coe.html. Baseline cost of energy.
NREL Photographic Information eXchange, also known as PIX, www.nrel.gov/data/pix/. Lots of great photos on the Internet of wind turbines and wind projects: small systems, grid connect, village power, hybrid systems, and wind farms.
Power Technologies Energy Data Book, 4th ed., www.nrel.gov/analysis/power_databook.
Subsidies, www.awea.org/pubs/factsheets/Subsidy.pdf
U.S. DOE, Energy Efficiency and Renewable Energy, planning, budgeting, and analysis:
www1.eere.energy.gov/ba/pba/index.html.
www1.eere.energy.gov/windandhydro/wind_budget.html
www.cfo.doe.gov/budget/08budget/Content/Highlights/Highlights.pdf
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PROBLEMS

1. What are the two most important factors in the cost of energy? (The factors that influence COE the most)
2. Calculate the simple payback for a Bergey 1 kW wind turbine. Go to www.bergey.com to get price and place it on a 20 m or 60 ft tower. It produces 2,000 kWh/year. Assume a value for O&M and FCR = 0.
3. Calculate the cost of energy (use Equation 12.3) for a 400 W (Air X) wind turbine (Southwest Windpower). Installed costs are $1,500, which includes 10 m tower and battery. Annual energy production is 400 kWh/year. Assume FCR and AOM = 0.
4. Calculate the cost of energy (use Equation 12.3) for a Bergey 10 kW wind turbine on a 30 m tower for a good wind regime. You can use a simple method for estimating the annual kilowatt-hours.
5. Calculate the cost of energy (use Equation 12.4) for a 50 kW wind turbine, which produces 120,000 kWh/year. The installed cost is $150,000, fixed charge rate of 10%, O&M is 1% of installed cost, and levelized replacement costs are $4,000/year.
6. Estimate the years to payback using Equation 12.7. IC = $150,000, r = 8%, AKWH = 120,000 at $0.09/kWh. Assume a fuel escalation rate of 4%. This problem has to be done numerically, assume an L, calculate, and then modify L in terms of your answer and do calculation again.
7. Explain life cycle costs for a renewable energy system.
8. In 2008, the COE for wind was around $60–80/MWh. What is the estimated COE for electricity generation (large plants) for photovoltaic, solar thermal, biomass, and geothermal?

9. The estimated cost of energy from a wind farm is around \$0.08/kWh. Make a comparison to proposed new nuclear power plants. What is their COE (retail rate) for latest nuclear power plants installed in the United States? (Do not calculate; find an estimate from any source.)
10. What are today's values for fuel inflation, discount rate, interest rate? What is your estimate for the year 2015?
11. A 100 MW wind farm (100 wind turbines, 1 MW) is installed in the class 4 wind regime. The production is around 3,000 MWH/turbine/year. The utility company is paying an estimated \$0.04/kWh for the electricity produced. Estimate the yearly income from the wind farm. If the landowners get 4% royalty, how much money do they receive per year?
12. For the previous problem, installed costs are \$1,600/kW, FCR = 9%, capacity factor = 35%, AOM = 0.008/kWh. Calculate the COE using Equation 12.4. You will need to estimate the levelized replacement costs or calculate LRC using Equations 12.5–12.7. Compare your answer to the \$0.05/kWh, which is the estimated price the wind farm is receiving. How can the wind farm make money?
13. A number of wind farms are again being installed in the United States. In Texas the wind farm boom has seen over 7,500 MW installed from 2000 to 2008. Why? Explain in terms of economics.
14. What is the price of oil, \$/bbl, today? Estimate the price for oil, \$/bbl, for the years 2010, 2020, and 2030. Compare to the U.S. Energy Information Administration projections for the same years. Place results in a table.
15. Estimate the price for oil, \$/bbl, if the costs for the U.S. military to keep the oil flowing from the Middle East are added.
16. Why were wind turbines installed primarily in California during 1981–1985? Discuss in terms of economics.
17. How much should the U.S. federal government fund for conservation and efficiency, renewable energy, and wind energy? Compare your answer to the FY 08 budget for the same activities. What was the FY 08 budget for fossil fuels and nuclear energy (nuclear fusion counts)? See "Links" section.
18. At what dollar level should your national government fund renewable energy? Wind? Fossil fuel? Nuclear? Compare your numbers to the national budget for this fiscal year, or the latest year for which information is available.
19. Estimate the cost of energy for a Bergey windpower, 10.1 kW, hybrid (PV/wind) system. You will have to estimate FCR and O&M.
20. Estimate the cost of energy for a Southwest Windpower, 1.3 kW, hybrid (PV/wind) system. You will have to estimate FCR and O&M.
21. Estimate the cost of energy just for the three, 100 kW, wind turbines at Toksook Bay, Alaska. You will have to estimate FCR, O&M, and LRC.
22. A village power system in China consists of 10 kW wind plus battery bank and inverter. IC = \$4,500/kW, energy production = 50 kWh/day, FCR = 0.03, AOM = \$0.01/kWh. Calculate the cost of energy.
23. A renewable village power system in China consists of 20 kW of wind and 10 kW of PV. Use an average cost of \$4,300/kW, annual energy production = 65,000 kWh, FCR = 0.03, AOM = \$0.01/kWh. Calculate the cost of energy. How does that compare to the present rate you are paying for electricity?

    For the following problems use data reported to the U.S. Federal Energy Regulatory Commission, http://eqrdds.ferc.gov/eqr2/frame-summary-report.asp. Pick any wind farm; however, if uncertain, pick Llano Estacado Wind (White Deer, installed capacity = 80 MW).
24. What is the rate of the power purchase agreement?

25. Installed cost was \$1 million/MW, \$80 million. For 2007, what was the income generated? Assume that is an average year. What is the time of simple payback?
26. For problem 25, take into account the additional \$20/MWh return for the production tax credit. Now what is the payback time?
27. Calculate the capacity factor for the wind farm for 2007.
28. Find another wind farm that is selling electricity at the market rate. For the latest quarter, what are the high, low, and average rates (\$/MWh)?

Wind Solutions

CHAPTER 2

Questions/Activities

1.

Date	U.S. Population	World Population
1/27/2008	303,318,773	6,646,783,764

Answers from previous years are given to show how population is increasing:

9/26/2005	297,269,083	6,468,918,642
9/13/2003	292,062,965	6,317,360,874
2/17/2002	286,470,333	6,206,243,040

2. a. Drive the speed limit. In 2008, with the high cost of gasoline, drive 10 km/h (5 miles/h) below speed limit on highways.
   b. Turn off lights in the house when not in use or when we leave the home.
   c. For replacement bulbs, buy compact fluorescent lights (or LEDs).
3. For 2008:
   Oil: 86 million bbl/day = $31.4 * 10^9$ bbl/year
   Coal: 6,382,000,000 metric tons
4. Energy and temperature are different. Proton has very little energy while cup of coffee will result in injury.
   Proton: For physics majors, $E = (3/2)\ kT$, where k = Boltzman's constant and T = Kelvin:

$$E = 1.5 * 1.4 * 10^{-23}\ (\text{J/K}) * 1 * 10^6\text{K} = 2 * 10^{-17}\ \text{J}$$

Or assume it is traveling fast, speed of light, $3 * 10^8$ m/s:

$$KE = 0.5\ mv^2 = 0.5 * 1.7 * 10^{-27} * 9 * 10^{16} = 7 * 10^{-11}\ \text{J}$$

Cup of coffee: Volume = 0.25 L = 250 cm^3 of water at T = 80°C = 353K
  Energy of one atom = 3/2 kT = $1.5 * 1.4 * 10^{-23}$ (J/K) $*$ 353K = $7.4 * 10^{-21}$ J
  Avagardo's number = $6 * 10^{23}$, number of atoms in 18 g of water
So for 250 g of water, energy = (250/18) $* 7.4 * 10^{-21}$ J $* 6 * 10^{23} = 6 * 10^4$ J.
No comparison, you *do not* want to put your finger in the cup of hot coffee.
Another way is to calculate heat stored in a cup of coffee: Assumption from 25 to 80°C, mass (m) = 250 g and c = heat capacity of water 1 cal/(g°C).

$$Q = \text{mc}[T(\text{final}) - T(\text{initial})] = 250\ \text{g} * 1\ \text{cal/(g°C)} * (80 - 25)°\text{C} = 1.4 * 10^4\ \text{cal}$$

Conversion 1 cal = 4.18 J

$$Q = 6 * 10^4 \text{ J}$$

5. The incandescent lightbulb is too hot to touch, while the fluorescent bulb is cooler. Light output is around the same.

Problems

1. $m = 0.5$ kg, $v = 10$ m/s
   $KE = 0.5 \text{ mv}^2 = 0.5 * 0.5 * 10^2 = 25$ J
2. Ten percent growth rate is a doubling time of 7 years. Five doubling times = 35 years. Can do by doubling times, starting with 100,000:

200,000	400,000	800,000	1,600,000	3,200,000

   Or five doubling times = $2^5 = 32$. So number is $32 * 100{,}000 = 3{,}200{,}000$ people.
3. $k = 0.5\%$, $DT = 69/0.5 = 138$ years.
4. You have to assume or obtain a growth rate for population. I chose 1%, which gives a doubling time of 69 years. Round to 70 years.

2010	$7 * 10^9$
2080	$14 * 10^9$
2150	$28 * 10^9$

5. Year 2008 there are 6.7 billion people in the world. You have to assume or obtain a growth rate for population. Growth rate is 1.2%.
   To calculate directly, use Equation 2.7, $k = 0.012$, $t = 92$, $kt = 1.104$:

$$r = 6.7 * 10^9 * e^{1.104} = 6.7 * 10^9 * 3.0 = 20 \text{ billion people}$$

   If you chose a smaller growth rate, 1%, the results are much the same.
   Estimate using doubling time: $DT = 69/1.2 = 57$ years.
   At 2065, $13.4 * 10^9$, and at 2122, $26 * 10^9$ people, so at 2100, estimate 19 to $20 * 10^9$ people.
6. Use Equation 2.7 and solve for time: $24 * 10^9 = 6.7 * 10^9 * e^{0.005t}$, then $t = 255$ years.
   Or use doubling times. $DT = 138$ years. So it would take 2 DTs to reach $24 * 10^9$ people, around 270 years.
7. Stabilization point = $11 * 10^9$, increase in population = $4.3 * 10^9$.
   4,300 million/20 million = 215 new cities the size of Mexico City.
   Can you imagine the infrastructure problems for building that many new cities?
8. 7% growth rate, $k = 0.07$, $DT = 10$ years.
   Electric generating capacity in United States = 1,100,000 MW.
   50 years is 5 DTs.

1,100,000	2,200,000	4,400,000	8,800,000	17,600,000	35,200,000 MW

   Amount of new capacity = 35,200,000 – 1,100,000 = 34,000,000 MW.
   Number of 1,000 MW plants = 34,000.

9. Ten percent growth is doubling time of 7 years. For 30 years that would be 4 DTs.
 2008 world electrical generating capacity is around 4,000 GW.
 So by 4 DTs, need 64,000 GW with 60,000 GW of new capacity.
 Number of 1,000 MW plants = 60,000.
 At \$5,000/kW each plant would cost $\$5 * 10^9$ and 60,000 plants would cost $\$300 * 10^{12}$.
10. Electricity demand China = 500,000 MW (2006). In 30 years need 250,000 MW of new capacity; 250,000 MW/300 MW = 830 plants.

$$830 \text{ plants} * 300{,}000 \text{ kW/plant} * \$2{,}000/\text{kW} = \$500 * 10^9$$

11. We need 250,000 MW of new capacity, which we are going to fuel by coal.
 90% availability means $0.90 * 2.5 * 10^8$ kW $* 8{,}760$ h/year $= 1.97 * 10^{12}$ kWh/year.
 Efficiency of the coal plant is 40%, so amount of coal energy needed is $2 * 10^{12}$ kWh/year divided by $0.40 = 5 * 10^{12}$ kWh/year.
 1 metric ton of coal has $2.2 * 10^{10}$ J $= 6 * 10^3$ kWh.
 Tons of coal/year $= 5 * 10^{12}$ kWh/year divided by $6 * 0^3$ kWh $= 8.2 * 10^8 =$ 820,000,000 metric tons of coal per year just to fuel China power plants.
12. $T_H = 700°\text{C} = 973\text{K}$, $T_C = 320°\text{C} = 593\text{K}$

$$\frac{T_H - T_C}{T_H} = \frac{973 - 593}{973} = 0.39 = 39\%$$

13. $T_H = 30°\text{C} = 303\text{K}$, $T_C = 10° = 283\text{K}$

$$\frac{T_H - T_C}{T_H} = \frac{303 - 283}{303} = 0.07 = 7\%$$

14. $T_H = 30°\text{C} = 383\text{K}$, $T_C = 71°\text{C} = 344\text{K}$

$$\frac{T_H - T_C}{T_H} = \frac{383 - 283}{383} = 0.1 = 10\%$$

15. Coal reserves in the United States $= 2.5 * 10^{11}$ metric tons.
 Coal production (2006) $= 1.05 * 10^9$ tons/year.
 Number of years $= 2.5 * 10^{11}$ tons$/1.05 * 10^9$ tons/year = 238 years.
 That is without any increase in production.
16. $S = 2.5 * 10^{11}$ tons, $k = 0.10$, $r_0 = 1.05 * 10^9$ tons

$$T = \frac{1}{k} = \ln\left(k\frac{S}{r_0} + 1\right) = \frac{1}{0.1}\ln\left(0.1\frac{2.5 * 10^{11}}{1.05 * 10^9} + 1\right)$$

$$T = 10 \ln(24.8) = 32 \text{ years}$$

17. Coal reserves in China $= 1.15 * 10^{11}$ metric tons. Coal production $= 2.38 * 10^9$ tons.

$$T = \frac{1}{k} = \ln\left(k\frac{S}{r_0} + 1\right) = \frac{1}{0.15}\ln\left(0.15\frac{1.15 * 10^{11}}{2.38 * 10^9} + 1\right)$$

$$T = 32 \text{ years}$$

18. Number of lights in my house = 40, average 100 W, on 4 h/day.
    Energy = 4 kW * 4 h/day = 16 kWh/day = 500 kWh/month = 6,000 kWh/year.
    That is a high estimate, because some of the lamps are smaller and some are fluorescent.
19. Efficiency of incandescent bulbs is 5%. Efficiency of fluorescent bulbs is around four times higher. Produce same amount of light for fewer watts. Therefore, I would use 1,200 kWh/year.
20. Maximum power in my house.
    If you use horsepower of a motor, then 1 hp = 0.75 kW.
    If you use volts (120 or 240) and current (amps), then $P = VI$ (volts * amps) = watts.

Use	kW
Lights	4.0
Hair dryers	3.2
Air conditioner	2.0
Stove, electric	11.7
Clothes dryer, electric	5.6
Toaster	1.0
Irons	1.6
Power tools, drills, etc.	2.0
Microwave	1.0
Other appliances (motors)	1.0
TV, computer, VCR, etc.	2.0
Fans	0.3
Disposal	0.3
Dishwasher	0.8
Refrigerator	0.8
Freezer	0.6
Garage door opener	0.4
Estimated total power	40

21. Oil consumption (2008) = $86 * 10^6$ bbl/day * 365 day/year = $3.1 * 10^{10}$ bbl/year.

$$2 * 10^{12}/3.1 * 10^{10} = 65 \text{ years}$$

22. Oil consumption growth of 2.5%.
    Can calculate directly form Equation 2.9, $T_e = 1/k \ln(k * S/R_o + 1)$.

$$k = 0.025,\ S = 2 * 10^{12},\ R_o = 3.1 * 10^{10}$$
$$T_e = (1/0.025) * \ln(0.025 * (2 * 10^{12}/3.1 * 10^{10}) + 1) = 38 \text{ years}$$

    If no increase in consumption, it would only last $2 * 10^{12}/3.1 * 10^{10} = 64$ years.
    Could use spreadsheet and increase consumption each year by 2.5% and add to get cumulative numbers. When reach cumulative value of S, that is the number of years.
23. Coal consumption growth of 5%.
    Can calculate directly from Equation 2.9, $T_e = 1/k \ln(k * S/R_o + 1)$

$$k = 0.05,\ S = 2 * 10^{12},\ R_o = 3.03 * 10^{10}$$
$$T_e = (1/0.05) * \ln(0.05 * [2 * 10^{12}/3.03 * 10^{10}] + 1) = 29 \text{ years}$$

24. Population China (2007) = 1,300,000,000 people. Population growth rate = 0.6%.
$r = 1.3 * 10^9 * e^{(0.006)(30)} = 1.5 * 10^9$ people in China in 30 years.
In United States, 300 million people, so take the ratio of cars to people for United States (2/3) and apply to China. So for China, 1,500 million people * (2/3) = 1,000 million cars. Barrels of gasoline needed = (1,000/200) * 10 million bbl/day = 50 million bbl/day. Since only half of oil is converted to gasoline, China would use 100 million bbl of oil/day. How does that compare to world oil production today?
25. Presently in United States, there are 104 nuclear power plants (106 GW; production, 788 TWH/year).
Amount of uranium oxide needed per year = 788 TWh $* 3 * 10^4$ kg/TWh $= 2.4 * 10^7$ kg $= 2.4 * 10^4$ metric tons. From Table 2.4, resource is $4 * 10^5$ metric tons.
Resource will last $4 * 10^5/2.4 * 10^4 = 17$ years.
26. Can calculate from Equation 2.9, $T_e = 1/k \ln(k * S/R_o + 1)$.

$$k = 0.02,\ S = 4 * 10^5,\ S = 2.4 * 10^4$$
$$T_e = (1/0.02) * \ln(0.02 * [4 * 10^5/2.4 * 10^4] + 1) = 14 \text{ years}$$

27. World nuclear (365 GW, 2700 TWh/year).
Amount of uranium oxide needed per year = 2,700 TWh $* 3 * 10^4$ kg/TWh $= 8.1 * 10^7$ kg $= 8.1 * 10^4$ metric tons. From Table 2.4, resource is $5 * 10^6$ metric tons.
Resource will last $5 * 10^6/8.1 * 10^4 = 62$ years.
28. Can calculate from Equation 2.9, $T_e = 1/k \ln(k * S/R_o + 1)$.

$$k = 0.04,\ S = 5 * 10^6,\ S = 8.1 * 10^4$$
$$T_e = (1/0.04) * \ln(0.04 * [5 * 10^6/8.1 * 10^4] + 1) = 32 \text{ years}$$

CHAPTER 3

Important: In physics the answer cannot be more accurate than the data that the calculation is based on. This is called significant figures or significant digits. Therefore, for handheld calculations, calculators, computers, and spreadsheets do not provide all the available numbers in the answer. Round off all answers to the correct significant digits.

1. Power in the wind increases with the cube of the wind speed. Power across a rotor increases by the square of the radius. Notice in the table that the numbers are rounded off. Also note that for the power in the wind across that swept area, the wind turbine cannot capture all that power. The power becomes quite large at high wind speeds and you must have a way to dump or not capture all the power available. Notice that the left two columns are the same as Table 3.3.

	Diameter, *m*	5	10	50	100
	Area, m^2	20	79	1,963	7,854
Wind Speed, m/s	**P/A, kW/m²**		**Power, kW**		
5	0.1	1.3	5	123	491
15	1.7	34	133	3,312	13,254
25	7.8	156	617	15,334	61,359

2. $P/A = 1$ kW/m^2. From Table 3.3 it is between 10 and 15 m/s. Use air density = 1 kg/m^3. From Equation 3.1, $v^3 = 2{,}000$, or $v = 13$ m/s.
3. Use Equation 3.7, $H_0 = 10$ m; calculate for $H = 20$ m and $H = 50$ m. Exponential = 1/7 = 0.14. Factor for increase in wind speed is

$$\left(\frac{20}{10}\right)^{0.14} = 2^{0.14} = 1.10$$

$$\left(\frac{50}{10}\right)^{0.14} = 5^{0.14} = 1.25$$

4. Use Equation 3.7. Similar to problem 3.

$$\left(\frac{50}{10}\right)^{0.2} = 5^{0.2} = 1.38$$

$$\left(\frac{100}{10}\right)^{0.2} = 10^{0.2} = 1.59$$

5. Use Equation 3.7. Similar to problem 3.

$$\left(\frac{80}{50}\right)^{0.2} = 1.6^{0.2} = 1.10$$

$$\left(\frac{100}{50}\right)^{0.2} = 2^{0.2} = 1.15$$

6. Use Equation 3.8, $z_0 = 1$ m. Could have chosen z_0 from 0.5 to 1 m.

$$\frac{\ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H_0}{z_0}\right)} = \frac{\ln\left(\frac{100}{1}\right)}{\ln\left(\frac{10}{1}\right)} = \frac{\ln 100}{\ln 10} = \frac{4.6}{2.3} = 2$$

7. $\rho = 1.226 - (1.194 \times 10^{-4})\, z$, where $z = 3{,}000$ m
   $\rho = 1.226 - (1.194 \times 10^{-4})\, 3{,}000 = 1.226 - .3582 = 0.8678$ kg/m^3
   % decrease = 0.3582/1.226 = 29%
   Power/area will be 29% less due to change in density with elevation (due to pressure change).
8. Temp. summer = 100°F = 311K, temp. winter = –20°F = 244K
   % change = (311 – 244)/311 = 22%
   On a hot day in the summer the power/area will be 22% less than on a cold day in the winter due to difference in density (due to temperature change).
9. Use Equation 3.17 and spreadsheet.

Wind Speed m/s	Frequency %	Histogram *h*
0.5	1.22	107
1.5	3.58	314
2.5	5.68	498
3.5	7.39	647
4.5	8.61	755
5.5	9.31	816
6.5	9.5	832
7.5	9.23	809
8.5	8.6	753
9.5	7.7	675
10.5	6.66	583
11.5	5.57	488
12.5	4.51	395
13.5	3.54	310
14.5	2.7	236
15.5	1.99	175
16.5	1.43	126
17.5	1	88
18.5	0	60
19.5	0	39
20.5	0	25
21.5	0	16
22.5	0	10
23.5	0	6
24.5	0	3
25.5	0	2
26.5	0	1
27.5	0	1
28.5	0	0
29.5	0	0

10. Use Equation 3.18 and spreadsheet.

Wind Speed m/s	Frequency %	Histogram *h*
0.5	0.03	265
1.5	0.06	544
2.5	0.08	718
3.5	0.09	817
4.5	0.09	854
5.5	0.08	844
6.5	0.07	797
7.5	0.06	726
8.5	0.05	641
9.5	0.04	550
10.5	0.03	460
11.5	0.02	376
12.5	0.01	300
13.5	0.01	235

(*Continued*)

(*Continued*)

Wind Speed m/s	**Frequency %**	**Histogram *h***
14.5	0.01	181
15.5	0.01	136
16.5	0	101
17.5	0	73
18.5	0	52
19.5	0	37
20.5	0	25
21.5	0	17
22.5	0	12
23.5	0	8
24.5	0	5
25.5	0	3
26.5	0	2
27.5	0	1
28.5	0	1
29.5	0	0
30.5	0	0
31.5	0	0

11. Use Equation 3.18.

Wind Speed m/s	**Frequency %**	**Histogram *h***
0.5	0.001	13
1.5	0.013	115
2.5	0.035	311
3.5	0.067	578
4.5	0.099	870
5.5	0.128	1,122
6.5	0.145	1,268
7.5	0.144	1,267
8.5	0.128	1,118
9.5	0.099	868
10.5	0.067	590
11.5	0.04	348
12.5	0.02	177
13.5	0.01	77
14.5	0	26
15.5	0	9
16.5	0	2
17.5	0	0
18.5	0	0

12. Around 85% of the time the wind is 5 m/s or larger.
13. Around 15% of the time the wind is 12 m/s or larger.
14. $I = (v \text{ avg})/\text{STD} = 8/1.5 = 5.3$.
15. $I = (v \text{ avg})/\text{STD} = 40/8 = 5$.

The solutions to problems 16–19 are included in the following table. Air density was set to 1 kg/m^3.

Bin j	Speed m/s	No. Obs	Freq f_j	$f_j\ v_j$	$P/A\ f_j\ v_j$
1	1	20	0.026	0.026	0
2	3	30	0.038	0.115	1
3	5	50	0.064	0.321	4
4	7	100	0.128	0.897	22
5	9	180	0.231	2.077	84
6	11	150	0.192	2.115	128
7	13	120	0.154	2.000	169
8	15	80	0.103	1.538	173
9	17	40	0.051	0.872	126
10	19	10	0.013	0.244	44
	SUM	780	1.00	10.2	751

16. Frequencies are given for each bin.

17. For $j = 5$, $\dfrac{P}{A}_j = 0.5 f_j v_j^3 = 0.5\ 0.\ 231\ 9^3 = 84\ \text{W/m}^2$.

    For $j = 10$, $\dfrac{P}{A}_j = 0.5 f_j v_j^3 = 0.5\ 0.\ 013\ 19^3 = 44\ \text{W/m}^2$.
18. Average wind speed is the sum of frequency * speed for each bin, v average = 10.2 m/s.
19. Wind power potential is sum of 0.5 frequency * speed cubed for each bin, P/A = 751 W/m^2.
20. $P/A = 0.5 * 10.2^3 = 531$ W/m^2. Value is smaller than the answer to problem 19. This is why wind power potential is not calculated from average wind speed.
21. Use Equation 3.17 and bin width of 2 m/s. V average = 10.2 m/s.

j	m/s	f_j	$0.5 * f_j v_j^3$
1	1	0.030	0
2	3	0.084	1
3	5	0.124	8
4	7	0.145	25
5	9	0.146	53
6	11	0.132	88
7	13	0.109	120
8	15	0.082	139
9	17	0.058	141
10	19	0.037	128
		0.95	703

If a bin width of 1 m/s is used, sum of frequencies would be closer to 1.

CHAPTER 4

1. Wind map value for Panhandle of Texas is class 4–5, 400–600 W/m^2 at 50 m.
2. Average wind speed is 8–9 m/s at 50 m height.
3. Estimate is 25–35%.

4. North areas off of United Kingdom, Ireland, and Denmark.
5. Southern Nicaragua.
6. Offshore of Corpus Christi.
7. Class 6.
8. Tubular tower, 13 cm in diameter. Anemometer should be placed six diameters away, 80 or more cm.
9. Lattice tower is 1.5 m on a side. Anemometer should be placed two to three diameters away, 3 to 4.5 m.
10. Tower is 4 m on a side. Anemometer should be placed two diameters away, 8 m. Practical length is 1–2 m. An 8 m away mounting will be difficult and expensive, so people do not always adhere to the guidelines.
11. Propeller anemometers have to be perpendicular to the wind. Because of the turbulence in the wind farm and being close to the wind turbines, the propeller anemometers overestimated the power coefficient (recorded lower wind speeds than actual values), so they were replaced with cup anemometers.
12. Deciduous trees in our region (High Plains of United States) are bent toward the north and northeast due to spring and early summer winds from the south and southwest. Because we know the answer, they indicate winds of around 6 m/s.
13. At the present time they are too expensive.
14. Measure wind speed and direction at three levels at six sites. Cost will run from $150,000 to $400,000.
    If you were taking data at one location (15 to 20 square mile area), your O&M costs are not as high. If you are taking data across a region or state, then the costs are much higher. If you could use some existing towers, that would reduce the costs. I went to the NRG website, www.nrgsystems.com, to get cost estimates. Also in the final analysis, I would round off values to the nearest $10 or even $100.
    If you go to 60 m towers or truss towers for hub heights (80 to 100 m), installed costs are quite a bit higher.
    50 m tower, NRG-NOW CELLogger = $14,450. 2 anemometers, 1 wind direction at each level; 10, 25, 50 m.
    For 2-year project estimate, $230,000 (2008 $).

Project Management	**Man-month**	**$/month**	**$**
Senior	4	7,000	28,000
Junior	6	5,000	30,000
Secretary/clerical	3	2,000	6,000
Subtotal			64,000
Equipment			
NRG-NOW replacement	6	14,450	86,700
Anemometers	24	285	6,840
Wind vane	8	205	1,640
Temperature	3	195	585
Data logger	1	1350	1,350
Mounting booms	24	200	4,800
Gin pole	1	700	700
GPS	1	200	200
Reader	1	60	60

(Continued)

Project Management	**Man-month**	**$/month**	**$**
PC base	1	800	800
PC data analysis	1	1500	1,500
Wire, $2.50/m	360	2.50	900
Shipping			1,500
Subtotal			107,575
Installation			
Erection, 5 man-days/site	36	140	5,040
100 miles to site, 4 × 4 pickup, $0.60/mile	1200	0.60	720
Operation and maintenance			
Scheduled, 1/year per site			
Personnel, man-days	15	140	2,100
Pickup, miles	2000	0.60	1,200
Unscheduled, 2/years per site			
Personnel, man-days	50	140	7,000
Pickup, miles	4800	0.60	2,880
Decommission			
Personnel, man-days	18	140	2,520
Pickup, miles	1200	0.60	720
Miscellaneous, storage, disks, etc.			3,000
Subtotal			25,180
Data Collection and Analysis			
5 man-days/month	120	140	3,000
DIRECT COST			199,755
Indirect cost 15%*direct costs			29,963
TOTAL			229,718

15. Amount of storage needed:
    a. 1 h avg. ∗ 24 h ∗ 365 days = 8,760 data points per channel ∗ 12 channels = 105,120 data points per year
    b. 1 min avg. ∗ 60 min. ∗ 24 h ∗ 365 days = 525,000 data points per channel

    12 channels = 6,307,200 data points per year
    1 min avg. would use sixty times more storage yearly. Of course, you know that, as there are 60 min in an hour.
    Data cards can store more data than previously, but you need to know how much data you can store before they have to be changed (see Section 4.1.4). The manufacturer will provide guidelines for averaging times and amount of data that can be stored on their data cards.
16. Meteorologists say that it takes 30 years to determine climate data. There are national (and some other) met stations with 30 years or more of data; however, that data is generally at 10 m height for airports. What the wind industry would like is baseline data at 40 to 50 m, and now with bigger turbines they would like some data at hub heights to 100 m. The problem is cost and time. It is difficult to obtain funding for a multiple-year program to obtain wind resource assessment for 40 to 60 m towers. Wind farms operate and accumulate data over years; however, there might be a problem of making private data available to the public.

My opinion: Would like 4 to 5 years of data on 50 to 60 m towers (wind speed and wind direction at 10, 30, and 50 or 60 m).

17. Fifty-meter pole tower with gin pole, \$12,500; labor, \$1,000; travel expenses, \$1,000. Estimated total is \$14,500.
18. Fifty meter trust tower, guyed (Rohn 45G), \$3,000; labor, \$4,000 (have to assemble tower sections); travel expenses, \$2,000 (need truck or assemble on site, which means more labor at the site). Use crane to raise tower, \$3,000. Estimated total is \$12,000.
19. One-hundred-meter trust tower, guyed (Rohn 55G), \$7,000; labor, \$10,000, travel expenses, \$5,000; crane, \$5,000, power (generator and gas), \$3,000. Estimated total is \$30,000.

CHAPTER 5

1. See Figure 1.7. Solidity is a ratio of area of blades to area of rotor.
   Notice that the solidity of the Savonius is 1 or greater. Assume 1.
   The giromill has a low solidity, around 0.2. Therefore, the difference in blade material is around 5/1.
   Another way, use rotor swept area, $10 * 10 = 100\ \text{m}^2$. Blade area of Savonius is $100\ \text{m}^2$ or greater. Giromill has three blades; assume blades are 10 m long, 0.5 m wide. Blade area = $3 * 10 * 0.5 = 15\ \text{m}^2$. Therefore, the ratio of Savonius to giromill is 100/15.
2. Assume capacity factor = 0.3. AKWH = 0.3 * 300 kW * 8,760 h/year = 788,000 kWh/year.
3. Assume capacity factor = 0.35. AMWH = 0.35 * 1.5 MW * 8,760 h/year = 4,600 MWh/year.
4. HAWT, $r = 50$ m. Area = $\pi r^2 = 3.14 * 2{,}500 = 7{,}850\ \text{m}^2$.
   Choose locations: (a) one near Amarillo, Texas, $P/A = 400\ \text{W/m}^2$; (b) one near Comodoro Rivadavia, Argentina, $P/A = 800\ \text{W/m}^2$.
   Use Equation 5.3; assume a capacity factor of 0.35 for Amarillo and a capacity factor of 0.40 for Comodoro Rivadavia.
   a. AKWH = CF * Ar * WM * 8.76 = 0.35 * 7850 * 400 * 8.76 = 9,627,000 kWh/year
   b. AKWH = CF * Ar * WM * 8.76 = 0.4 * 7850 * 800 * 8.76 = 22,000,000 kWh/year
5. Darrieus turbine, 34×42.5 m. Area = $0.6\ H * D = .6 * 34 * 42.5 = 867\ \text{m}^2$.
   Use capacity factor of 0.3 and wind map values for Denmark, $500\ \text{W/m}^2$, and mid-Germany, $300\ \text{W/m}^2$.

   AKWH = CF * Ar * WM * 8.76 = 0.3 * 867 * 500 * 8.76 = 1,139,000 kWh/year
   AKWH = CF * Ar * WM * 8.76 = 0.3 * 867 * 300 * 8.76 = 684,000 kWh/year

6. Giromill 10×12 m. Area = $H * D = 10 * 12 = 120\ \text{m}^2$.
   Use capacity factor of 0.25 and wind map values of 250 and $300\ \text{W/m}^2$. Small giromill will not be on very tall tower.
7. Estimate is around 3.3 GWh/year.
8. Use Figure 5.13, wind speed = 20 m/s.
   Use Equation 5.1, $P = T\omega$.
   a. At constant rpm (line A in figure), 160 rpm, torque estimated at 15,000 Nm.

   $$\omega = 2\pi * \text{rpm}/60 = 2 * 3.14 * 160/60 = 17\ \text{rad/s}$$
   $$P = T\omega = 12{,}000\ \text{Nm} * 17\ \text{rad/s} = 204{,}000\ \text{Nm/s} = 204{,}000\ \text{W} = 204\ \text{kW}$$

   b. At maximum power coefficient (line B in figure).

$$T = 11{,}000 \text{ Nm},\ \omega = 220 \text{ rpm} = 23 \text{ rad/s}$$
$$P = T\omega = 11{,}000 * 23 = 253{,}000 \text{ Nm/s} = 253 \text{ kW}$$

c. At constant torque (line C in figure).

$$T = 6{,}000 \text{ Nm},\ \omega = 310 \text{ rpm} = 32 \text{ rad/s}$$
$$P = T\omega = 6{,}000 * 32 \text{ Nm/s} = 192{,}000 \text{ Nm} = 192 \text{ kW}$$

This is not a viable operating point because of the high rpm. Also notice that the power is largest for answer b, line of maximum power coefficient.

9. Torque = 6,000 Nm, rpm = 160 = 17 rad/s. $P = T\omega = 6{,}000 * 17$ Nm/s = 102 kW.
10. Frequency = number in the bin divided by total number of hours.

m/s	Frequency
1	0.014
2	0.043
3	0.068
4	0.087
5	0.099
6	0.104
7	0.103
8	0.097
9	0.086
10	0.074
11	0.061
12	0.048
13	0.036
14	0.027
15	0.019
16	0.013
17	0.009
18	0.005
19	0.003
≥20	0.005
25	

11. Mean wind speed is 8.2 m/s. Rayleigh distribution is calculated from that mean wind speed, bin width of 1 m/s. Estimated annual energy production is calculated by multiplying power curve times number of hours (wind speed histogram). It is always better to have actual data for the wind speed histogram, rather than a calculated distribution. Anemometer height for power curve measurements and anemometer height for wind speed are not known, so assume that both are at hub height. Power curve values should be at the midpoint of the wind speed bin.

    From spreadsheet, energy = 3,400.000 kWh/year. Need to reduce value for availability, use 95 to 98%. At 95%, estimated energy is 3,200 MWh/year. May have to reduce value for air density, for example, Panhandle of Texas at 1,100 m, has air density of 1.1 kg/m^3. This would give a 10% reduction to 2,900 MWh/year.

Class j	Speed m/s	Frequency	Hours	Power Curve kW	Energy kWh
1	1	0.023	202	0	0
2	2	0.045	391	0	0
3	3	0.063	553	0	0
4	4	0.078	679	0	0
5	5	0.087	764	34	25,983
6	6	0.092	807	103	83,073
7	7	0.092	808	193	156,031
8	8	0.089	776	308	238,860
9	9	0.082	715	446	319,071
10	10	0.073	637	595	378,872
11	11	0.063	548	748	410,011
12	12	0.052	457	874	399,557
13	13	0.042	370	976	361,014
14	14	0.033	291	1,000	290,645
15	15	0.025	222	1,000	221,968
16	16	0.019	165	1,000	164,870
17	17	0.014	119	1,000	119,167
18	18	0.010	84	1,000	83,853
19	19	0.007	57	1,000	57,465
20	20	0.004	38	1,000	38,366
21	21	0.003	25	1,000	24,960
22	22	0.002	16	1,000	15,828
23	23	0.001	10	1,000	9,785
24	24	0.001	6	1,000	5,899
25	25	0.000	3	0	0
		0.998	8743		3,405,281

12. Cut-in wind speed = 5 m/s, rated wind speed = 14 m/s.
13. Cut-in wind speed = 4 m/s, rated wind speed = 10 m/s.
14. Primary method of control for power output is control of rpm.
15. Primary method of control for shutdown is feathering of blades, full-span pitch control.
16. Time for shutdown or to reduce power output is 3–6 s.
17. Any system. If students have read ahead, there are examples in Chapters 8 and 10.
18. Problems with tethered wind turbine: cable (what are size, weight, and length?), warning lights, small planes, winch to reel in or lower system, high wind, and speed control.

CHAPTER 6

1. Blade, r to center of mass = 5 m, mass = 500 kg, F = 320 Nm.

$$T = r * F = 5 \text{ m} * 320 \text{ Nm} = 1{,}600 \text{ Nm}^2 = \text{J}$$

2. Use Equation 6.9, $P = F * v$, and substitute force from Equation 6.8.

$$P = 0.5 * \rho * v^2 * A * C_D * \text{v}$$

Notice that power loss is proportional to velocity cubed.
$C_D = 1$, and assume $\rho = 1$ kg/m^3.
Strut is 4 m × 0.025 m, rpm = 180.

ω = rpm * 2π/60 = 180 * π/30 = 18.8 rad/s.
Area for 1 m section = length * width = 1 m * 0.025 m = 0.025 m^2.
Power loss for each section, $P = 0.5\ v^3 * A = 0.0125\ v^3$, watt.
Take r at the midpoint of the section. Have to find velocity at center of each section, $v = \omega * r$.

Section	Radius *m*	$v = \omega * r$ m/s	Power *W*
1	0.5	9.4	10
2	1.5	28.2	280
3	2.5	47.0	1,298
4	3.5	65.8	3,561
		Sum	5,150

For three struts, the power loss would be 15 kW, which means do not use struts, have blades.

3. rpm = 80, ω = rpm * 2π/60 = 80 * π/30 = 8.4 rad/s.
Show diagram. Strut has radius from 0.25 to 2.25 m.
$C_D = 1$, and assume ρ =1 kg/m^3.
Take differential area of strut, $dA = D * dr = 0.05$ dr, where D is the diameter.
For one strut, $P = 0.5\ v^3 * A$, $dP = 0.5\ (\omega r)^3\ 0.05$ dr.

$$P = 0.025 * 8.4^3 \int_{0.25}^{2.25} r^3 dr = 148 \left.\frac{r^4}{4}\right|_{0.25}^{2.25} = 3.7(25 - 0.004) = 92\ W$$

Power loss for four struts would be 370 W.
Can do calculation numerically, similar to problem 2.
For one strut:

$A = 0.025$		$\omega = 8.4$	
Section	Radius *m*	$v = \omega * r$ m/s	Power *W*
1	0.5	4.2	1
2	1	8.4	7
3	1.5	12.6	25
4	2	16.8	59
		Sum	93

Notice how close the numerical result is to the calculus result.

4. Power out is from Equation 6.12; substitute into Equation 6.7 for power coefficient.
From calculus take derivative, dC_P/du, and set equal to 0. Solve for u.

$$\frac{d}{du}\left[u(v_0 - u)^2\right] = 0$$

$$(v_0 - u)^2 + 2u(v_0 - u)(-1) = 0$$

$$(v_0 - u) - 2u = 0$$

$$u = v_0/3$$

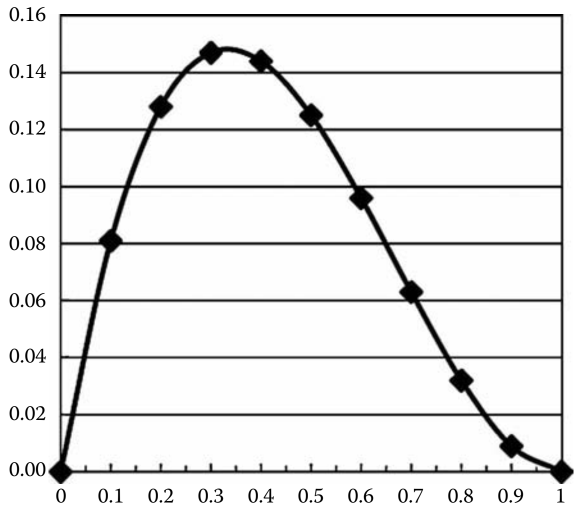
Substitute $u = v_0/3$ in Equation 6.12 and you have maximum $C_P = 4/27\ C_D$. For $C_D = 1$ the efficiency is 15% for a drag device.
Numerical solution: calculate $C_P = u(1 - u)^2$, where u goes from 0 to v_0 by tenths.

u	C_P
0.1	0.08
0.2	0.13
0.3	0.15
0.4	0.14
0.5	0.13
0.6	0.10
0.7	0.06
0.8	0.03
0.9	0.01
1	0.00

Maximum occurs between 0.3 and 0.4, so do that by hundredths.

u	C_P
0.31	0.14759
0.32	0.14797
0.33	0.14814
0.34	0.14810
0.35	0.14788
0.36	0.14746
0.37	0.14685
0.38	0.14607
0.39	0.14512
0.4	0.14400

This shows that C_P maximum occurs for $u = 0.33$.
Or from a plot, estimate value of u for peak C_P.



5. If the solidity increases, the peak of the aerodynamic efficiency occurs at lower tip speed ratios.
6. a. If it operates at constant tip speed ratio, then it operates at maximum efficiency at any wind speed.
   b. If it operates at constant rpm, it reaches maximum efficiency at only one wind speed. See Figure 6.13.
7. Maximum efficiency is 59%. This was calculated by using conservation of energy and conservation of momentum.
8. Low-solidity rotors reach their maximum C_P at higher tip speed ratios.
9. Take the derivative of Equation 6.18 with respect to α and set equal to 0.
   Same as problem 4, value is $\alpha = 1/3$.
   Substitute that value in Equation 6.18.
   Maximum $C_P = 16/27 = 59\%$ for a lift device.
   Numerical solution: calculate $4\alpha(1 - \alpha)^2$, where α goes from 0 to v_0 by tenths.
   Same as problem 4, except C_P is four times larger.
   For lift and drag devices the peak of C_P occurs at the same value, (wind speed)/3; however, the efficiencies are different.
10. Tip speed ratio = 7, TSR = speed of tip of blade divided by wind speed.

$$v = \omega * r, \ \omega = v/r$$

Have to change from rad/s to rpm.
Table of rpm for various radii and rotor tip speeds.

Radius	Tip Speed, m/s		
m	**70**	**140**	**210**
2.5	268	535	803
5	134	268	401
25	27	54	80
50	13	27	40

Notice that as radius increases, rpm gets smaller, even though the TSR is the same. As you can see, at high wind speeds, you cannot let the rotor operate at maximum C_P, since the rpm would be too large. It would fly apart, unless you had a very strong structure (much more cost). If wind turbine operates at constant rpm (induction generator), the design point of maximum C_P determines the rpm.

11. In the final analysis, you want to produce as much energy, kWh, as possible at the lowest cost. The cube of the wind speed histogram is proportional to the energy. So you would probably choose the maximum efficiency at below or near the peak of the energy curve for a site. Use Figure 3.12 as an example. This would be in the range of 8–12 m/s. However, with larger megawatt wind turbines, at higher hub heights, it would be in the range of 10–15 m/s.
    Data for problems 12–18: rpm = 65, rated power = 300 kW at 18 m/s, hub height = 50 m, tower head weight = 3,091 kg, mass of one blade = 500 kg; rotor: hub radius = 1.5 m, radius to tip of blade = 12 m.

$$\omega = \text{rpm} * \pi/30 = 65 * \pi/30 = 6.8 \text{ rad/s}$$

12. Velocity of the tip, $v = \omega * r = 6.8 * 12 = 82$ m/s.

13. Velocity of the blade root. Since r is small, v will be smaller.

$$v = \omega * r = 6.8 * 1.5 = 10 \text{ m/s}$$

14. For center of blade, $v = \omega * r = 6.8 * 6 = 41$ m/s.

$$KE = 0.5\, mv^2 = 0.5 * 500 * 41^2 = 4.2 * 10^5 \text{ J}$$

If you did it by calculus, would the answer be larger or smaller?

$$\text{Blade length} = 12 \text{ m} - 1.5 \text{ m} = 10.5 \text{ m}$$

Divide into ten sections, each section is 1.05 m long, mass of each section = 50 kg.

		ω	**Mass**
		6.8	50
Blade Section	***r*** **m**	***v*** **m/s**	***KE*** **J**
1	2	13.6	4,624
2	3.05	20.7	10,754
3	4.1	27.9	19,432
4	5.15	35.0	30,660
5	6.2	42.2	44,437
6	7.25	49.3	60,762
7	8.3	56.4	79,637
8	9.35	63.6	101,060
9	10.4	70.7	125,033
10	11.45	77.9	151,554
		Sum	627,954

$$KE = 6.3 * 10^5 \text{ J}$$

15. $P = 300$ kW, $\omega = 6.8$ rad/s
$T = P/\omega = 300{,}000/6.8 = 44{,}000$ Nm.
16. $F/A = 0.5\, \rho\, v^2$, let density = 1 kg/m^3
$F/A = 0.5\ (100) = 50$ N/m^2
Total force = $50 * \text{area} = 50 * 3.14 * 12^2 = 23{,}000$ N.
17. Energy = 800,000 kWh, area = $\pi r^2 = 3.14\ (12)^2 = 452$ m^2
Specific output = annual energy/area = 800,000/452 = 1,770 kWh/m^2.
This is large compared to actual industry values (see Chapter 8). Energy/swept area depends on efficiency of system and also on the wind regime.
18. Output/weight = 800,000 kWh/3,091 kg = 260 kWh/kg
Data for problems 19–25: rpm = 21 = 2.2 rad/s, rated power = 1,000 kW, rated wind speed = 13 m/s, hub height = 60 m, tower head weight = 20,000 kg; rotor: radius to tip of blade (rotor) = 28 m, hub radius = 1.5 m, mass of one blade = 3,000 kg.

19. Velocity of the tip, $v = \omega * r = 2.2 * 28 = 62$ m/s.
20. Velocity of root of blade, $v = \omega * r = 2.2 * 1.5 = 3$ m/s.
21. For center of blade, $v = \omega * r = 2.2 * 14 = 31$ m/s.

$$KE = 0.5\ mv^2 = 0.5 * 3{,}000 * 31^2 = 1.4 * 10^6 \text{ J}$$

Hub is at 1.5 m, so blade is 28 – 1.5 = 26.5 m long. Divide that into ten sections and calculate for midpoint. Mass of each section = 300 kg. However, for actual blades, mass will change along the blade, which means inner sections would have more mass.

		ω	**Mass**
		6.8	50
Blade Section	***r*** **m**	***v*** **m/s**	***KE*** **J**
1	2.8	6.2	5,692
2	5.5	12.0	21,564
3	8.1	17.8	47,633
4	10.8	23.7	83,898
5	13.4	29.5	130,361
6	16.1	35.3	187,019
7	18.7	41.1	253,875
8	21.4	47.0	330,927
9	24.0	52.8	418,176
10	26.7	58.6	515,622
		Sum	1,994,767

$KE = 2 * 10^6$ J. With calculus would get better answer.

22. $T = P/\omega = 1{,}000{,}000/2.2 = 4.5 * 10^5$ Nm.
23. $F/A = 0.5\ \rho v^2$. Let density = 1 kg/m^3.
    $F/A = 0.5\ (225) = 112.5$ N/m^2
    Total force = 112.5 * area = 112.5 * 3.14 * 28^2 = 2.8 * 10^5 N.
24. Area = 2,460 m^2
    Specific output = annual energy/area = 2,800,000/2,460 = 1,100 kWh/m^2.
25. Output/weight = 2,800,000/20,000 = 140 kWh/kg.

CHAPTER 7

1. $V = IR = 2$ amp * 100 ohm = 200 V
2. $P = I^2R = 4 * 100 = 400$ W
   To transmit power, you want high voltage and low current to reduce losses from resistance. Even if copper has low resistance there are still power losses.
3. Carter 25; maximum power = 30 kW, rated power = 25 kW, 240 V. Single-phase generator.

$$P = VI$$
$$I = P/V = 30{,}000/240 = 125 \text{ amps, average value}$$
$$I_P = 1.4 * I = 1.4 * 125 = 175 \text{ amps}$$

Because of losses in wire, need to know the length of wire, distance from generator to transformer.

4. The values given are root mean square values, so the peak voltage is higher by 1.4 * *V*.

$$V_P = 154, 336, 672 \text{ V}$$

5. Equation 7.10. $P = VI \cos \Phi = 240 * 20 * \cos 20 = 4{,}800 * 0.41 = 1{,}900$ W.
So power is 1.9 kW, which is a large reduction from 4.8 kW.
6. A three-phase generator means that there are three circuits (three coils of wire), *V* and *I* for each, and shifted by 120° for each phase.
7. $\omega = 2\pi *$ frequency $= 6.28 * 60 = 376$ rad/s.
8. $P = T * \omega$, $P = 500$ kW = 500,000 W, rpm = 1,200, $\omega = 1{,}200 * \pi/30 = 126$ rad/s

$$T = P/w = 500{,}000/126 = 4000 \text{ Nm}$$

This is the torque for the high-speed shaft of the gearbox. The wind rotor rpm will be much smaller; therefore, the torque will be higher, as have the same amount of power. Higher torque needs a larger shaft. See Figure 5.10 for relative sizes of high-speed and low-speed shafts.
9. Efficiency is a maximum around a slip of 0.04.
10. Total length of wire is 75 m.
Generator is rated at 480 V, three-phase.

$$I = P/V = 30{,}000/480 = 63 \text{ amps}$$

Need to worry about peak values, $I_P = 1.4 * 63 = 88$ amps. However, since it is three-phase, need 52 amps.
From Table 7.1, need no. 6 wire.
Always go to larger value, so it is box corresponding to 50 amps and 76 m.
11. $P = 100$ kW, $V = 480$ *V*, three-phase. Length of wire is 40 m.

$$I = P/V = 100{,}000/480 = 208 \text{ amps}$$

$I_P = 290$ amps; since it three-phase, need 170 amps.
From Table 7.1, need no. 3 wire.
13. Advantages: inexpensive, simple control to connect to grid, mass produced, disconnected when loss of load due to utility fault, stall control essentially gives constant output in high winds.
Disadvantages: less efficient operation, loss of load means fast shutdown, little slip means wind gust loads transferred to power train.
14. Advantages: higher efficiency, inertia of rotor can absorb wind gusts, pitch control allows for high wind and overspeed shutdown.
Disadvantages: more expensive, need more complicated electronic control.
15. For induction generators, they are shut down. If have low-voltage ride through, then depending on time length of fault, wind turbines may not be shut down.
16. SCADA lets wind farm operators control power and monitor each wind turbine. Also, SCADA builds a database for operation and maintenance.
17. Variable-speed wind turbines use power electronics to convert to constant frequency and constant voltage of the utility grid.
18. Controllers monitor the condition of the wind turbine, control switches for different operations and functions, and may collect statistics on operation.

19. Inverters convert variable frequency and voltage to constant frequency and constant voltage of the utility grid. Inverters have been used from watts to kilowatts. Small wind turbines with permanent magnet alternators that are connected to the grid use inverters.

CHAPTER 8

1. kWh/kW is the energy produced divided by the rated power (size of the generator). So, numbers range from 412 for Flowind to 2,833 for the Nordtank. In reality, this calculation is in hours, or the equivalent number of hours that the unit was at the rated power. There are two main factors: (1) what wind regime (energy produced) and (2) size of the generator. If it is a poor wind regime, lower kWh/kW, and if the generator is too big for the rotor size, lower kWh/kW.
2. Average power = annual kWh/9=8,760 hour, capacity factor = average power/rated power.
   Fayette, $CF = 41{,}000/(8{,}760 * 90) = 0.052$.
   Vestas 23, $CF = 434{,}000/(8{,}760 * 200) = 0.25$.
   Bonus 120, $CF = 276{,}000/(8{,}760 * 120) = 0.26$.
3. Average capacity factor = 17%
4. Enertech 44/40 means it is 44 ft diameter and rated at 40 kW.
   Area = $\pi r^2 = 3.14\ 6.7^2 = 141\ \text{m}^2$.
   a. Specific output = annual kWh/area = 49,467/141 = 350 kWh/m^2.
      If change ratio for full year, specific output = 12/7 * 350 = 600 kWh/m^2.
   b. Specific output = annual kWh/area = 86,592/141 = 614 kWh/kW.
5. Enertech 44/25:
   a. Specific output = annual kWh/area = 91,372/141 = 648 kWh/m^2
   b. Hours = 3,254/0.64 = 5,084, or number of hours for 7 months (April–October, hours = no. days * 24).

   Average power = 49,467 kWh/5084 h = 9.7 kW.
   Capacity factor = avg. power/rated power = 9.7/25 = 0.39.
6. Enertech 44/60; 44 ft diameter, rated power = 60 kW.
   a. Specific output 91,732/141 = 651 kWh/m^2.
   b. Average power = 91,732/(365 * 24) = 10.5 kW.

   Capacity factor = avg. power/rated power = 10.5/60 = 17.5%.
7. May, specific output = 9,078/141 = 94 kWh/m^2; August, 2,443/141= 17 kWh/m^2.
   Of course, specific output depends on the wind, so yearly values are a better way to compare wind turbines.
8. Carter 300, 24 m diameter, area = 452 m^2.
   a. Specific output = 600,000/452 = 1,327 kWh/m^2
   b. Output per kW = 600,000/300 = 2,000 kWh/kW
   c. Output per mass = 600,000/14,250 = 42 kWh/kg
   d. Output per installed cost = 600,000/180,000 = 3.3 kWh/$

   When you compare problems 8 and 9, you have to realize that Vestas is still producing wind turbines and Carter is not. Problems with maintenance and capitalization led to the company going out of business. Notice that the V27 has a larger diameter and a smaller rated power. Also, this is a comparison between lightweight two-blade and heavier three-blade wind turbines.

9. V27, 27 m diameter, area = 572 m^2.
   a. Specific output = 500,000/572 = 874 kWh/m^2.
   b. Output per kW = 500,000/225 = 2,222 kWh/kW.
   c. Output per mass = 500,000/22,800 = 22 kWh/kg.
   d. Output per installed cost = 500,000/225,000 = 2.2 kWh/$.
10. Carter 300, avg. power = 600,000/(365 ∗ 24) = 68 kW, CF = 68/300 = 23%.
    Vestas V27, avg. power = 500,000/(365 ∗ 24) = 57 kW, CF = 57/225 = 25%.
11. Estimate for V90, wind map value of 500 W/m^2 and CF = 35%, V90 rotor area = 6,360 m^2.
    AMWH = 0.35 ∗ 500 ∗ 5,027 ∗ 0.00876 = 9,700 MWh/year.
    Estimate for V52, generator size method, CF = 35%. AMWH = 0.35 ∗ 1.65 ∗ 8,760 = 5,000 MWh/year.
12. From Table 8.5, need pump diameter of 1.8 cm. Could pump around 2 cubic m/h.
13. From Table 8.5, need pump diameter of 2.2 cm. Could pump around 3 cubic m/h.
14. From Table 8.5, need pump diameter of 1.0 cm. Could pump around 1 cubic m/h.
15. Multiply number of minutes times flow (L/min) for each bin and sum to get total volume of water pumped. 10,000 L = 1 m^3.
    Same spreadsheet is used for problems 15 and 17.

	V average	5					
				Farm Windmill		**Electric–Electric**	
Class *j*	**Speed m/s**	**Frequency**	**No. Minutes**	**Flow L/min**	**Volume *L***	**Flow L/min**	**Volume *L***
1	1	0.06	2,629				
2	2	0.11	4,785	0.0	0		
3	3	0.14	6,135	0.4	2,303		
4	4	0.15	6,566	5.3	34,956	0.0	0
5	5	0.14	6,187	11.6	71,667	0.0	0
6	6	0.12	5,256	15.8	83,133	3.2	16,909
7	7	0.09	4,077	19.3	78,563	18.0	73,417
8	8	0.07	2,909	21.7	63,059	36.2	105,390
9	9	0.04	1,919	22.7	43,493	53.0	101,764
10	10	0.03	1,174	20.8	24,369	66.2	77,683
11	11	0.02	668	19.0	12,708	75.7	50,597
12	12	0.01	354	13.9	4,921	85.1	30,104
13	13	0.00	175	10.3	1,801	88.8	15,523
14	14	0.00	81	9.2	740	83.3	6,718
15	15	0.00	35			70.7	2,458
16	16	0.00	14			59.1	828
	Sum	0.99	42,965		421,713		481,391

For farm windmill, water pumped = 42 m^3.
Notice that if frequency distribution does not add to 1 (close), you have made a mistake.
Student answers will vary due to estimation of flow from graph.
With spreadsheet, easy to change average wind speed. At 6 m/s, farm windmill = 50 m^3; electric–electric = 83 m^3.

16. Bergey Windpower, Southwest Windpower, ?
17. Electric–electric system, water pumped = 48 cubic m. See problem 15 for spreadsheet.
18. Enertech 44/25, 68,000 kWh/year; 44/60, 104,000 kWh/year.
    Student answers will vary due to estimation of power curves from graph.

	V **average**	6					
				Enertech 44/25		**Enertech 44/60**	
Class *j*	**Speed m/s**	**Frequency**	**No. Hours kW**	**Power kWh**	**Energy kW**	**Power kWh**	**Energy**
1	1	0.04	374				
2	2	0.08	700	0.0	0		
3	3	0.11	942	0	0	0	
4	4	0.12	1,078	0	0	0	0
5	5	0.13	1,107	4	4,430	3	3,322
6	6	0.12	1,046	5	5,228	6	6,273
7	7	0.10	919	10	9,187	11	10,106
8	8	0.09	757	14	10,598	19	14,383
9	9	0.07	588	18	10,581	26	15,284
10	10	0.05	432	20	8,632	34	14,675
11	11	0.03	300	23	6,908	46	13,816
12	12	0.02	198	26	5,159	53	10,517
13	13	0.01	125	28	3,490	55	6,854
14	14	0.01	74	30	2,235	60	4,469
15	15	0.00	42	31	1,315	65	2,756
16	16	0.00	23	32	736	68	1,565
17	17	0.00	12	33	393	70	833
18	18	0.00	6	33	194	72	423
19	19	0.00	3	33	91	74	205
20	20	0.00	1	34	42	76	95
	Sum	0.99	8,705		68,498		104,021

19. For 2005, 3,974,759,861 kWh = 3.97 TWh.
    Vestas, installed capacity = 563,985 kW.
    Kenetech, number installed = 3,598.
20. Power will be reduced from 30% to 50%.
21. Llano Estacado Wind, White Deer, Texas:
    Installed capacity = 80 MW.
    From Figure 8.5, $CF = 0.34$. AMWH = 0.34 ∗ 80 ∗ 8,760 = 239,000 MWh/year.
24. Vortex generators, small vanes to mix laminar flow with boundary layer.
    Suction or blowing air through holes in the blade.
25. Active stall control, since blade pitch can be changed to still obtain power output. The other solution is to use airfoils, which are less sensitive to surface roughness.

CHAPTER 9

1. Rule of thumb, 5–10 m above the building. So tower should be around 25 m tall, which is 80 ft. Place it 10 m away from the building.
2. Rule of thumb, tower height should be 5–10 m above the trees or move tower farther away from trees. So tower should be 40 m tall. Need to look in a catalog for cost of towers; guyed lattice tower would be the cheapest. Need to check manufacturer's brochure for recommended tower size (strength of structure) for that size wind turbine (example, 10 kW from Bergey Windpower). Stand-alone towers, Rohn SSV, cost more but do not need space for guy wires. Bergey website has tower costs.

3. Building is 15 m high, so the comparison is between additional 10 m of tower height at the building and distance of ten building heights, which gives a power reduction of 17%. Because you are farther away, will need larger size wire (see handbook on wiring or Table 7.1). Need a detailed analysis, as the costs are around the same for taller tower or farther away.
5. Class 3 wind is 150–200 W/m^2 at 10 m height. Lower value is 150 W/m^2, mid-value is 175 W/m^2. Terrain exposure, E is 80 m. For grassland, roughness length = 0.01 m. If you use 0.03 m, that is OK. H_h = 50 m. Use Equation 9.1 and calculate for P_{avg} for 150 and 175 W/m^2.

$$\frac{P}{P_{avg}} = \frac{\left(\ln\left[\dfrac{H_h + E}{z_0}\right]\right)^3}{\left(\ln\left[\dfrac{H_h}{z_0}\right]\right)^3}$$

$$\ln[130/0.01] = \ln 1{,}300 = 7.17,\ \ln 800 = 6.68$$

$$P = \{7.17^3/6.68^3\}\ 150\ \text{W/m}^2 = 1.2 * 150\ \text{W/m}^2 = 184\ \text{W/m}^2$$
$$P = \{7.17^3/6.68^3\}\ 175\ \text{W/m}^2 = 1.2 * 175\ \text{W/m}^2 = 210\ \text{W/m}^2$$

If you used the bottom of the class, you would still be in the same class for an exposure of 80 m. If you used the middle of the class, then you would increase the wind class from 3 to 4.
6. Selected 1 MW, 60 m diameter wind turbine, with 5D by 10D spacing. Fifty wind turbines are arranged in a grid of three rows with 17, 17, 16 turbines in each row. Rotor area = 2,800 m^2. Assume capacity factor of 35%. Estimate annual energy production for one turbine.
AMWH = CF * area * WM * 0.00876 = 0.35 * 2,800 * 500 * 0.00876 = 4300 MWh/year.
Use availability of 0.95, 4,000 MWh/year per turbine.
Estimated annual energy production = 50 * 4,000 =200,000 MWh/year.
7. Estimate array losses for 3D by 6D spacing. Array loss for row 2 = 10%, array loss for row 3 = 15%. Turbine in row 2, energy = 0.9 * 4,000 = 3,600 MWh/year. Turbine in row 3 = 0.85 * 4,000 = 3,400 MWh/year.
Estimated annual energy production = 17 * 4,000 + 17 * 3,600 + 16 * 3,400 = 183,000 MWh/year.
Total estimated annual energy production = 50 * 4.4 * 10^6 kWh = 220 * 10^6 kWh.
8. Choose 1 MW wind plants, 60 m diameter, spacing 5D by 10D. Each turbine requires a space of 300 by 600 m, or an area of 180,000 m^2, which is 18 ha. Total area for fifty turbines is 900 ha.
This does not allow any space for a buffer zone around the wind farm. So you would need over 1,000 ha, or 10 km^2. That results in 5 MW/km^2.
9. Turbine = 3 MW, 4D by 8D spacing, D = 90 m. Space per turbine = 32 * 90 * 90 = 26 ha. 1 km^2 = 100 ha, so could place four turbines per km^2, which is 12 MW/km^2. Notice this is over double the result for problem 8.
10. Row of 3 MW turbines, 2D spacing, D = 90 m. Space per turbine = 180 m, so 1,000 m/180 m = 5 turbines. That is, 15 MW/km.
11. With complex terrain, the spacing will generally be larger than for plains or rolling hills. In general, the overall spacing could be larger than 10D by 10D. From previous problems, answers will probably vary from 3 to 5 MW/km^2.

12. Raster based, takes more data space since every pixel has a value. Vector based, means only need endpoints. In final analysis it primarily depends on cost and ease of use.
14. Estimated spacing 4D by 8D, $D = 56$ m. Area allocated to a turbine is 100,400 $m^2 = 10$ ha, or 10 MW/km^2. 1 sq. mile = 2.6 km^2. However, note in Figure 9.11, with proper arrangement you could place eighteen turbines in a square mile (7 MW/km^2), so the estimated spacing is a little large.
15. There were two rows, so two roads around 1 mile long.
    Road area = 2 * 7 m * 1,600 m = 22,400 m^2 = 2.2 ha. Base area of each turbine = 10 * 10 = 100 m^2. So 16 turbines = 16,000 = 1.7 ha.
    Land area taken out of production = 4 ha.
    Because there were county roads in place, the land taken out of production is around 0.25 ha per turbine. However, they had to upgrade the county roads with grading and caliche.
16. Area of wind farm is around 12 square miles. For 80, 1 MW wind turbines, which result in 7 MW/sq. mile.
17. Hard to tell, but guess is around 2D in a row, and 3 to 5D from row to row.
18. This is a difficult problem because of the many parameters. Students will have to do quite a bit of searching.

    a. How much land does a 50 MW wind farm occupy? 10–20 km^2
    b. Type of terrain: plains, hills, passes, ridges, and complex terrain?
    c. Size turbines? Hub height?

    Again, it is a question of cost and time. What kind of risk are the developer and investment bankers willing to accept? Answer depends on the terrain and the availability of long-term database in similar nearby terrain.
    My opinion: However, wind farm developers and meteorologists who consult for wind farm developers make these decisions:

    a. Period of data collection: Long-term reference database is available nearby in similar terrain, 1 year. No reference database, 2–3 years.
    b. Number of met towers:

       Plains terrain: Tall towers, 50 m; hub height, 1–2. Short towers, 20–25 m height; 4–6.
       Complex terrain: Tall towers, 50 m; hub height, 2–4. Short towers, 20–25 m height, 6–10.

    50 MW wind farm would be fifty 1 MW wind turbines. Would you place a met tower at every proposed location? Would you then move the shorter towers to try to find a better site? For plains, definitely not. For complex terrain, one met tower per five turbines? In California, in complex terrain, some project operators actually moved some small wind turbines after installation to improve energy production. It would have been cheaper to install more met towers and move them. Also, this is impractical for large wind turbines.
    Costs will have wide variationm from \$1 to 4 million.
    Wade Weichmann's response (from actual wind farm in rolling hills area): I have encountered very different numbers from different sources on the number of met stations. I know that at Lake Benton I, Minnesota, 22 met stations were erected for the 143-turbine site for 3 years (15 square miles). On the other hand, Spera stated in *Wind Turbine Technology* that it could be cost justified to install one met tower per turbine site for large-scale turbines. I believe the number of stations would depend on the topography of the site. A flat topography would need less met towers to get accurate data that could be correlated to long-term regional data mentioned earlier. One-year duration was also mentioned in the *Wind Resource Assessment Handbook* to predict power density to within 10%. I believe 2 years

would strengthen the predictability of power density. Also, the tallest sensors on the met towers should be placed at hub height.

19. Wind speed is around 5 m/s from the northeast.
20. Data should be collected:
    a. 2 to 3 years
    b. 1 year
    c. 6 months to 1 year
21. Elevation of mesa is around 1,600 m. Trails.com purchased Topozone. Have a free 14-day trial. Go to www.awstruewind.com or to www.newmexico.org/map and use terrain.
22. General rule; can install 5–9 MW/km^2 for plains and rolling hills, and 8–12 MW/km for ridgeline.
23. Power per area = 535,342/110,788 = 4.8 MW/km^2.
24. Using general rule, use 8 MW/km^2, then could install $8 * 110{,}788 = 880{,}000$ MW. Capturable power to be in the same ratio as in Table 9.3; capturable power = $17/54 * 880{,}000 = 280{,}000$ MW.
25. Mesa Redonda, wind speed at 100 m height, 9.1 m/s.

CHAPTER 10

1. Wind-assist system is where wind turbine is combined with another power source to produce power on demand.
2. *Wind Power Monthly*, www.windpower.com. Windicator is now under Wind Insight. Previous answers given for comparison:

Date	World	Largest	Cap, MW	China, MW
Jan 08	93,881	Germany	22,247	5,906
Nov 03	31,243	Germany	12,001	468
Apr 02	24,471	Germany	8,752	399

3. End of year 2008, 94,200 MW. For 2013, my guess is 260 GW. Past growth, which has been exponential, was 25% per year, doubling time = 2.5 years. Five years in the future would be two doubling times = 376 GW, which is too much. Cannot have continued exponential growth, even in the wind industry. However, my 2002 guess was 120,000 MW by 2010, which will be low. For the United States, end of 2007 = 17,000 MW. Guess for 5 years in the future is 70,000 MW.
4. Offshore wind for 2007 is around 1000 MW.
5. Yes, both grid-connected and stand-alone, from 1 kW to 50 kW.
6. Yes, school districts have from two to five 50 kW wind turbines.
7. Yes, should receive same incentives that wind farms receive.
8. Main difference is in control and operation of the diesels. Low penetration, the diesels run all the time. High penetration requires more complicated controls, with dump loads, storage, and being able to shut down the diesel generators.
9. National Wind Technology Center site: www.nrel.gov/wind.
   Sometimes it is hard to distinguish between R&D and non-R&D programs.
   R&D: Low-wind-speed technologies, advanced component technology.
10. NREL, non-R&D programs: information and outreach, utility grid integration, environmental issues, wind resource assessment.

11. Joanes, Brazil, 50 kW system; four 10 kW wind turbines, 10 kW PV, 228 kWh battery bank, rotary converter (from Northern Power website).
12. Major advantage is people now have electrical power for schools, clinics, and homes. Also, there is the possibility of productive use. Major disadvantages are higher cost, limited electricity, institutional issues of who pays and how much.
13. Wind electric can pump enough water for small irrigation and villages.
14. Annual efficiencies; electric system is 12–15%, farm windmill is 5–6%.
15. Federal tax credits and avoided cost set by California Energy Commission.
16. Vestas.
17. Vestas, 90 m diameter, 3 MW, 105 m tower.
    Siemens, 107 m diameter, 3.6 MW, 80 m or site-specific tower.
18. Yes, Wildorado, 70 turbines, rated power 2.3 MW.
19. Applications are electricity, pumping water, making ice.
20. Aerospace industry was used to cost plus contracts. U.S. federal R&D supported lightweight two-bladed wind turbines, which had higher O&M and was not competitive with European wind turbines.
21. Lots of examples: China, Alaska, Europe, Australia, etc.

CHAPTER 11

3. Ancillary costs are additional costs the utility incurs because there are wind turbines on the grid.
4. Two main environmental issues are birds and possible impact on playa lakes.
5. Discussion question. Know the difference between the tax credits of the early 1980s (based on units installed, \$/kW) and the production tax credit of the 1990s (\$/kWh).
6. R&D, demonstration projects, guaranteed loans, commercialization projects, subsidies for village power are examples. Need to back up your statements with reasons.
7. Some examples are net energy billing, tax breaks, incentives from economic development commissions.
10. Coal plant externalities: acid rain, greenhouse gas emissions, environmental aspects of mining coal, ash disposal.
11. www.dsireusa.org; states with net metering of 100 kW or greater, as of 2008: AZ, CA, CN, District of Columbia, HI, IA, MA, MD, MI, NE, NH, NJ, NY (12 kW for farm-based wind), ND, OH, OK, OR, RI, VT, VA, WA.
15. Number of states with renewable portfolio standards as of 2008: 33.
16. Value is around \$5–8/MWh.
18. Installed capacity for world, 94,000 MW (2007). Production estimated at $0.35 * 94{,}000 * 8{,}760 = 290{,}000{,}000$ MWh/year. U.S. coal plants emit around 1 kg of carbon dioxide per kWh, or 1 metric ton per MWh. Therefore, wind-generated electricity avoided 290,000,000 metric tons of carbon dioxide per year.
19. Europe installed capacity = 57,000 MW (2007). Energy production $= 0.35 * 57{,}000 * 8{,}760 = 174{,}000{,}000$ MWh/year. Coal plants emit 1 ton/MWh, so wind avoided 174,000,000 tons of carbon dioxide.
    U.S. installed capacity = 17,000 MW (2007). Energy production $= 0.35 * 17{,}000 * 8{,}760 = 52{,}000{,}000$ MWh/year. Coal plants emit 1 ton/MWh, so wind avoided 52,000,000 tons of carbon dioxide.
20. Around \$1,000,000/km (\$ 2008).
21. Birds, around one per year per turbine. Bats are the same, except for the East United States, thirty per year per turbine.
22. Falls, blades.

CHAPTER 12

1. From the sensitivity analysis, Figure 12.1, the most important factors are annual energy production and initial installed costs.
2. Bergey 1 kW wind turbine produces 2,000 kWh/year. Value of electricity for remote site is \$0.50/kWh. From Bergey website, remote package, with batteries: \$6,000. Installation adds another \$500, so total cost is \$6,500.
   Value/year = 2,000 kWh/year ∗ \$0.50/kWh = \$1,000/year.
   Use Equation 12.1, payback = IC/(AKWH ∗ \$/kWh) = 6,500/1,000 = 7 years.
   Of course, this is very dependent on AKWH and the value of the electricity.
3. Air X, IC = \$1,200, AKWH = 400, FCR = 0.05, AOM = 0.
   COE = (IC ∗ FCR + AOM)/AKWH = (\$1,200 ∗ 0.05)/400 = 60/400 = \$0.15/kWh.
4. Go to Bergey site, www.bergey.com; value package for 10 kW, grid intertie = \$40,600. With shipping and installation, IC = \$46,000; assume FCR = 0.08, AOM = \$100/year. Assume capacity factor = 25%, AKWH = CF ∗ GS ∗ 8,760 = 0.25 ∗ 10 ∗ 8,760 h = 21,900 kWh/year.
   COE = (IC ∗ FCR + AOM)/AKWH = (\$46,000 ∗ 0.08 + \$100)/21,900 kWh/year.
   COE = 3,780/21,900 = \$0.17/kWh.
5. IC = \$150,000, AKWH = 120,000, FCR = 0.10, AOM = 150,000 ∗ 0.01 = \$900, LCR = \$4,000/year.
   COE = (150,000 ∗ 0.10 + 1,500 + 4,000)/90,000 = 20,500/120,000 = \$0.17/kWh.
6. IC = \$150,000, $r = 0.08$, AKWH = 120,000 at \$0.09/kWh, $\alpha = 0.06$.
   Value per year f_0 = 120,000 ∗ \$0.08/kWh = \$9,600 per year.
   Calculate left-hand side of Equation 12.7, f_0/c = \$9,600/\$150,000 = 0.064.
   Then for values of α and r, guess at L and calculate right-hand side of Equation 12.7. From first answer, estimate new L and calculate again. I chose $L = 10$ as a starting point. Answer is 12 years to payback.

a	**r**				**LHS**
0.04	0.08				0.064
		Calculate RHS of Equation 12.7			
L	**$(1 + r)^L$**	**$(1 + \alpha)^L$**	**Num.**	**Dem.**	**RHS**
10	2.2	1.48	0.069	1.04	0.067
20	4.7	2.19	0.298	5.55	0.054
15	3.2	1.80	0.152	2.54	0.060
12	2.5	1.60	0.097	1.51	0.064

   The price for oil in 2002 was around \$20/bbl, and the fuel inflation rate was close to zero. This type of calculation shows the difficulty of trying to predict future energy costs, which are primarily driven by the price of oil. In 1980, a fuel inflation rate of 7% was considered low. With spreadsheets it is easy to vary the parameters.
7. Life cycle costs are total costs over the lifetime of the system, including disposal or salvage costs at the end. When externalities are included in fossil fuel costs, then life cycle costs for renewable energy systems are cheaper. However, these external costs are estimated at widely different values, from zero to \$0.10/kWh for coal plants. Also, we are used to purchasing with cheap down payment and monthly payments. The big unknown is the future O&M costs for small wind turbines.
8. See Figure 12.5.

9. The last nuclear power plants generate electricity at \$0.10–0.13/kWh. On the South Texas Project, construction started in 1976 and generation began in 1988. That is why stranded costs are included in electric restructuring. For new nuclear plants, COE will probably be close to \$16–20/MWh. One reason costs of nuclear plants are high is because of the long construction period.
10. Previous times *I* taught the course.
    1998 values: fuel inflation = 0; discount rate from the feds, 4.5%; interest rate to borrow from bank, 7–?% (this depends on length of loan and type of loan, for large wind farm project).
    2002 values: fuel inflation = 0; discount rate from the feds, 1.75%; prime rate, 4.75%; interest rate to borrow from bank, 7–?%.
    2008 values: fuel inflation = 5%; discount rate from the feds, 2.25%; prime rate, 5%; interest rate to borrow from bank, 7–?%.
11. Total production = $100 * 3000$ MWh/year = 300,000 MWh/year. Payment = \$40/MWh.
    Income = \$40/MWh * 300,000 MWh/year = \$12,000,000/year.
    Land owners, royalty = $0.04 * \$12 * 10^6$/year = \$300,000/year.
12. Calculate COE for one wind turbine:
    IC = \$1,600,000, FCR = 0.09,
    AKWH $=3 * 10^6$, AOM = \$0.05/kWh $* 3 * 10^6$ kWh/year = \$15,000/year.
    Estimated LCR = \$15,000/year.
    COE = $(1{,}600{,}000 * 0.08 + 15{,}000 + 15{,}000)/(3 * 10^6)$.
    COE = $158{,}000/(3 * 10^6)$ = \$0.053/kWh.
    The wind farm receives a production tax credit of \$0.02/kWh for 10 years plus accelerated depreciation.
13. The wind farm boom in Texas was driven by the mandated Renewable Portfolio Standards of 2,000 MW of new renewable by 2009, which was increased to 4,500 MW by 2015. The production tax credit was scheduled to end as of December 31, 2008.
14. July 3, 2008, price of oil was \$141/bbl.
    Estimated price for future in today's dollars.

Year	**2010**	**2020**	**2030**
08 estimate	\$160	\$200	\$250
Jun 08 EIA	\$90	\$65	\$70

15. Cost of Oil War II (Iraq War) is around \$100,000,000,000 per year. Amount of oil produced by Middle East is around 22 million bbl/day, or 8,000,000,000 bbl/year. So the cost of that oil is increased by \$12/bbl. If it were just Iraq oil, 2 million bbl/day, then that cost is increased by \$130/bbl.
16. The reasons were federal tax credits and that the California Energy Commission set the avoided costs for wind energy. Wind farm developers could make primarily one of two assumptions: lower cost but guaranteed \$/kWh over a long time period, or that fuel inflation would be greater in the future. Those that selected the second were wrong.
17. My opinion for the federal energy program is the following with incentives in the same rank. Fossil fuels are finite, and they are a mature industry, so money needs to go for R&D, not tax incentives for drilling, etc. Nuclear is also a mature industry, so again, money needs to go for R&D, not commercialization. Total incentives for nuclear are hard to determine. Nuclear and fossil fuels receive more support than energy efficiency and renewable energy in the federal budget.

	Millions of dollars		DOE FY 08
1	Conservation and energy efficiency	1,500	1,236 (includes renewable)
2	Renewable energy	1,000	
3	Nuclear (includes fusion)	300	875
	Civilian radioactive waste management	495	
	Nuclear waste disposal	202	
4	Natural gas	200	863 fossil
5	Coal (clean)	100	

How do you pay for it? My opinion, we need a large tax on oil (gasoline and diesel), prices comparable to Europe, so we will buy fuel-efficient vehicles. In 2008, gas prices reached \$4/gallon in the United States, and finally people were concerned about fuel efficiency. Also, we will need nuclear energy for generation of electricity; however, waste disposal and nuclear proliferation are primarily political problems. There are risks, and there will be accidents. For your perusal, try a little book on risks, John Ross's *The Polar Bear Strategy*. (1999, Basic Books, Reading, MA.)

19. Cost for Bergey 10.1 kW hybrid system, \$75,100. Installed costs are around \$100,000.
    AKWH = 20,000, FCR = 0.08, AOM = \$500.
    COE = (\$100,000 ∗ 0.08 + \$500)/20,000 = \$0.43/kWh.
20. Southwest Windpower does not list prices on its website.
    IC = \$15,000, AKWH = 2000, FCR = 0.08, AOM = \$200.
    COE = (\$15,000 ∗ 0.08 + \$200)/2,000 = \$0.70/kWh.
21. Northwind 100 prices are not available on its website.
    In remote Alaska, installed costs are around double the cost of the unit at the plant.
    IC = \$300,000, AKWH = 300,000, FCR = 0.08, AOM = \$800, LRC = \$12,000.

$$\mathrm{COE} = \frac{(\mathrm{IC}^*\mathrm{FCR}) + \mathrm{LRC} + \mathrm{AOM}}{\mathrm{AEP}}$$

    COE = (300,000 ∗ 0.08 + 12,000 + 800)/300,000 = \$0.12/kWh.
22. IC = \$45,000, AKWH = 50 ∗ 365 = 18,000, FCR = 0.03, AOM = \$180.
    COE = (45,000 ∗ 0.03 + 180)/18,000 = \$0.085/kWh.
23. IC = 30 ∗ 4,300 = \$129,000, AKWH = 65,000, FCR = 0.03, AOM = \$650.
    COE = (129,000 ∗ 0.03 + 650)/65,000 = \$0.07/kWh.
    For Llano Estacado Wind:
24. Power purchase agreement = \$0.02489/kWh (2007).
25. *Q*1 = \$1,473,008; *Q*2 = \$1,350,000; *Q*3 = \$1,229,000; *Q*4 = 1,776,000.
    Total income = \$5,897,000.
    Simple payback = \$80,000,000/\$5,897,000 = 14 years.
26. For 2007, energy = 236 MWh.
    Income for 2007 from PTC = \$20/MWh ∗ 236,000 MWh = \$4,720,000.
    Assume it is the same for each year, so total income = \$10,000,000 per year.
    Now simple payback = 8 years.
28. Average power = 236,000 MWh/8760 h = 26.9 MW.
    Capacity factor = 26.9/80 = 34%.
28. FPL Energy Oklahoma Wind, 2008 Q1:
    Peak = \$23.60/MWh, off-peak = \$12.00/MWh, avg. = \$18.04/MWh.
    FPL Energy Hancock County Wind, 2008 Q1:
    High = \$43.09/MWh, low = \$22.64/MWh, avg. = \$28.09/MWh.