ENERGY AND THE ENVIRONMENT
Abbas Ghassemi, Series Editor

WIND ENERGY

THIRD EDITION

Renewable Energy and the Environment

Vaughn Nelson
Kenneth Starcher

CRC Press
Taylor & Francis Group

Wind Energy

Renewable Energy and the Environment

Taylor & Francis Series in Energy and the Environment

Series Editor
Abbas Ghassemi
New Mexico State University, Las Cruces, USA

Energy Resources:
Availability, Management, and Environmental Impacts
Kenneth J. Skipka and Louis Theodore

Geothermal Energy:
Renewable Energy and the Environment, Second Edition
William E. Glassley

Environmental Impacts of Renewable Energy
Frank R. Spellman

Introduction to Renewable Energy, Second Edition
Vaughn C. Nelson and Kenneth L. Starcher

Introduction to Bioenergy
Vaughn C. Nelson and Kenneth R. Starcher

Hydroelectric Energy:
Renewable Energy and the Environment
Bikash Pandey and Ajoy Karki

Geologic Fundamentals of Geothermal Energy
David R. Boden

Solar Radiation:
Practical Modeling for Renewable Energy Applications
Daryl R. Myers

Solar and Infrared Radiation Measurements
Frank Vignola, Joseph Michalsky, and Thomas Stoffel

Forest-Based Biomass Energy:
Concepts and Applications
Frank Spellman

Textbook of Environmental Biotechnology
Pramod Kumar, Vipin Kumar, and Pravin Kumar Sachan

Wind Energy:
Renewable Energy and the Environment, Third Edition
Vaughn Nelson and Kenneth Starcher

For more information about this series, please visit:
https://www.crcpress.com/Energy-and-the-Environment/book-series/CRCENERENVI

Wind Energy

Renewable Energy and the Environment

Third Edition

Vaughn Nelson and Kenneth Starcher

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper

International Standard Book Number-13: 978-1-138-61534-2 (Hardback)

Library of Congress Cataloging-in-Publication Data

Names: Nelson, Vaughn, author. | Starcher, Kenneth, author.
Title: Wind energy : renewable energy and the environment / Vaughn Nelson and Kenneth Starcher.
Description: Third edition. | Boca Raton : Taylor & Francis, a CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa, plc, 2018. | Includes bibliographical references.
Identifiers: LCCN 2018027424 | ISBN 9781138615342 (hardback : alk. paper)
Subjects: LCSH: Wind power. | Wind power plants.
Classification: LCC TJ820 .N44 2018 | DDC 621.31/2136--dc23
LC record available at https://lccn.loc.gov/2018027424

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Contents

Preface

The big questions: How do we use science and technology so that spaceship Earth will be a place for all life to exist? How do we address the two major problems of overconsumption and overpopulation? We are citizens of the planet Earth, and within your lifetime there will major decisions over the following: energy (including food), water, minerals, land, environment, and war (which I can state will happen with 99.9% probability). The previous statement on war was written over 30 years ago when Nelson first taught introductory courses on wind energy and solar energy. Since then, the United States has been involved in a number of armed conflicts, so the prediction on war was easily fulfilled.

Since the first edition was published, the population of the Earth has increased from 6.5 billion to 7.4 billion (2017 numbers). We are all part of an uncontrolled experiment regarding the effect of human activities on the Earth's environment. This has led to global problems: climate change due to greenhouse gas emissions, deforestation, collapse of fish stocks due to overfishing, loss of habitat and extinction of species, lack of water resources, expansion of deserts, degradation of ecosystems due to pollution and fragmentation, and other lesser problems. Thus, we have passed the point of sustainable use of Earth's resources. Renewable energy is part of the solution for the problem of finite resources of fossil fuels and the environmental impact from greenhouse gases. Renewable energy is now part of national policies with significant goals of generation of energy within the next decades.

Essentially, we have not really done much to resolve the enormous problems of overpopulation and overconsumption. As before, the first priority of national and global policies should be conservation and efficiency, and the second priority is the need to transition from fossil fuels to renewable energy. The underdeveloped countries are in transition and their energy use, materials consumption, and emission of greenhouse gases will soon be in line with those of developed countries. China is the main example, as they are now essentially an industrialized country. The continued energy consumption of large amounts of fossil fuels cannot continue. If it does, the world is headed for a catastrophe.

The major change since 2007 has been the large annual increase of wind energy. By the end of 2017, the cumulative numbers installed in wind farms were around 360,000 wind turbines with an installed capacity of 540 GW. About 1,400,000 small wind turbines (less than 100 KW) with an estimated capacity of 1.4 GW were in use. Wind energy has become part of the solution for the transition to renewable energy, especially for the generation of electricity.

This third edition contains updates on wind energy installation and capacity and fossil fuel production. The section on distributed wind has been expanded and a new section on repowering and decommissioning has been added.

Acknowledgments

We are deeply indebted to colleagues at the Alternative Energy Institute (AEI, terminated in 2015) of West Texas A&M University (WTAMU), and at the Wind Energy Group (program canceled in 2012) at the Agricultural Research Service, U.S. Department of Agriculture (USDA), Bushland, Texas. The students in our classes and the students who worked at AEI have provided insights and feedback. Many others, including numerous international researchers and interns, worked with us on energy projects at AEI and the USDA. Thanks also to the Instructional Innovation and Technology Laboratory at WTAMU for preparing computer drawings.

Vaughn wants to express gratitude to his wife, Beth, "who has put up with me all these years. As always, she is very supportive, especially in visiting all those wind farms to obtain information and take photos and accompanying me on many trips to different parts of the world. An interesting note: Our granddaughter Dana Nelson obtained a degree in Mechanical Engineering from UT Austin and now works for GE Wind."

Ken credits his wife, Madeleine, with "making me get up each morning and making it well worthwhile to come home each evening. I have never really had a 'job,' but the lifetime of involvement in renewables has been worth all the years of doing it."

Authors

Dr. Vaughn Nelson has been involved with renewable energy, primarily wind energy, since the early 1970s. He is the author of four books (five books on CD) and has published more than 50 articles and reports. He also served as the principal investigator on numerous grants and conducted more than 60 workshops and seminars from local to international levels.

Dr. Nelson's primary work focused on wind resource assessment, education and training, applied research and development, and rural applications of wind energy. Presently, he is a Professor Emeritus of physics at West Texas A&M University (WTAMU). He retired as the Dean of the Graduate School, Research, and Information Technology in 2001. He was founder of the Alternative Energy Institute (AEI) and director from its inception in 1977 through 2003. He returned as director for another year in July, 2009. The Alternative Energy Institute was terminated in 2015.

Dr. Nelson served on a number of State of Texas Committees, most notably the Texas Energy Coordination Council, for 11 years. He received three awards from the American Wind Energy Association, one of which was the Lifetime Achievement Award in 2003, was named a Texas Wind Legend by the Texas Renewable Industries Association in 2010, and received an award for Outstanding Wind Leadership in Education from Wind Powering America in 2013. He also served on the boards of directors for state and national renewable energy organizations.

In the series, Energy and the Environment, Dr. Nelson is the author of *Wind Energy* (2009; Second Edition, 2013) and *Introduction to Renewable Energy (*2011) and with Kenneth Starcher the Second Edition (2015) and also with Kenneth Starcher, *Introduction to Bioenergy* (2016).

Dr. Nelson earned a PhD in physics from the University of Kansas, an EdM from Harvard University, and a BSE from Kansas State Teachers College in Emporia. He was a member of the Departamento de Física, Universidad de Oriente, Cumana, Venezuela for 2 years and then was at WTAMU from 1969 until his retirement.

Kenneth Starcher began his college career and involvement with renewables the same semester, Fall 1976. It led to a BS in physics/computer science at West Texas State University (1980) and then in 1980–1981 he was at Texas Tech University taking courses in electrical engineering, electronics, and physics. He received an MS in engineering technology at WTAMU (1995), and then took some courses in agricultural economics at WTAMU.

Starcher has been the field worker for most of the projects at the Alternative Energy Institute (AEI) since 1980. He has been the educational funnel for on-site training and public information for students and public workshops for AEI. He has served as a trainer at wind and solar training workshops locally, nationally, and internationally. He served as a research technician, research associate, assistant director, director, and associate director (Training, Education and Outreach) for the Alternative Energy Institute from 1977 to 2015.

He served as a board member of the American Wind Energy Association, was on the Executive Board of Class 4 Winds and Renewables, was chosen as the Individual Member of the year for the Texas Renewable Energy Association in 2005, the Small Wind Educator at the Small Wind Conference in 2010, and was awarded an Outstanding Wind Leadership Education Award from Wind Powering America in 2013.

Starcher has installed and operated more than 85 different renewable energy systems, ranging in scale from 50 W to 500 kW. He has served as a consultant for wind companies in the United States and produced wind resources maps for U.S. counties and states, as well as for Honduras and Thailand.

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 are solar energies that fall into two classifications:

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

Renewable energy: Radiation, wind, biomass, hydro, and ocean thermal and waves. Many people discount renewable solar energy; some even call it an "exotic" source of energy. However, it is the source of all food, most fibers, and heating and cooking in many parts of the world [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, it is replenished from below when it is released through the Earth's surface.

Fossil fuels are the main source of energy in most industrialized nations, however, the use of renewable energy has increased and there are goals for a substantial amount of renewable energy to replace fossil fuels. Based on the widespread use of fossil fuels, and combined with growing demands and an increasing world population, the need to 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 began in antiquity. Vertical axis windmills for grinding grain were reported in Persia in the 10th century and in China in the 13th century [2]. At one time, wind was a major source of energy for transportation (sailboats), grinding grain, and pumping water. Windmills and 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 were even used for industrial purposes such as sawing wood. As the Europeans colonized the world, windmills were built all over the world.

The principal long-term use of wind (except for sailing) has been to pump water. In addition to the famous Dutch windmills, another famous example is the historical use of sail-wing blades to pump water for irrigation on the island of Crete. On these windmills, 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 Windmills

At one time, over 9,000 windmills operated in The Netherlands. A number of different designs were used, from the early post mills to the taller mills whose tops rotated to keep the blades perpendicular to the wind. Today, Dutch windmills are famous attractions in The Netherlands (Figure 1.1).

Machines for pumping large volumes of water from a low head were as large as 25 m in diameter and most parts were made of wood. Even the helical pump, an Archimedean screw, was made of

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

wood (Figure 1.2). The mills were quite sophisticated in terms of the aerodynamics of the blades. A miller would rotate (yaw) the top of the windmill from the ground with a rope attached to a wooden beam on the cap so the rotor would be perpendicular to the wind. Others used small fan rotors to yaw the big rotors. The rotational speed and power were regulated by the amount of sail 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. Fire was a major hazard faced by thatched windmills.

1.1.2 Farm Windmills

Farm windmills were of the utmost importance when Americans were settling in the Great Plains of the United States [3]. 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 a few in isolated farmhouses and museums.

By 1900, most windmills were made of metal. They still had multi-blade vanes, and the blades were 3–5 m in diameter (Figure 1.4). Although the use of farm windmills peaked in the 1930s and 1940s, when over six million were in operation, these windmills are still manufactured and continue to pump water for livestock and residence uses. The American Windmill Museum in Lubbock, Texas has an outstanding collection of farm windmills (Figures 1.5 and 1.6) from the early wood mills to the later metal types. The museum collects small wind turbines (Figure 1.7), blades for several small wind turbines, and a large 1.5-MW General Electric wind turbine on display. Electricity is provided on-site by a Vestas V47 660-kW turbine on a 40-m tower.

Most farm windmills currently in use are in Africa, Argentina, Australia, Canada, and the United States. Because farm windmills are fairly expensive, a resurgence of design changes has focused on creating less expensive systems. Another major advance is the development and commercialization of stand-alone electric–electric systems for pumping enough water for irrigation, village use, or both [4].

FIGURE 1.2 Dutch windmill (thatched) museum. Notice water flow at bottom of windmill into the canal. Nelson in much younger days next to helical pump.

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

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

The farm windmill proves that wind energy is a valuable commodity, even though the proportion of the energy market is small. For example, an estimated 30,000 farm windmills operate in the Southern High Plains of the United States. Even though their individual power output is low (0.2–0.5 kW), they collectively provide an estimated output of 6 MW.

If the windmills for pumping water were converted to electricity from the electric grid, the transition would require around 15 MW of thermal power from a generating station and over $1 billion for transmission lines, electric pumps, and other equipment. This does not consider the dollars

FIGURE 1.5 Some of the many old windmills in the pavilion, at the American Windmill Museum in Lubbock, Texas. (Photo courtesy of Coy Harris.)

FIGURE 1.6 Old windmills on towers at the American Windmill Museum in Lubbock, Texas. The Vestas V47 is in the background.

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 seeking alternatives such as solar pumps rather than purchasing new windmills.

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

1.1.3 Wind Chargers

As electricity became commercially practical, some isolated locations were too far from generating plants and transmission lines were too costly. Therefore, a number of manufacturers built

FIGURE 1.7 Small wind turbines at American Windmill Museum in Lubbock, Texas. Parentheses indicate turbine size in meters and rated power in kilowatts. Left to right, Urban Green Technology (1.4 × 0.9, 1.0), Air Dolphin (1.2, 1.0), Honeywell (2.2, 1.0), Raum (4.0, 4.0), Windspire (3.0 × 0.6), Skystream (Southwest Windpower, 3.7, 2.1). Tower heights are around 10 m.

stand-alone wind systems to generate electricity (Figures 1.8 and 1.9), based on a propeller-type rotor with two or three blades. Most of the wind chargers had direct current generators (6–32 V) and some later models generated 110 V. The electricity was stored in wet-cell lead–acid batteries that required careful maintenance for long life.

These systems with two or three propeller blades are quite different from farm windmills that utilized several blades covering most of the rotor-swept area. Farm windmills were well engineered for pumping low volumes of water, but too inefficient for generating electricity because the blade design and large numbers of blades meant slow rotor speed.

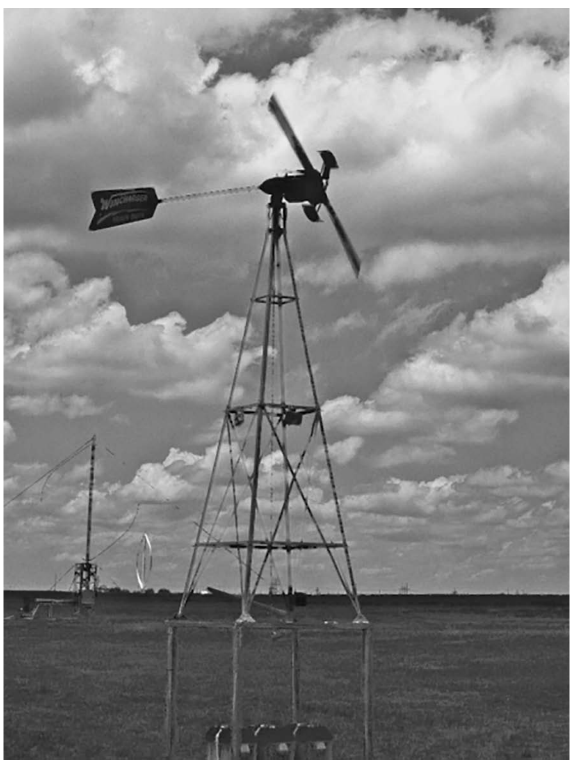


FIGURE 1.8 Direct current 100-W, Windcharger with flap air brakes at U.S. Department of Agriculture's ARS Wind Station at Bushland, Texas. Notice 4-kW and 100-kW Darrieus wind turbines in the background.

FIGURE 1.9 Jacobs 4-kW direct current generator. It was still in use in the 1970s on a farm near Vega, Texas, USA.

Wind chargers became obsolete in the United States when inexpensive (subsidized) electricity 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

A number of attempts were made to design and construct large wind turbines for utility use [5–10]. These designs centered on different concepts for capturing wind energy (Figure 1.10) and included airfoil-shaped blades with horizontal or vertical rotor axes, Magnus effect, and Savonius designs. A vertical axis presents no rotor orientation problems arising from different wind directions.

A rotating cylinder in an airstream will experience a force or thrust perpendicular to the wind. This is known as the Magnus effect. In 1926, Anton Flettner built a horizontal axis wind turbine with four blades. 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 midpoint. The rotor (on a 33-m tower) was 20 m in diameter and had a rated power of 30 kW at a wind speed of 10 m/s.

Julius D. Madaras proposed mounting vertical rotating cylinders on railroad cars propelled by the Magnus effect around a circular track. The generators were to be connected to the axles of the cars. In 1933, a prototype installation consisting of a 29-m tall cylinder, 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 concept was abandoned.

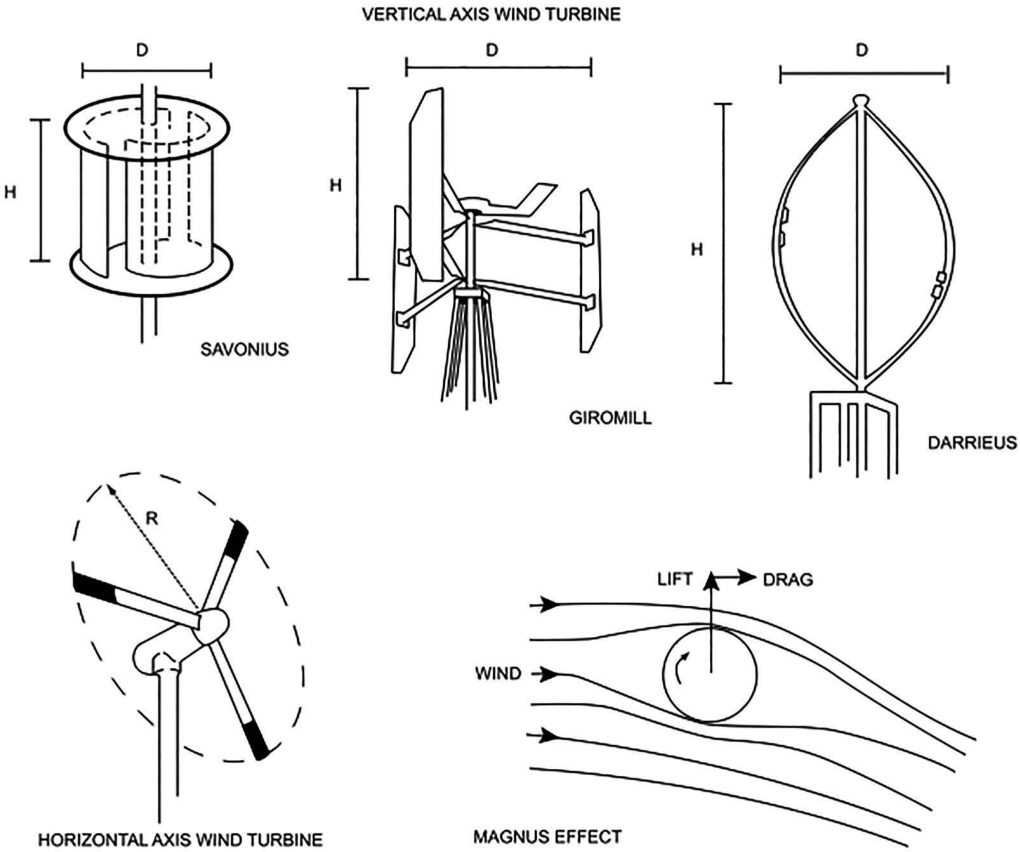


FIGURE 1.10 Diagrams of different rotors.

The Magnus effect was used in Flettner rotors used to propel ships [11,12], and one ship operated using rotors for fuel savings from 1926 to 1933. In 1984, the Cousteau Society built a sailing ship called the *Alcyone*, which used two fixed cylinders with an aspirated turbosail [13].

In Finland, Sigurd Savonius built S-shaped rotors that resembled two halves of a cylinder separated by a distance smaller than the diameter. In 1927, Georges Darrieus invented a wind machine whose blade was shaped like a jumping rope. His patent for a giromill also covered straight vertical blades. The Darrieus design was later reinvented by researchers in Canada [14].

In 1931, the Russians built a 100-kW wind turbine near Yalta on the Black Sea. The rotor was 30 m in diameter and sat 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 made 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.

The Smith-Putnam wind turbine (Figure 1.11) was developed, fabricated, and erected between 1939 and 1941 [15]. The turbine was placed on a 38-m tower located on Grandpa's Knob in Vermont and connected to the grid of Central Vermont Public Service. The rotor was 53 m in diameter. Its 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 pitches 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

FIGURE 1.11 Smith-Putnam wind turbine, 1,250 kW. (Photo courtesy of archive of Carl Wilcox.)

downwind side of the tower and the blades were free to move independently (teeter perpendicular to the wind) due to wind loading.

Testing of the wind turbine started in October of 1941, and in May of 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 was not replaced until March, 1945 because of a shortage of materials due to World War II. After the bearing was replaced, the unit operated as a generating station for 3 weeks, then 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 a utility grid, the project was not pursued because of economics. Photos of the construction of the Smith-Putnam wind turbine are available online [15].

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 [6].

After World War II, research and development efforts on wind turbines were centered in Europe. E.W. Golding summarized the efforts in Great Britain [7], and further efforts were reported in the conference proceedings of the United Nations [8]. The British built two large wind turbines. One was built by the John Brown Company on Costa Hill, Orkney, in 1955. The 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 ran only intermittently in 1955 due to operational problems.

The other unit was built by Enfield, based on a design by Edouard Andreau, a French engineer, and 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. The unit was different in that the blades were hollow. When they rotated, the air flowed through an air turbine connected to an alternator at ground level and exited from the tips of the blades (Figure 1.12). The unit was moved to Grand Vent, Algeria, for further testing in 1957. Frictional losses were too large for it to be successful.

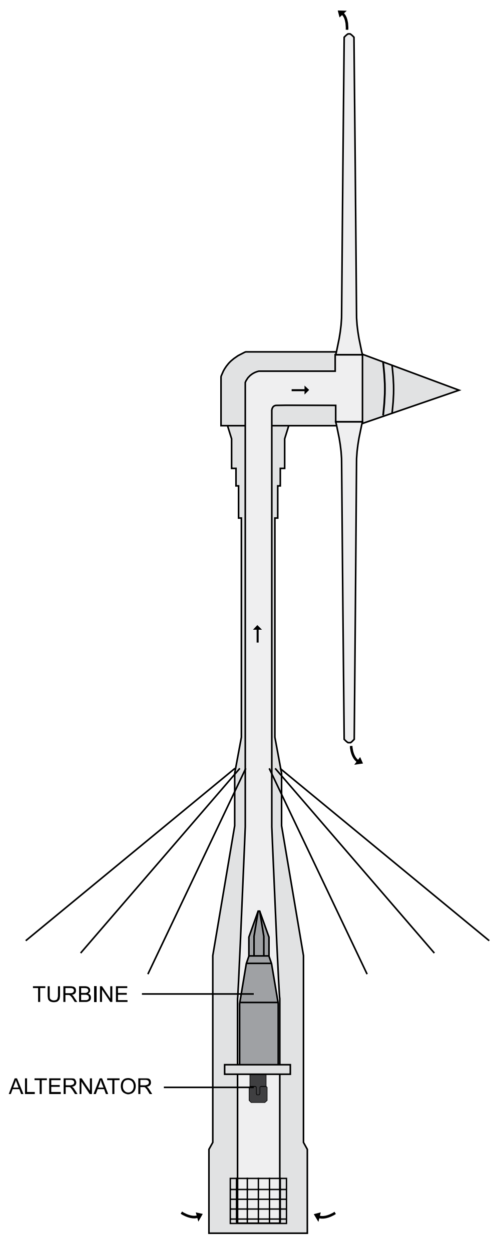


FIGURE 1.12 Enfield-Andreau wind turbine (100 kW).

The French built several prototype wind turbines from 1958 to 1966. An 800-kW wind turbine located at Nogent Le Roi had a rotor diameter of 31 m and was operated at constant speed by a rotor connected to a synchronous generator. The top weighed 162 metric tons and was mounted on a 32-m tower. The 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. Although the prototypes clearly showed the feasibility of connecting wind turbines to electric grids, the French decided in 1964 to discontinue further wind energy research and development.

During the 1950s, Ulrich Hütter of Germany designed and tested wind turbines that remained the most technologically advanced for the next two decades. The downwind rotors had lightweight fiberglass blades (Figure 1.13) mounted on a teetered hub with pitch control and coning. A 10-kW unit was developed and tested and led to a larger unit, 34 m in diameter that produced 100 kW at 8 m/s [16]. This unit operated around 4,000 h from 1957 to 1968. However, the experiments proceeded slowly due to lack of funds and blade vibration problems.

In Denmark, several hundred systems based on the design by Pool La Cour [17] were built, with rated power from 5 to 35 kW. The units had rotor diameters around 20 m and four blades connected mechanically to a generator on the ground. By 1900, around 30,000 wind turbines operated at farms and homes and by 1918, some 120 local utilities operated wind turbines, typically 20–35 kW for a total of 3 MW and produced about 3% of the Danish electricity.

Danish interest waned in subsequent years, until a crisis in electricity production occurred during World War II. Because the Danes had no fossil fuel resources, they looked at connecting wind turbines into their national grid, and the Danish government started a program to develop large-scale wind turbines to produce electricity. During World War II, a series of wind turbines in the 45-kW range were developed with direct current (DC) generators and produced around 4 million kWh per year.

The Danes had the only successful program that began in 1947 with a series of investigations of the feasibility of using wind power, and continued until 1968 [8, 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 and the system used a 45-kW generator.

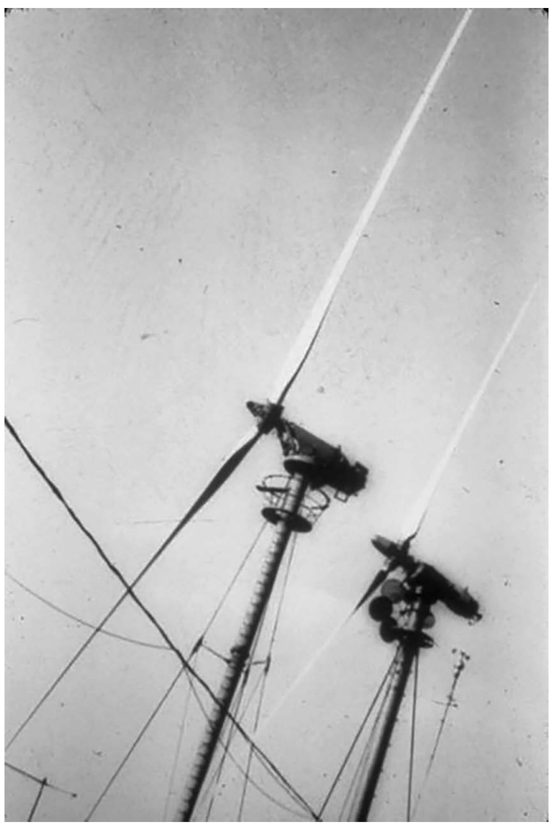


FIGURE 1.13 German wind turbines: left 100 kW, right 10 kW. (Photo courtesy of NASA-Lewis.)

FIGURE 1.14 Gedser 200-kW wind turbine. (Photo courtesy of Danish Wind Industry Association.)

The results of the two experimental turbines were encouraging and culminated in the Gedser wind turbine (Figure 1.14).

The unit was erected in 1957, and from 1958 to 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 26-m high tower was made of prestressed concrete. The rotor was upwind of the tower, and the blades were fixed pitch types with tip brakes for overspeed control. The wind turbine had an asynchronous generator (rated for 200 kW at 15 m/s) that provided stall control and also had an electromechanical yaw mechanism. Denmark and the United States furnished funds to place the Gedser wind turbine in operation for a short period in 1977 and 1978 for research that involved tests for aerodynamic performance and structural load limits.

The successful Danish program was overshadowed by the failures of other large machines due to technical problems, mainly stresses from vibration and control issues at high wind speeds. Some were economic failures despite agreement that no scientific barriers prevented the use of wind turbines tied to utility grids. In the 1960s, development of wind machines was abandoned because petroleum was available and inexpensive.

1.2 WIND FARMS

Wind farms appeared in California in 1982, as a result of federal laws and incentives along with mandates for avoided costs set by the California Energy Commission. The early years of wind farm history were dominated by installations in the United States and Denmark. By the 1990s, Europe surpassed the United States after large numbers of units were constructed in Germany (Figure 1.15a). By the end of 2017, the worldwide installed capacity (Figure 1.15b) was estimated at 540 GW with the largest capacity installed in China. In addition, there are small wind turbines with about 1.4-GW capacity.

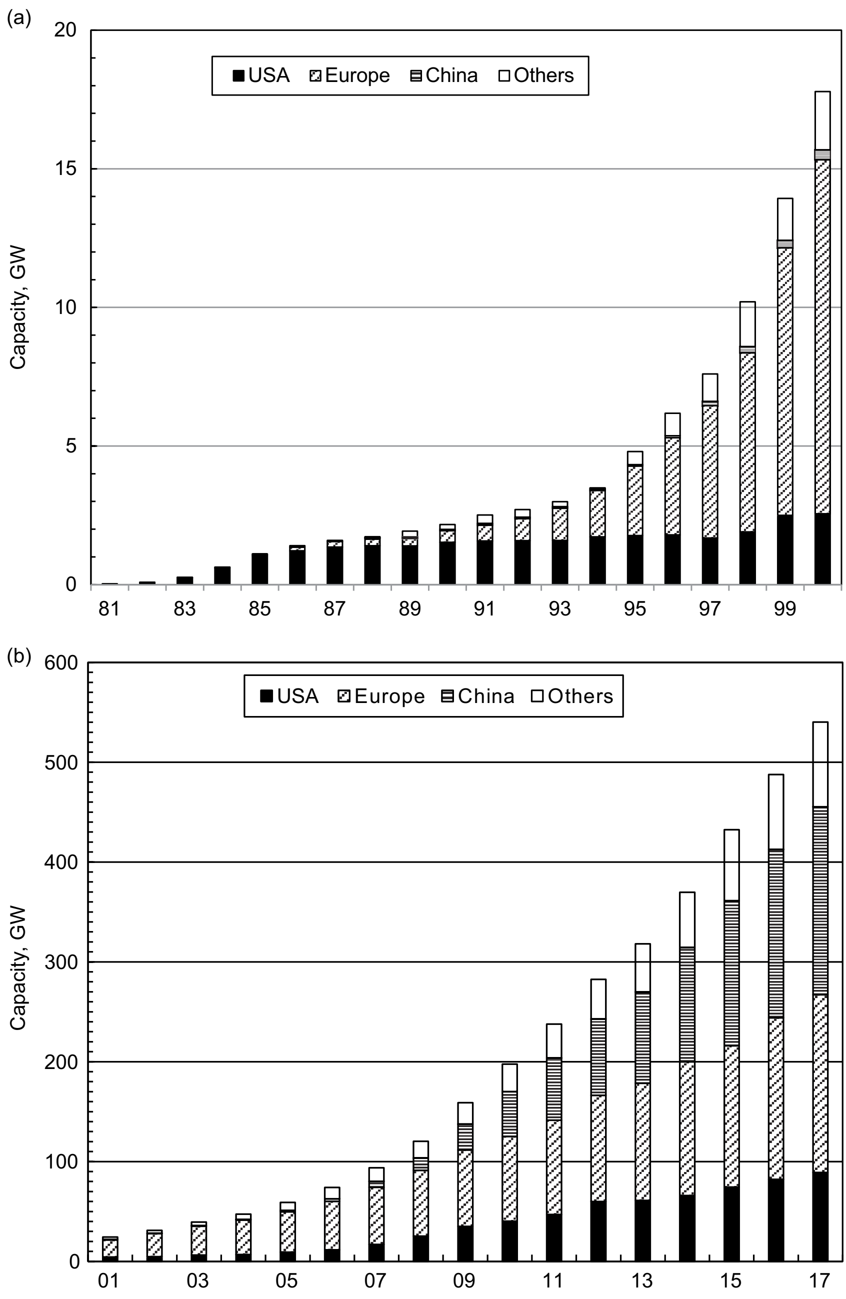


FIGURE 1.15 (a) World installed capacity of wind turbines, 1981–2000. (b) World installed capacity of wind turbines, 2001–2017. Notice that scale is much larger.

In the first edition of this book, based on 2007 data, V. Nelson estimated that global installation would reach 240 GW by 2012—an underestimate of over 40 GW. Turbine sizes increased from 10- to 20-m diameter units generating 25–100 kW to megawatt units of 60- to 100-m diameters installed on towers exceeding 100 m in height. In 2018, a wide selection of onshore turbines are available from 1.5 to 5 MW and offshore turbines up to 9.5 MW are available, both with rotor diameters and tower heights over 150 m. Around 17 GW had been installed in offshore wind farms by the end of 2017.

Electricity from wind farms is the cheapest renewable energy and less expensive than that produced by new coal and nuclear power plants. However, the increase of natural gas production in the United States decreased the prices of combined cycle gas turbines.

Wind power grew at an average rate of 28% per year from 1995 to 2012. However, the average rate from 2013 to 2017 was 14% per year. These numbers demonstrate the problem of exponential growth. At some point, a linear increase will become a norm and eventually the number of new installations per year will decrease.

V. Nelson's global prediction in 2012 was that wind power would reach 600 GW by 2020; this will be realized in 2019. By using a linear addition of 40 GW per year, the capacity will be around 1,000 GW by 2030 to meet the goals for wind power set by China, Europe, and the United States. In any case, the numbers for wind power to date and for the future are astounding.

1.3 SMALL SYSTEMS

Small systems, in general, are wind turbines rated to 100 kW. They are designated micro (0–1.5 kW), small (1.5–50 kW), and mid (50–500 kW). As of 2017, the number installed (Table 1.1) was around 1,400,000 units (around 2,000,000 produced) with a capacity around 1.4 GW.

Estimating the number installed and the total capacity as of 2017 is difficult, because of the number of manufacturers and also because China has produced and installed the most units since the 1980s. However, around 150,000 of those earlier units (50 or 100 W) in China have been retired and/or replaced by larger units. We estimate that another 30,000 units in other parts of the world are no longer operational.

Most small systems are not connected to grids and utilize battery storage. Most fall within the size range of 50–300 kW. However, in the United States and other parts of the developed world, a fairly large market has developed for small (1–10 kW) wind systems connected to grids through inverters. Telecommunications systems need high reliability and some are hybrid combinations of wind, photovoltaic (PV), and diesel energy and battery storage. Some of their locations are accessible only by helicopter.

As around 1.1 billion of the world's population does not have electrical power and costs of diesel generation have increased, a number of hybrid installations now power villages. Most are hybrid systems powered by wind and PV cells or wind only, both utilizing battery storage. Another system combines wind and diesel power. Some systems include storage and others have wind turbines added to existing diesel power plants [17]. The wind–diesel systems range in size from less than 100 kW with one or more wind turbines to hundreds of kilowatts and multiple wind turbines, and even megawatt wind turbines.

1.4 DISTRIBUTED WIND

Distributed wind is another term for wind projects that involve local financial participation and control. These projects cover a wide range of sizes and types: small wind systems for homes and farms; mid-size wind turbines (up to megawatt size) for schools and businesses; multi-megawatt wind

TABLE 1.1
Small Wind Systems Worldwide

Application	Number
Total, electric generation	1,400,000
Village power; wind, wind hybrid, wind diesel	2,500?
Telecommunications, military	3,500?
Farm windmill	300,000

farms owned by cooperatives and municipalities; and wind farms involving independent power producers that generate tens of megawatts.

Denmark and Germany built their early markets on local or cooperative owners. Distributed wind is also used for a wind project inside the utility meter. Energy is used on-site or there is the possibility of net metering. Small wind connected to a grid would be classified as distributed wind.

LINKS

American Windmill Museum. https://windmill.com.

Danish Wind Industry Association. History of wind energy. www.windpower.org/en/knowledge/windpower_wiki.html.

Darrel Dodge. http://telosnet.com/wind. Good overview of history of wind power development.

Erik Grove-Nielsen. Winds of change: 25 years of wind power development on planet earth. www.windsof-change.dk (2/21/2013). Photo history of developments from 1975 to 2000; site also has brochures of wind turbines.

European Wind Energy Association. 2007. *The road to maturity*. www.ewea.org/fileadmin/ewea_documents/documents/publications/WD/2007_september/wd-sept-focus.pdf.

Windmillers' Gazette. http://windmillersgazette.org.

International Molinological Society. www.molinology.org.

P. Gipe. 2016. *Wind Energy for the Rest of Us*. www.wind-works.org/cms/. Chapters 3 and 4 on history, book has lots of color photos.

REFERENCES

1. V. Smil and W.E. Knowland. 1983. *Energy in the Developing World: Biomass Energies*. Plenum: New York.
2. D.G. Sheppard. 1994. Historical development of the windmill. In D.A. Spera, Ed., *Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering*. ASME Press: New York.
3. T.L. Baker. 1984. *A Field Guide to American Windmills*. University of Oklahoma Press: Norman.
4. V. Nelson, R.N. Clark, and R. Foster. 2004. *Wind Water Pumping*, CD. *Bombeo de Agua con Energía in Spanish*. Contact Ken Starcher. West Texas A&M University. kstarcher@wtamu.edu
5. P.C. Putnam. 1948. *Power from the Wind*. D. Van Nostrand: New York.
6. P.H. Thomas. Electric power from the wind, 1946. Wind power aerogenerator, 1949. Aerodynamics of the wind turbine, 1954. Fitting wind power to the utility network. Federal Power Commission Reports.
7. E.W. Golding. 1955. *The Generation of Electricity by Wind Power*. Halsted Press: New York.
8. United Nations. 1994. *Proceedings of the United Nations Conference on New Sources of Energy: Wind Power*, Vol. 7.
9. D.J. Vargo. 1975. Wind energy developments in the 20th century. NASA Technical Reports Server, http://ntrs.nasa.gov/.
10. F.R. Eldridge. 1980. *Wind Machines*, 2nd ed. Van Nostrand Reinhold: New York.
11. S.D. Orsini. 1983. Rotorships: sailwing ships without sails. *Oceans*, 16, January/February.
12. C.P. Gilmore. 1984. Spin sail. *Popular Science*, 224: 70.
13. J.A. Constants et al. 1985. *Alcyone: Daughter of the Wind and Ship of the Future*. Paper presented at Asian Development Bank Regional Conference on Sail–Motor Propulsion.
14. R.J. Templeton and R.S. Rangi. 1983. Vertical axis wind turbine development in Canada. *IEEE Proceedings*, 130A: 555.
15. P. Gipe. www.wind-works.org/cms/index.php?id=5.
16. U. Hütter. 1964. Operating experience obtained with a 100-kW wind power plant N73-29008/2. Kanner & Associates and National Technical Information Service.
17. V.C. Nelson et al. 2001. *Wind Hybrid Systems Technology Characterization*. West Texas A&M University and New Mexico State University: Canyon, TX and Las Cruces, NM. www.researchgate.net/publication/267362970_WIND_HYBRID_SYSTEMS_TECHNOLOGY_CHARACTERIZATION.

2 Energy

2.1 GENERAL

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.

We have been and we will be clever in manipulating and using physical laws in terms of science and the application of science: technology. Just think over the past century, from first flight of airplanes (1903), to man landing on the moon (1969), and to exploration of the solar system by robotic systems, and from the special theory of relativity (1905) which predicted the relation between mass and energy to the atomic bomb (1945). Another major technology advance is the invention of the transistor (1947), which led to integrated circuits and myriad electronic devices. As a result, much of the population of the world has mobile phones with almost instant access to songs, video, and a tremendous amount of information available on the Internet in their hands.

There are only four generalized interactions (forces between particles) in the universe; nuclear, electromagnetic, weak, and gravitational [1]. In other words, all the different types of energy in the universe can be traced back to one of these four interactions. This interaction or force is transmitted by an exchange particle. The exchange particles for electromagnetic and gravitational interactions have zero rest mass and so the transfer of energy and information is at the speed of light, 3.0×10^8 m/s (186,000 miles/s). Even though the gravitational interaction is very, very, very weak, it is noticeable when there are large masses. The four interactions are a great example of how a scientific principle covers an immense amount of phenomena.

A major unifying concept is energy, and how energy is transferred. There are many different types of energy. Kinetic energy is energy available in the motion of particles, for example, wind or flowing water. Potential energy is the energy available because of the position between particles, for example, water stored in a dam, the energy in a coiled spring, and energy stored in molecules (gasoline). There are many examples of energy; mechanical, electrical, thermal (heat), chemical, magnetic, nuclear, biological, tidal, geothermal, and so on.

The source of solar energy is the nuclear interaction at the core of the sun, where the energy comes from the conversion of hydrogen nuclei into helium nuclei. This energy is primarily transmitted to the Earth by electromagnetic waves, which can also be represented by particles (photons). Of the solar energy (3.85×10^6 exajoules/year) that arrives on the Earth, a fraction (2.25×10^3 exajoules/year) is then transformed into wind energy and then a very small amount of that is transformed into energy used by humans. The night sky of the Earth taken by satellite illustrates the tremendous amount of energy consumed by humans (Figure 2.1).

Industrialized societies run on energy, a tautological statement in the sense that it is obvious. The world numbers for the latest year of data available are:

Population	7.6×10^9 (2017)
Gross domestic product	(GDP) \$88 $\times 10^{12}$ (2017)
Energy consumption	607 exajoules (2016)
Carbon dioxide emissions (CO_2)	33×10^9 tons (2016)

FIGURE 2.1 Nighttime image of Earth from satellites. (NASA, Visible Earth. http://eoimages.gsfc.nasa.gov/images/imagerecords/55000/55167/earth_lights_4800.tif.)

Population, gross domestic product (GDP), consumption and production of energy, and production of pollution (CO_2) for the world are interrelated (Figure 2.2).

Three noticeable developments are the largest hydroelectric project in the world: Three Georges Dam (22-GW capacity) on the Yangtze River in China; the Fukushima nuclear disaster in Japan, which resulted in all their nuclear plants being shut down for some time; and horizontal drilling and fracking to obtain oil and gas from shale formations. Horizontal drilling and fracking of shale formations has actually stopped the decline in production of oil and gas in the United States and this technology will then be used in other parts of the world to extend the time and amount of oil and gas production.

The large change in energy consumption between 2005 and 2015 is caused by growth in China and India (Figure 2.3). Seventy-six percent of the energy consumed in the world in 2015 (Figure 2.4) was from fossil fuels such as petroleum, coal, and natural gas, while in the United States it was 80%. Notice that renewable energy for production of electricity was 7% (more than nuclear power) while non-hydroelectric is 2% (Figure 2.4). Wind and solar energy for production of electricity has been increasing rapidly the last few years and the mandates for ethanol has increased the use of biofuels. Developed countries consume the most energy and produce the most pollution, primarily due to the larger amount of energy consumed per person. On a per-person basis, the United States is the worst for energy consumption and carbon dioxide emitted.

The major sources regarding world and regional energy (Energy Information Administration, International Energy Agency, and BP World Energy) may use different units, for example, quads (quadrillion BTUs), million tonnes of oil equivalent (Mtoe), millions of barrels of oil, or exajoules (EJ). Another difference is in generation of electric energy, where output is in terawatt-hours (TWh) or billion kWh. In the Energy Information Administration spreadsheets they give electric generation

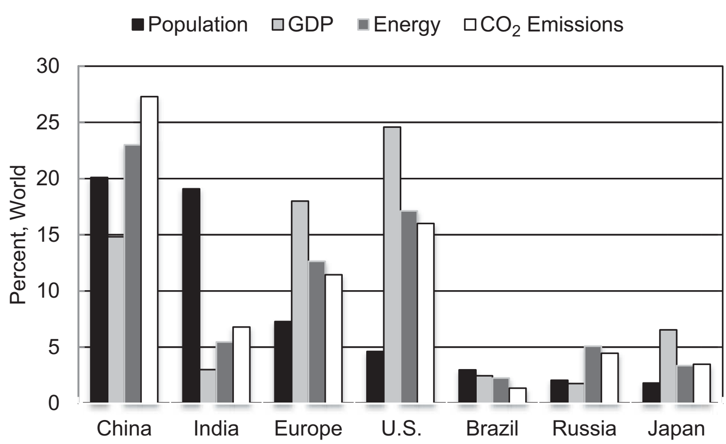


FIGURE 2.2 Comparison of population (rank in the world, 2017), gross domestic product (2017), energy consumption (2016), and carbon dioxide emissions (2016).

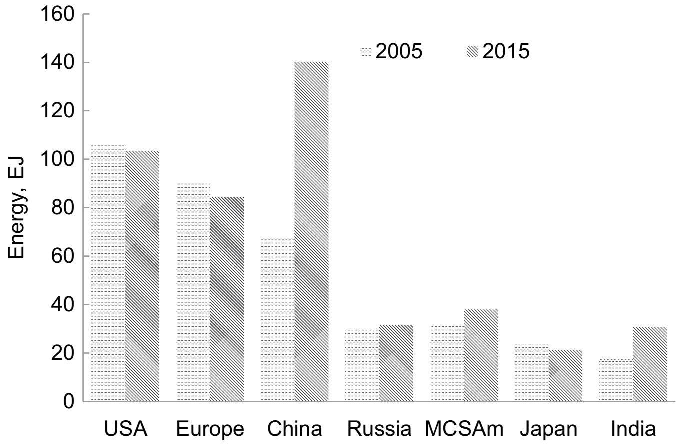


FIGURE 2.3 Comparison of energy consumption from 2005 to 2015. MCSAm stands for Mexico, Central and South America.

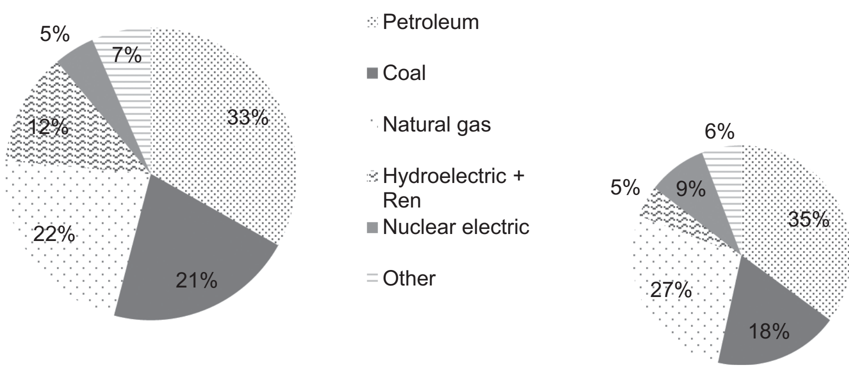


FIGURE 2.4 World energy (left) and United States (right) energy consumption by source in 2015.

in billion kWh or quads for some sources, however, there is not a direct conversion. If electric generation is given in terms of thermal energy, generally they account for energy input to generate the output, so there is the efficiency of the steam plants fueled by fossil fuels, nuclear, and biomass, around 38%. Therefore, one Mtoe (4.2×10^{16} J) produces around 4.4 TWh (1.6×10^{16} J) of electricity.

The United States has 6% of the world population (2018), however, in the world, the United States generates around 21% of the gross production, 19% of the CO_2 emissions, and is at 19% for energy consumption. When Europe is added to the United States, they consume around 40% of the world energy. Notice that the countries listed in Figure 2.1 consume 72% of the energy, produce 67% of the world GDP, and produce 74% of the CO_2 emissions. For the United States and other developed countries, energy consumption is smaller than for 2005 because of the recession of 2008 and because CO_2 emissions were reduced due to the Kyoto Treaty (the United States did not sign), and in the United States due to displacement of coal by natural gas for generation of electricity.

In the underdeveloped part of the world, China has essentially become an industrialized country and now leads the world in energy consumption and CO_2 emissions. Due to the large use of coal and the emerging vehicle fleet (more vehicles sold per year than in the United States). The next largest countries in terms of population, China and India, are beginning to emulate the developed countries in terms of consumption of energy, consumption of material resources, and greenhouse gas emissions. One dilemma in the developing world is that a large number of villages and settlements in rural areas do not have electricity.

The energy consumption in the United States increased from 32 quads in 1950 to 101 quads in 2005. One quad = 10^{15} British thermal units = 1.055 exajoules. Primarily due to the shock of the oil crisis of 1973, there was an increase in efficiency in the industrial sector. However, you must remember that correlation between GDP and energy consumption does not mean cause and effect. The oil crisis of 1973 showed that efficiency is a major component in the use of energy and in gross national product (GNP).

It is enlightening to consider how the United States has changed in terms of energy use since World War II. Ask your grandparents about their lives in the 1950s and then compare the following with today.

- Residential: Space heating and cooling, number of lights, amount of space per person
- Transportation: Number and types of vehicles in the family
- Commercial: Space heating and cooling for buildings, lights
- Industrial: Efficiency

A thought on energy and GDP: Solar clothes drying (a clothesline) does not add to the GDP, but every electric and gas dryer contributes, however, they both do the same function. We may need to think in terms of results and efficient ways to accomplish a function or process and the actual life cycle cost. Why do we need heavy cars or sport utility vehicles with big motors that accelerate rapidly to transport people?

2.1.1 Renewable Energy

Solar energy is referred to as renewable and/or sustainable energy because it will be available as long as the sun continues to shine. Estimates for the remaining life of the main stage of the sun are another 4–5 billion years. The energy from the sun, electromagnetic radiation, is referred to as insolation. The other main renewable energies are wind, bioenergy, geothermal, hydro, tides, and waves. Wind energy is derived from the uneven heating of the Earth's surface due to more heat input at the area of the equator, with the accompanying transfer of water and thermal energy by evaporation and precipitation. In this sense, rivers and dams for hydro energy are stored solar energy. The third major aspect of solar energy is the conversion of solar energy into biomass by photosynthesis. Animal products such as oil from fat and biogas from manure are derived from solar energy. Another renewable energy is geothermal, due to heat from the Earth from decay of radioactive particles and residual heat from gravitation during formation of the Earth. Volcanoes are fiery examples of geothermal energy reaching the surface from the interior, which is hotter than the surface. Tidal energy is primarily due to the gravitational interaction of the Earth and the moon.

It is difficult to estimate total renewable energy supply and an educated estimate is that 19% of the world's energy comes from renewable energy, with biomass being the major contributor such as the use of wood and charcoal, crop residue, and even animal dung for cooking and some heating. This contributes to deforestation and the loss of topsoil in developing countries. Production of ethanol from biomass is now a contributor to liquid fuels for transportation, especially in Brazil and the United States. In contrast, fossil fuels are stored solar energy from past geological ages.

2.1.2 Advantages and 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 arid and semi-arid 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 bat mortality at wind farms, and geothermal brine. In addition, wherever a large power facility is to be located, there will be perceived and actual problems for 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 (NIMBY). In the United States, there was considerable opposition to a wind farm offshore from 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.

2.1.3 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, or 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 balance or 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 positive.

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 and/or environmental costs on a product, and the government paying for research and development. 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 huge incentive for the production of oil, a 27.5% depreciation allowance taken off the bottom line of taxes.

2.2 DEFINITIONS 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:

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

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 in the U.S. what a *piano* is and he or she would likely understand the object, but to someone unfamiliar with the instrument, a piano might be described as "a big black box, you hit him in teeth and he cries." By the same token, therefore, 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 Joules, calories, British thermal unit (BTU), kilowatt-hours (kWh), and even barrels of oil. A very useful converter is the *Unit Juggler*, www.unitjuggler.com.

Natural gas is sold by the mcf (which is 1,000 cubic feet) and 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 (United States) or long ton = 2,400 lb, and 1 short ton = 2,000 lb. Metric tons (referred to as tonnes outside the United States) 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 kinetic energy (KE):

$$\text{KE} = 0.5mv^2 \tag{2.2}$$

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.

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

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.

$$E = Pt \tag{2.4}$$

Example 2.2

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

Example 2.3

Ten 100-watt light bulbs 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 measure of the potential for transfer of heat from a hot place to a cold place. Do not equate temperature to heat (energy). As an example of the difference between heat (energy) and temperature: Would you rather stick you finger in a cup of hot coffee, $T = 90°C$, or get hit by a high-speed proton, $T = 1,000,000°C$? One has much more energy that the other one.

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 [2], 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 because 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.

As an aside for the scientists and students of science, the following most famous equation says that mass is just a very concentrated form of energy. Conversion of a small amount of mass gives a lot of energy (e.g., an atomic or hydrogen bomb or a nuclear reactor).

$$E = mc^2$$

where c is the speed of light.

2.4 ENERGY DILEMMA IN LIGHT OF THE LAWS OF THERMODYNAMICS

There is not an energy crisis. Energy cannot be created or destroyed, only transformed to another form. Therefore, we have an energy dilemma in the use of finite energy resources and their effects 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. The other major aspect of the energy dilemma is the high energy content of liquid fuels for transportation, which means they are difficult or costly to replace.

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. Texas increased the speed limit on some highways to 129 kph (80 mph). In reality, to save energy, the United States should have a national speed limit of 105 kph (65 mph) on the interstate highways, and a reduction to 96 kph (60 mph) on interstate highways in the East.

2.4.2 Efficiency

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

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

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:

$$Eff = \frac{T_H - T_C}{T_H} \qquad (2.5)$$

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 $T_K = T_{\text{Celsius}} + 273$. 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 (973 K), and on the downside the steam is cooled by water to 300°C (573 K). The maximum efficiency possible is around 0.41 or 41%.

Because 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 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
Electricity to light (incandescent, CFL, LED)	5, 20, 30
Overall efficiency, coal to light	1.6, 6.6, 9.9

You can see why fluorescence lights, efficiency 15–25%, for commercial buildings and compact fluorescence lights (CFLs) and light-emitting diodes (LEDs), efficiency 25–50%, for your home are so important. Although, CFLs and LEDs cost more, the higher efficiencies mean a reduction for the need for new power plants. Countries, states, and even cities now have regulations for increased efficiency of lights, which means that incandescent lighting is being phased out. 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.

As a corollary to the second law efficiency, a system for producing energy must be a net energy gainer, the *energetics* of the system. Other terms for energetics are energy balance, energy return, or energy returned on energy invested. 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, especially irrigated corn from wells?

Prior to the oil crisis of 1973, industry and business maintained that efficiency was not cost-effective and that the GDP was tied directly to the amount of energy used. However, industry changed and the United States saved billions of dollars since 1973 by increased efficiency in industry and higher efficiency for transportation. Now higher efficiency for appliances, lights, and other aspects for homes are saving energy. However, much more conservation and efficiency has to be done in the coming decades.

An example of efficiency is cogeneration, today referred to as combined heat and power. In the production of electricity, the low-grade (lower-temperature) energy can be used for other processes. In most electric power plants where electricity is generated by steam (coal, oil, gas, and even nuclear), 60% of the heat is not used. Combined cycle gas turbines have higher efficiencies as heat from the first cycle is also used. In Europe, some electric power plants have heating districts associated with them.

Efficiency in transportation is an example of the difficulty in formulating a rational energy policy that would convert the world to sustainable energy within the environmental limitations. Every U.S. president since 1973 has called for energy independence, primarily due in reaction to the cost of imported oil. The financial crisis of 2008, with the automobile industry needing government money to operate in 2009, demonstrate the failure of past energy policies. 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–$1.4/L ($4–$5/gallon) before they would buy a fuel-efficient vehicle. Of course, Europeans have been paying those prices for quite a long period. Another note is that vehicles powered by fuel cells using hydrogen are much more efficient than

those with internal combustion engines. Why do we not have millions of those vehicles on the road today? It is not surprising that with oil over $100/bbl in 2008, the sale of fuel-efficient vehicles increased. Then again, as gasoline became cheaper in the United States, sales of fuel-efficient vehicles declines. The safety issue means everybody should drive a large SUV or a big pickup—to heck with fuel efficiency

Looking back, the obvious answer was to increase fuel efficiency and mandate a substantial tax on gasoline after the oil crisis of 1973. There was progress on fuel efficiency as in 1975 the U.S. Congress passed laws for corporate average fuel economy (CAFE) 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 on imported oil. The problem was that sports utility vehicles (SUVs) were counted as light trucks, and their fuel consumption is around 5.5 km/L (12 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. Under President Obama, an agreement reached in 2011 with major automotive manufacturers (except Volkswagen) was that the CAFE should be raised to 23 km/L (54.5 mpg) for cars and light trucks by 2025. However, President Trump is considering reducing that number. The European Union (EU) and Japan fuel economy standards for 2012 are around 19 km/L (45 mpg) and their proposed standards for 2025 will still be greater than that of the United States.

An interesting note: The big three U.S. automobile manufacturers have received over $\$2 \times 10^9$ in R&D from the government for the Partnership for New Generation of Vehicles [3]. The goal was a sedan for five people that would obtain 34 km/L (80 mpg). Later, automotive manufacturers said that there was no way to reach that goal. President G. W. Bush promoted 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 [4], strongly advocated hybrid cars and light-weight cars. Guess what? Hybrid cars entered the market in 2000 and in 2018 there are a lot of hybrid, plug-in hybrid, and electric vehicles on the market. A personal note, Nelson purchased hybrid models for a number of years and in 2012 bought an electric vehicle, a Nissan Leaf (average 6 km/kWh, range around 100 km), and then traded for another Leaf in 2017 (average 6 km/kWh, range around 160 km). Starcher owns a Toyota Prius (15 km/L).

In the United States, federal tax credits (2009) include a new tax credit, starting at $2,500 and capped at $7,500, for plug-in hybrid and electric vehicles. The first 250,000 vehicles sold by each manufacturer get the full tax credit, and then it phases out like the hybrid vehicle tax credits were phased out with more vehicles sold. Just think what the large numbers of hybrid and electric cars will do to help alleviate the present energy dilemma. Again, the question is: Where should the federal government place its incentives? It will 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? Our opinion is that an additional $0.15/l ($0.50/gal) tax on a gallon of gasoline would just about pay for Oil War II and the war in Afghanistan and would help drive purchases of more efficient cars.

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 higher oil prices, which will surpass the price of $100/bbl even with the production from oil shale formations.

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 2.5) 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 one.

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

$$T2 = 69/R \tag{2.6}$$

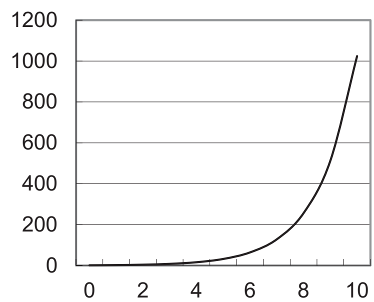


FIGURE 2.5 Exponential growth at growth rate of 100% per year.

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

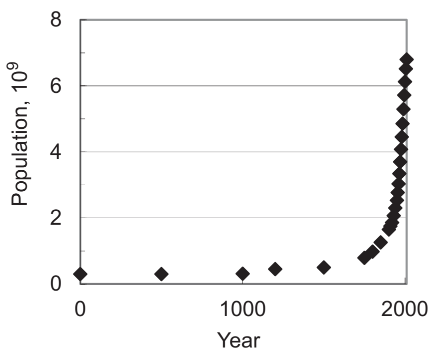


FIGURE 2.6 World population from year 0 to 2015.

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

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 2.6, only the time scale along the bottom would be different (Figure 2.6). The projection of the growth of population in the future (Figure 2.7) assumes the growth rate will decrease to 0.5% in 2050. The United Nations (UN) 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.

2.6 USE OF FOSSIL FUELS

Even though the recession of 2008 reduced demand for energy in the developed countries, the world demand increased from 510 EJ in 2007 to 607 EJ in 2016. Due to the increase demand in

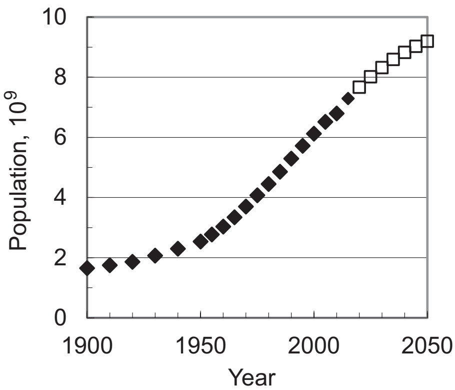


FIGURE 2.7 World population from 1900 to 2050 (UN projection for 2020 to 2050 under median variant).

China and India, consumption of fossil fuels (Figure 2.9) also increased because fossil fuels supplied around 75% of the total energy. As of 2017, the quantity of fossil fuels consumed per year is astounding; 36 Gbbls of petroleum, 3.6 Tm^3 of dry natural gas, and 8.2 Gt of coal. Then as the fuel is burned, the carbon content is emitted into the atmosphere as carbon dioxide. Note that in graphs of production, the area under the curve is equal the quantity consumed to that point. However, for the long term, it is physically impossible to continue to consume fossil fuels with exponential growth rates or even to continue at the present rate of demand due to the finite amount of the resource. Two excellent sources of energy data for the world, regions, and countries are the U.S. Energy Information Administration (EIA), www.eia.gov, and BP's Statistical Review of World Energy, www.bp.com.

2.6.1 Petroleum

The magnitude of the problem can be seen in the cost of imported oil in the United States (Table 2.3). In 1973, when petroleum consumption was 5.8 Gbbl/year and approximately 37% was imported, the cost was around $92,000,000,000 ($\$92 \times 10^9$) per year for oil at $42/bbl (if the cost is adjusted for inflation it would be higher, over $100/bbl in 2017 dollars). Even though imported oil was reduced in the 1980s, the cost for that imported energy was still quite expensive. In the 1990s, oil consumption and imports in the United States increased again (Figure 2.8). Due to the world financial crisis in 2008, petroleum consumption in the United States decreased to 6.5 Gbbl, with 62% imported at $100/bbl, for a cost around $\$400 \times 10^9$. The cost for imported oil reached $\$316 \times 10^9$ by 2007. The amount of imported oil reached 50% by the mid-1900s as demand was at a high of 7.2 Gbbl in 2005. However, U.S. production started increasing in 2009 and by 2017 the imports were down to 23% of demand. The price of oil has and will be very volatile, as from 2002 to 2018 it ranged from $27–157/bbl. With low oil prices importing nations received a break and most of the exporting nations were in trouble as oil was a major source of funding for the government. Notice that crude oil production and oil supply/consumption are different, as petroleum supply includes crude oil, natural gas liquids, plant liquids, and other liquids. Demand and imports decreased due to the recession of 2008, increased production of crude oil in the United States., and increased efficiency; thereby the cost of imported oil was reduced to $\$284 \times 10^9$ by 2016.

The advent of horizontal drilling and fracking to obtain oil and gas from shale formations has actually stopped the decline in production of oil and gas in the United States. This technology

TABLE 2.3
Estimated Yearly Cost of Imported Oil for United States

	Demand (Gbbl)	Pro (Gbbl)	Import (Gbbl)	$ bbl	Cost ($×10⁹)
1973	6.2	4	2.2	42	92
1990	6.1	3.52	2.61	37	97
2007	6.9	2.51	4.39	72	316
2012	6.0	3.17	2.78	102	284
2017	6.1	4.73	1.40	55	77

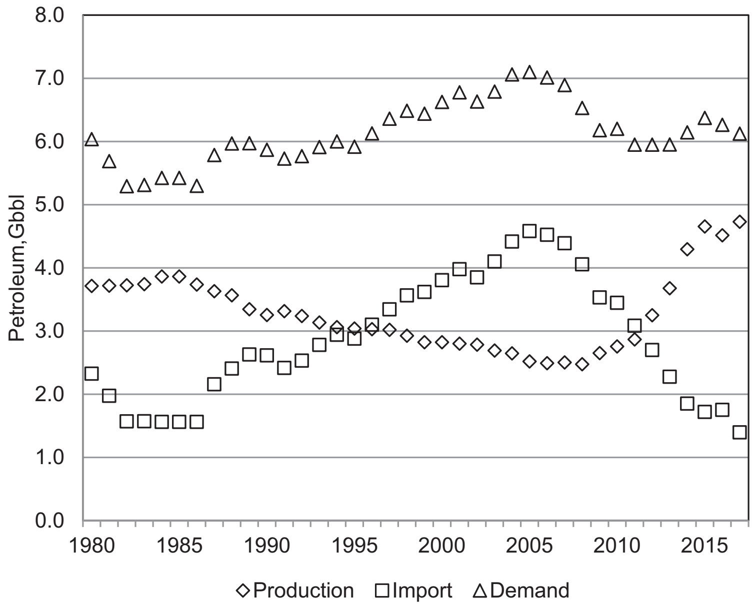


FIGURE 2.8 U.S. oil demand, production, and imports.

will then be used in other parts of the world to extend the time and amount of oil and gas production in the future. Note that the depletion rate from the shale formations will be faster than for conventional oil.

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 a resource can be made from past production, as production and consumption of a finite resource will probably be similar to the bell curve. M. King 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. conventional oil production would peak mid-1970s, and he was very close, as the actual peak occurred in 1970. Petroleum production then decreased until 2005 (Figure 2.8), even with the production from Alaska and offshore oil fields. The increase in production starting in 2006 has reached the levels of peak production in 1970 (Figure 2.8) and is expected to continue to increase until 2025, and after that date there will again be a declining rate of domestic production. The U.S. Energy Information Administration is predicting U.S. petroleum production in 2030 at 7.0 Gbbl for the reference case, compared with 4.7 Gbbl in 2017, which is over a 100% increase in production from the low values from 2004 to 2008.

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 that the resource is available. However, the end result is still the same.

World oil production [6,7] will follow the same pattern as oil production in the United States. Notice that the bell curve predicts world oil production (Figure 2.9) will peak around 2025. There are a number of websites on peak oil. The oil poster (www.oilposter.org, 2/21/2013) is very well done, and it shows the world oil peak at 2010. Future production is stretched out because it includes heavy oil, deep-water oil, polar oil, shale oil, and natural gas liquids, all of which will be more expensive. Note the cost of the BP oil leak (Horizon) in the Gulf of Mexico in 2010. 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. The U.S. EIA makes low, reference, and high forecasts for demand, production, and prices. Over the years, the range on price has been large, for example, price of oil for the reference case for 2030 was \$20/bbl (forecast 2000), \$45/bbl (forecast 2006), \$130/bbl (forecast 2013), and \$92/bbl (forecast 2018). For EIA predictions, U.S. and International, check the forecast and analysis section, www.eia.gov/analysis/.

2.6.2 Natural Gas

People are touting natural gas for vehicles (compressed natural gas) because of cost of imported oil, the predicted future decline of production of oil, and increased use of natural gas for generating electricity (because low price natural gas has less emissions). However, over the long term the problem is the same, a finite resource will be used fairly quickly [8] with increasing demand. The production of natural gas (Figure 2.10) is increasing across the world and production of natural gas in the United States surpassed Russia in 2011 due to increased production from shale [9]. The two countries produced 50% of world production in 1995 and 37% in 2016. Total production in the United States will be less as reserves are around 9 Tm^3 compared to Russia with 31 Tm^3. Present

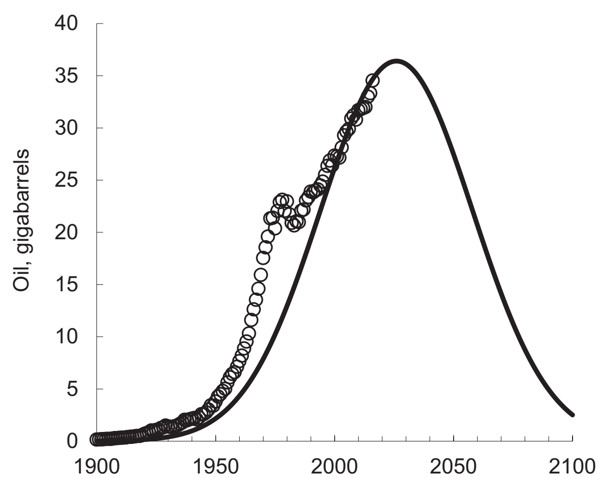


FIGURE 2.9 World oil production and predicted curve using bell curve.

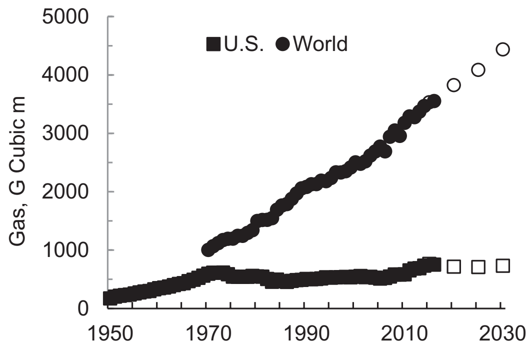


FIGURE 2.10 World and U.S. production of natural gas and predictions.

reserves in the United States would last less than 100 years at the 2017 rate of consumption, however, predictions are for increased consumption to the year 2030 by U.S. EIA. The peak of natural gas production will probably occur between 2030 and 2050. The production of natural gas in the United States from shale formations increased from 8% in 2007 to 50% in 2015. There was a corresponding reduction in a high price of $11/mcf in 2008, to a low of $1.79/mcf in May 2012. Even though it rebounded to $3.00/mcf in October 2012, low prices means a lower number of new gas wells.

Also, natural gas is an important feedstock for fertilizer and has also been promoted as the feedstock for a future hydrogen economy, both of which would require enormous amounts of natural gas. Carbon dioxide emissions in the United States have decreased since 2008 due to decreased demand and due to replacement of coal by natural gas for the production of electricity.

It is important to remember that new wells are needed for both oil and natural gas to replace decreased production from previous wells. More wells have been drilled in the United States than in any other region of the world, as U.S. drilling accounted for over 30% of the world total. Since 1949, over 2.7 million oil and gas wells (exploratory, developmental, dry) have been drilled in the United States., and around 850,000 are still in production. For example, Saudi Arabia has the largest oil reserves in the world and has only drilled around 11,000 wells [10 (Chap. 5),11].

2.6.3 Coal

Each fossil fuel industry touts the use of its product. The coal industry is promoting the sustainable development of coal and conversion of coal to liquid fuels. Clean coal, which is really stretching its total environmental impact, is the promotion of coal plants that sequester carbon dioxide. Coal provided 21% of the primary energy for the world (Figure 2.4) and 43% of global electricity.

Production of world coal (Figure 2.11) has increased to 8.2 Gtons in 2016, primarily due to increased production in China. China is the largest producer and consumer of coal. Eighty-six percent of electricity in China is provided by coal, and China is constructing new coal generation plants, planned for 450 GW by 2040. Also, coal provides a major portion of heating and cooking in China. The negative effects are the increased carbon dioxide emissions and environmental impacts as every major city in China has problems with air pollution (also due to their large increase in vehicles).

The United States has the largest coal reserves, 252 Gtons, and estimates are that it will last 200 years. Of course, use of coal produces pollution and carbon dioxide emissions. For more information, go to the U.S. EIA or for the industry viewpoint, check the American Coal Council, www.americancoalcouncil.org.

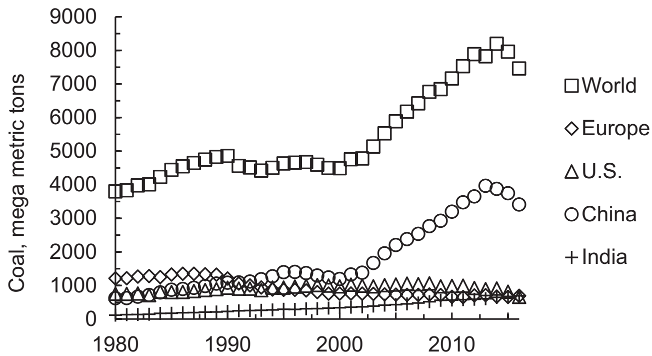


FIGURE 2.11 World and major producing nations coal production.

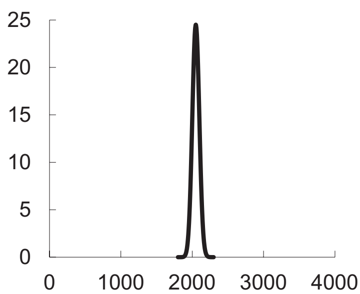


FIGURE 2.12 Fossil fuel exploration and use in human history from year 0 (project to 4000). Compare this graph with Figure 2.9.

In the long term, the use of fossil fuels could be called the "fickle finger of fate" (Figure 2.12). 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 2018 [12] there were 448 nuclear power reactors (capacity of 392 GW) in operation in the world, 58 (capacity 59 MW) under construction, and 166 in permanent shutdown. China is leading the way with 19 plants under construction. However, date of operation for many new plants will be some years away as the construction period is long and there may be delays.

In 2016, nuclear plants (plants or stations may contain more than one reactor) provided 2,617 TWh (Figure 2.13), 11% of global electricity with the largest percentage in France at around 72% from 58 reactors. The EIA is predicting the generation of 3,800 TWh for the world from nuclear power plants in 2030, around a 50% increase.

As of 2016, in the United States there are 61 plants (99 operating reactors, capacity 106 GW, production 806 TWh/year). There is a revival of interest in nuclear power in the United States with one new nuclear reactor online in 2016 and four plants (5.6 GW) under construction, and a number of applications for licenses.

The percentage of U.S. electricity from nuclear power declined from 23 to 20% as new electric plants produce electricity from natural gas, wind farms, and now solar photovoltaics is entering

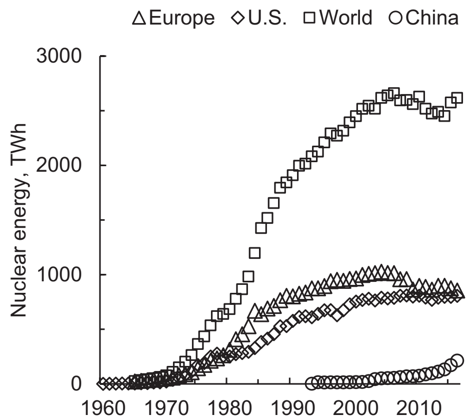


FIGURE 2.13 Production of electricity from nuclear power plants. Europe and the United States have a large portion of the total.

the market. Nuclear power has had a large amount of funding for R&D in the United States and continues to receive substantial federal funding, and now the industry is seeking federal funding for construction. The advantages of nuclear power are no carbon dioxide emissions and they furnish base load; however, thermal plants still need water, and the amount of uranium ore is finite. One solution is to construct breeder reactors.

The major disasters of civil nuclear power reactors are Three Mile Island, United States, 1979; Chernobyl, Russia (near Kiev, Ukraine), 1986; and Fukishima, Japan, 2011, due to a tsunami. The last two still have major exclusion zones due to radioactive fallout. The Fukishima reactors, lost capacity of 12 GW and resulted in all nuclear power plants in Japan being shut down for over a year. At the end of 2014, only two nuclear plants out of 48 that could be operational were back on line. However, by the end of 2017, 42 nuclear reactors were operational, two under construction, and 18 in permanent shutdown. After the accidents at Chernobyl and Fukishima, several countries in Western Europe are phasing out nuclear power, around 35 GW.

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:

$$r = r_0 e^{kt} \tag{2.7}$$

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

Example 2.6

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.

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

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):

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

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

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

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:

$$C = \int r\,dt = \int_0^T r_0 e^{kt}\,dt$$
$$C = \frac{r_0}{k}\left(e^{kT} - 1\right) \tag{2.8}$$

The cumulative consumption is the area under the curve, for example, world oil production in Figure 2.9; the estimated resource is the area under the predicted curve. Because those values were in a spreadsheet, the sums would give the total consumption to date and estimated total resource. Through 2016, the world had consumed 1,426 Gbbl of oil from an estimated resource of 2,800 Gbbl (this includes tar sands in Canada and heavy oil in Venezuela). What are the environmental impacts of using tar sands and shale oil?

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:

$$S = \frac{r_0}{k}\left(e^{kT_E} - 1\right)$$
$$T_E = \frac{1}{k}\ln\left(k\frac{S}{r_0} + 1\right) \tag{2.9}$$

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.

TABLE 2.4
Estimated 2016 Resources and Reserves

Resource	Amount
U.S. oil	48×10^9 bbl
U.S. natural gas	8.7×10^{12} m^3
U.S. coal	252×10^9 t
U.S. uranium (2008 data)	1.7×10^5 t @ \$80 kg
	13.8×10^5 t @ \$260 kg
World oil; includes heavy, sands, shale	1.7×10^{12} bbl
World natural gas	187×10^{12} m^3
World coal	1139×10^9 t
World uranium (2015 data)	2.1×10^6 t @ \$80 kg
	7.6×10^6 t @ \$260 kg

Sources: U.S. Energy Information Administration, www.eia.gov.
BP Statistical Review of World Energy June 2017, www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.
Uranium 2016: Resources, Production, and Demand, www.oecd-nea.org/ndd/pubs/2016/7301-uranium-2016.pdf.
t, metric tons; bbl, barrels, m^3, cubic meters.

Example 2.7

How long will conventional world oil last if consumption grows at 3%/year?
$r_0 = 30 \times 10^9$ barrels/year, $S = 1{,}700 \times 10^9$ barrels, $k = 0.03$
Place values in Equation (2.10):

$$T_E = \frac{1}{0.03}\ln\left(0.03\frac{1700*10^9}{30*10^9}+1\right) = 33\ln(2.7) = 33*0.99 = 33 \text{ years}$$

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
…	…	…
31	7.50E+10	1.55E+12
32	7.73E+10	1.62E+12
33	7.96E+10	**1.70E+12**
34	8.20E+10	1.78E+12
35	8.44E+10	1.87E+12

Bold is the year the resource is used up.

So at around 33 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.

The simplest estimate for T_E is to use estimated reserve and divide that number by the present annual consumption. Of course, as supply declines, prices will increase, and demand will decrease, so the T_E will be longer.

Example 2.8

There are around 1,700 Gbbl left of the world conventional oil, and at a rate of consumption of 34 Gbbl/yr, the lifetime is

$$T_E = 1{,}700/34 = 50 \text{ year}$$

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 CLIMATE CHANGE

Global warming is a good example that physical phenomena do not react to political or economic statements. For the first time in human history we are having an impact on the global scale, as global warming is primarily due to human activity.

The trend is to use the term "climate change" because it does not have same negative impact (political) as global warming. Some in industry and many politicians deny that there is global warming and some accept that there is global warming but deny that it is due to humans [13]. Some in industry maintain that we cannot reduce the production of CO_2 because of economics and because the science for CO_2 and global warming is not completely certain. Remember that the same comments were said about the ozone problem and addiction to tobacco.

For meteorologists, climate refers to the average of 30 or more years. Of course the climate has and will change, for example, there was the snowball Earth and the very warm Earth when the sea level was over 30 m higher than today. We are in the Holocene, an interglacial period beginning around 10,000 years ago and now we are entering the Anthropocene, the epoch where impact of humans is noted on a global scale. The results of this uncontrolled experiment will be within physical laws, and global warming due to increased greenhouse gases is one aspect. We will delineate between natural climate change and climate change due to humans by using *climate change-A*.

Glacial and interglacial periods [14] of the Earth are due to the changes in the orbit and the spin axis, which affect the geographical and seasonal distribution of insolation by as much as 10–20%, but hardly affect the mean annual solar insolation. The eccentricity of the orbit changes from zero to six degrees over a cycle of around 100,000 years, the tilt of the spin axis varies from 22.1° to 24.5° over a cycle of around 41,000 years, and the day in the year when the Earth is closest to the sun varies over a cycle of around 20,000 years due to precession of the tilt axis. These insolation changes, over long periods, affect the building and melting of ice sheets. Interglacial periods tend to occur during periods of peak solar radiation in the summer in the Northern Hemisphere. Glacial periods tend to occur with the Earth closest to the sun in January, which means warmer winters and cooler summers in the Northern Hemisphere, resulting in the building of ice sheets. Due to these changes, the Earth should be entering another glacial period, except it will not happen due to climate change-A. Paleoclimate data also show periods of fairly fast climate changes to a new state, primarily due to positive feedbacks.

The other aspect is the strong correlation between temperature and carbon dioxide in the atmosphere (Figure 2.14), methane in the atmosphere, and sea level. There is a lag time between temperature and carbon dioxide as expected for natural climate change, due to delay of carbon dioxide exchange with the ocean, which is several hundred years.

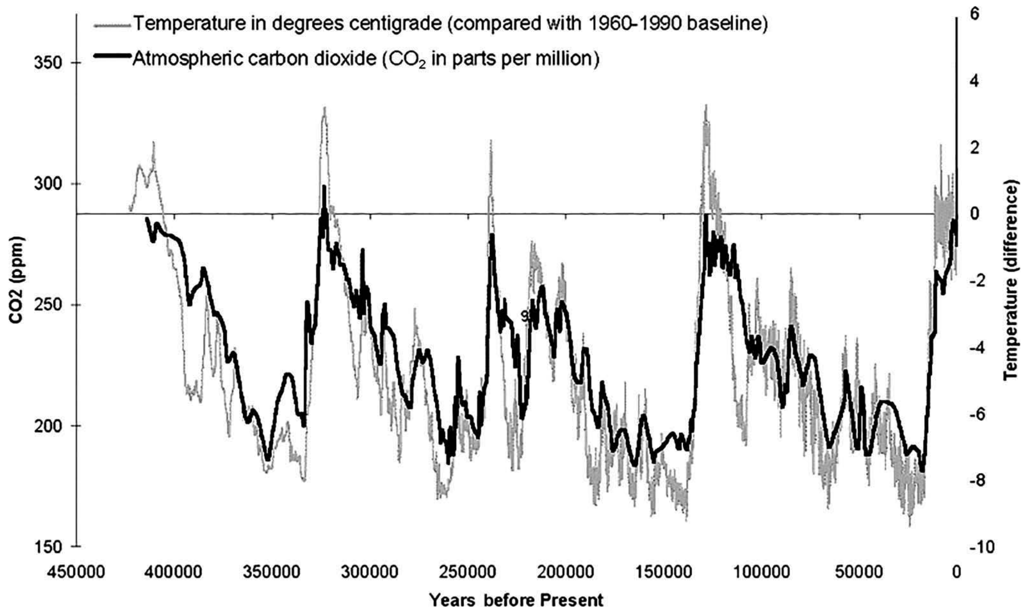


FIGURE 2.14 Temperature (°C) compared to carbon dioxide in the atmosphere. (Available at www.brighton73.freeserve.co.uk/gw/paleo/400000yearslarge.gif.)

2.10.1 Climate Change-A

The following facts are the background for information and comments on climate change-A.

1. The climate of past geologic ages has varied by a significant amount with temperatures ranging from −5°C to +5°C (−9°F to +9°F) from today.
2. The amount of carbon dioxide in the atmosphere has increased since the industrial revolution, primarily due to humans.
3. Changing the concentration of the greenhouse gases in the atmosphere will change the energy balance, i.e., the amount of heat retention and thereby the temperature of the atmosphere.
4. Oceans absorb carbon dioxide. An increase of carbon dioxide in the ocean results in more carbonic acid.
5. Sea level has risen by 0.2 m (8 in.) since 1900. Sea level is higher due to warmer water having more volume and the melting of ice sheets and glaciers.
6. Aerosols, such as sulfur dioxide, and other fine particles result in cooling due to reflection of incoming solar radiation. Major sources of aerosols are volcanoes and the dust produced by the burning of coal.

Knowledge of the interactions among the components in the system is a difficult scientific endeavor. Climate models are based on equations about energy and matter to simulate the atmosphere, oceans, land and sea ice, and vegetation cover. Climate models can be tested by using past data to compare observed climate with predicted climate. The models reproduce observed continental surface temperature patterns and trends, including the larger increase since 1950 and the cooling due to large volcanic eruptions [15]. Today's models are a fairly good, which means that they have incorporated most of the important factors and their interactions. However, they are still models, which are dependent on input. For example, two effects that are still a problem are the complexity of clouds and aerosols and the effect of increased temperatures on the melting of ice sheets. You must

remember that the predictions of regional climate are more difficult, however, check Figure SPM.8 [15, p. 22] for predicted changes for 2081–2100.

2.10.2 Greenhouse Effect

The atmosphere admits solar radiation and reduces infrared radiation from the surface from going out, thereby maintaining an energy balance with a higher temperature (Figure 2.15). The greenhouse gases and their concentrations in the atmosphere are water vapor (around 1%), carbon dioxide (0.04%), methane (0.00018%), nitrous oxides, and other trace gases. The amount of effect per molecule and the residual time differ for each, for example, methane (CH_4) is around 20 times more effective at holding heat in than CO_2, but its residual time is a few years. Note for the students, remember that temperature and heat are different as heat is thermal energy and temperature is an indicator of potential flow for heat (always from high to low temperature). The greenhouse effect is amply demonstrated on a sunny day by your car interior with the windows closed. The incident light passes through the windows and is absorbed by the material inside, which then radiates (infrared) at the corresponding temperature. The windows are opaque to infrared radiation, and the interior becomes hotter until there is again an energy balance.

The amount of carbon dioxide in the atmosphere changes the temperature at which the energy balance occurs. Venus, our sister planet, is a drastic example of a dense CO_2 atmosphere where the surface temperature is 467°C, hot enough to melt lead. Mars has lost most of its atmosphere because it has less gravity due to less mass. The comparison of the atmosphere for the three planets is interesting in terms of the difference in average temperature (Table 2.5). Note that the percent of CO_2 in the earth's atmosphere is very small, however another 100–200 parts per million (ppm) will result in a significant change in the temperature and thus climate-A.

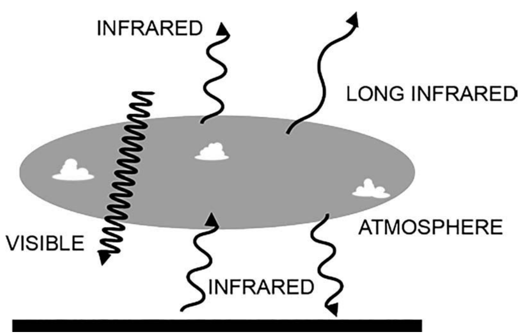


FIGURE 2.15 Greenhouse effect due to transmission, absorption, and emission of electromagnetic radiation.

TABLE 2.5
Comparison of Planets in the Habitable Zone of the Sun

	Temperature			
	°C	°F	Pressure (bar)	Carbon Dioxide (%)
Venus	467	873	92	96.5
Earth	7.2	45	1	0.04
Mars	–60	–80	0.004	95.3

2.10.3 Atmospheric Carbon Dioxide

There is an increase in carbon dioxide and methane in the atmosphere due to the increased use of fossil fuels, agriculture (deforestation and land use), and production of cement. Most scientists say the result is global warming and there will be other effects such as more extreme storms and melting of ice (sea, glaciers, ice sheets). There are a number of sites on the Web with information on atmospheric carbon dioxide and the effects on climate change-A.

The amount of CO_2 in the atmosphere before the industrial revolution was 275 ppm (Figure 2.16), now it is at 406 ppm, which means humans have increased the amount by 131 ppm. In 2017, the production of CO_2 from human activity was around 41 Gt/yr with around 37 Gt/yr from the burning of fossil fuels. The estimated total production of CO_2 from 1850 to 2017 is 2,100 Gt. In the early period, from 1850 to 1950, the primary sources were Europe, led by the United Kingdom, then the United States, however, China surpassed the United States as the largest emitter in 2008 (Figure 2.17). Now, most predictions on global warming and climate change-A are for problems (even catastrophe) by 2050–2100 unless carbon dioxide emissions for the world are reduced to 1990

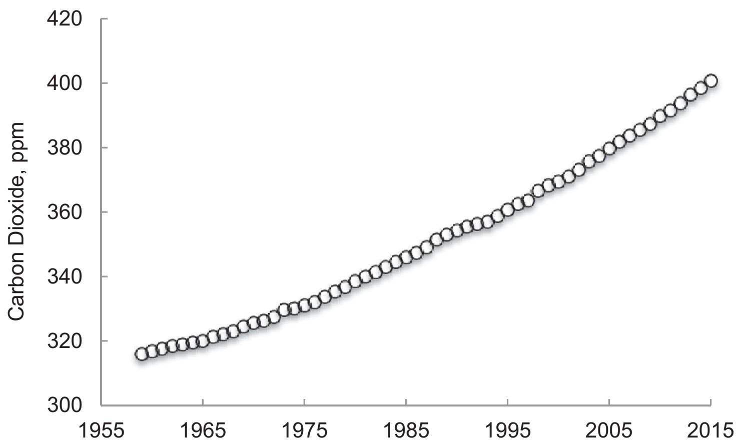


FIGURE 2.16 Annual mean atmospheric carbon dioxide concentration. (NOAA Mauna Loa data.)

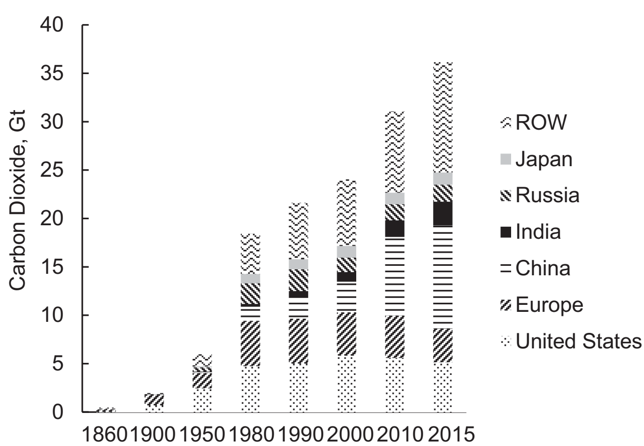


FIGURE 2.17 Carbon dioxide emissions from burning of fossil fuels.

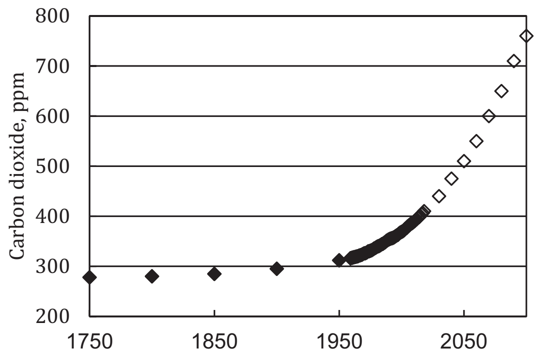


FIGURE 2.18 Carbon dioxide in the atmosphere and projected growth without emission reductions.

levels. Concentration of carbon dioxide in the atmosphere (Figure 2.18) are projected to double due to future energy use based on today's trends.

2.10.4 Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC), a scientific body under the auspices of the UN, was established in 1988 to assess the scientific information on climate change [16]. The IPCC reviews and assesses the most recent scientific, technical and socio-economic information and provides Assessment Reports (AR) from working groups and a synthesis report for policy makers. The IPCC does not conduct any research nor does it monitor climate related data or parameters. Thousands of scientists from all over the world contribute to the process on a voluntary basis.

Working Group I assesses the physical scientific aspects of the climate system and climate change [15]. Topics include changes in greenhouse gases and aerosols in the atmosphere; observed changes in air, land, and ocean temperatures, rainfall, glaciers and ice sheets, oceans and sea level; historical and paleoclimatic perspective; biogeochemistry, carbon cycle, gases and aerosols; satellite data and other data; climate models; climate projections, causes and attribution of climate change.

Working Group II assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adaptation [17]. The information is considered by sector (water resources, ecosystems, food and forests, coastal systems, industry, human health) and regions.

Working Group III assesses options for mitigating climate change through limiting or preventing greenhouse gas emissions and enhancing activities that remove them from the atmosphere. The costs and benefits of the different approaches to mitigation are analyzed, along with the available instruments and policy measures.

Some of the main points from the Synthesis Report are:

> Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history.
>
> Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen.
>
> Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane, and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are *extremely likely* to have been the dominant cause of the observed warming since the mid-20th century.

> Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive, and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks.
>
> Many aspects of climate change and associated impacts will continue for centuries, even if anthropogenic emissions of greenhouse gases are stopped. The risks of abrupt or irreversible changes increase as the magnitude of the warming increases.
>
> Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.

As part of the U.S. National Climate Assessment, a climate change report is mandated every 4 years. The executive summary of the latest report [17] states "This assessment concludes, based on extensive evidence, that it is extremely likely that **human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century**. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence."

2.10.5 Policy

International policy to reduce CO_2 emissions began with the Kyoto Protocol in 1997, whereby industrialized countries would reduce their CO_2 emissions by 5.2% compared to 1990 levels. After 55 countries signed, the Protocol entered into force in 2005, with the first commitment period being from 2008 to 2012, (now 192 parties have signed). President Clinton signed the Kyoto Protocol in 1998, however, the Senate never approved the treaty, so the United States was not a participant. The goal was to keep temperature below a 1.5°C increase by 2100.

There have been a number of meetings. A meeting in Lima in 2014 set forth a framework that would obligate major polluters to pay, however, China, India, and the United States indicated they would not ratify any treaty that will commit them legally to reduce CO_2 emissions. In 2014, the EU reached a binding agreement to reduce greenhouse gas emissions by 40% by 2030, compared with 1990 levels. They also agreed to boost (in a non binding commitment) the use of renewable energy to 27% in the total energy mix and increase energy efficiency to at least 27%. The meeting in Copenhagen, June 2015, provided explicit emission pledges by all the major economies, including for the first time, China and other major developing countries, however, there was no clear path toward a treaty with binding commitments. In 2017, President Trump withdrew the United States from the Paris Accord.

Under President Obama there was support for reduction of greenhouse gas emissions by the administration, however, there was strong opposition by many in industry and in Congress, especially from the republicans. In August 2015, President Obama and the Environmental Protection Agency (EPA) announced the Clean Power Plan, whereby the carbon pollution from the power sector in 2030 will be 32% below 2005 levels. The plan covers around 1,000 fossil fuel fired power plants. States and utilities will have 15 years to meet the final goal with mandatory reductions beginning in 2022. Of course, the reaction from industry and from a number of politicians was opposition; carbon reduction costs too much, will reduce jobs, low income people will have to pay more for electricity; it is against the constitution and states will file lawsuits against the plan; and finally the science behind climate change is uncertain and unproven, and emissions due to human activities do not have an impact. Under the Trump administration those regulations are being undone.

2.10.6 Information and Comments

From 1750 to 2018, CO_2 emissions to the atmosphere by humans were over 3,000 Gt and about 40% of these emissions have remained in the atmosphere. Predictions regarding temperatures depend on

abatement, when it occurs and at what level. The projected increase for 2100 with a medium level of abatement for temperature is 1.1°C–2.6°C and for sea level rise is 0.32–0.63 m. Projected increase for no abatement for temperature is 2.6°C–4.8°C and for sea level rise is 0.45–0.82 m [21, p. 23]. Another prediction is that a level of 500 ppm of carbon dioxide in the atmosphere by 2100 will increase the average temperature by around 3°C and the sea level will rise by 0.6 m. If tipping points are reached due to more positive feedback and a continued high rate of burning fossil fuels, then the temperatures and sea level rise will be higher. High scenarios would have sea level rise of 10 m, affecting millions of people living in low coastal areas. Note: a tipping point is where a new state is reached with higher temperature and even reducing CO_2 to previous values will not result in the same temperature.

A few say that the level of 450 ppm is too high and we must reduce it to 350 ppm [18, www.350.org], which can only happen with the drastic change of shutting down coal power plants or sequestering of CO_2 from those plants, or even the extraction CO_2 from the atmosphere.

The estimated lifetime of the greenhouse gases in the atmosphere are: Aerosols, weeks; methane, 10 years: nitrous oxide, 100 years: CO_2, half in 30–50 years and 15–40% after a 1,000 years. The residual time of carbon dioxide in the atmosphere means that the world will be warmer, even if we reduced carbon dioxide emissions to the 1990 levels within a few years. Therefore, the possible future paths are continued or even an increase of emissions (worst case), abatement of emissions to 1990 levels, mitigation, and adaptation (which will become more costly as we dither about abatement).

Around 10% of the land on Earth (1,480 Mha) is covered with ice and on the average around 7% of the ocean (2,300 Mha) is covered by ice. With rising temperatures there is less sea ice (Figure 2.19) and now the Northwest Passage across the Arctic Ocean is a reality. There are already conflicting claims on resources of the Arctic Ocean by the surrounding nations. The other major concern is the melting of glaciers and the ice sheets in Greenland and Antarctica. If the Greenland ice sheet melted, the sea level would be 7 m (23 ft) higher. Historical global concentrations of carbon dioxide of 400–650 ppm show sea levels around 22 m (72 ft) higher [19]. Just think how many people live at an elevation within 20 m of sea level. Where will they go, what are the costs, and who will pay?

The increased carbon dioxide in the ocean means a higher acidity that could have a detrimental impact on marine organisms and ecosystems. Laboratory experiments have shown that acidification has a negative effect on the growth of corals and other organisms that secrete carbonate. The consequences of increased CO_2 on marine organisms and ecosystems are not yet clear.

There is a large quantity of methane in ice, hydrates, in deep permafrost, and on the oceanic continental shelf where there are low temperatures and high pressure. A major scientific question involves the affect of higher temperatures on the emission of methane from the permafrost.

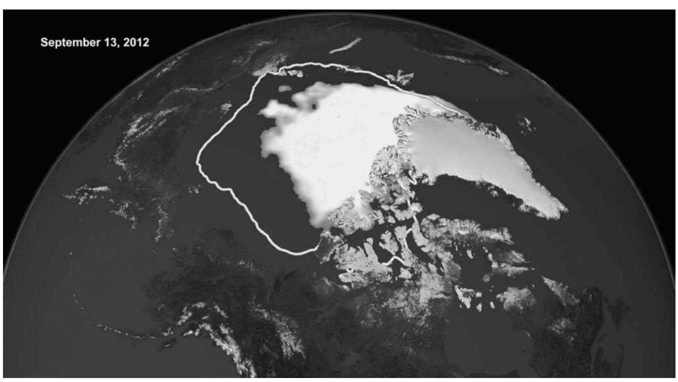


FIGURE 2.19 Arctic sea ice in September, 2012, compared to median extent 1979–2000 for September (white line). (https://earthobservatory.nasa.gov/Features/WorldOfChange/sea_ice.php?all=y.)

Will it be a major problem, driving climate change-A to a state of melting of the Greenland and Antarctic ice sheets? The amount of methane hydrates in the ocean is estimated to be larger than the combined oil, natural gas, and coal resources. There are two demonstration projects to mine the hydrates, Japan and Alaska. Models of permafrost dynamics and emissions indicate a relatively slow positive feedback, on time scales of hundreds of years. Again, there is a major scientific question: Will higher temperatures affect methane hydrates in the ocean?

2.10.7 Geoengineering

Because reducing greenhouse gas emissions is difficult, some scientists have proposed two general technological solutions, carbon dioxide removal and solar radiation management [20]. The capacity of the oceans to absorb carbon dioxide and the time frame is of major significance for the future climate.

1. Capture CO_2 from the atmosphere and sequester it in sedimentary formations or the deep ocean, dumping large amounts of iron in the ocean to create algae blooms (some of that carbon would finally be deposited in the deep ocean), and biochar to increase vegetation. Carbon dioxide removal by biological methods and most chemical weathering methods have physical or environmental limitations due to the need for implementation on a global scale and over a long period of time. A database of carbon capture and sequester (CCS) projects is available [MIT Carbon Capture & Sequestration Technologies. CCS Project Database. http://sequestration.mit.edu/tools/projects/index.html].
2. Reduce or reflect solar radiation by placing large amounts of sulfur dioxide in the atmosphere, make clouds whiter, place mirrors in space, paint all roofs white. These could modify the global water cycle and would not reduce CO_2 in the atmosphere.

Both methods have side effects and problem of unforeseen consequences to ecosystems. The IPCC states that there is insufficient knowledge to quantify how much CO_2 emissions could be partially offset by removal of CO_2 on a century timescale, however, to keep temperature increases within 2°C by 2100 would require removing CO_2 from the atmosphere.

If participant countries continue with emissions above the targets, then they are required to engage in emissions trading. Participating countries in Europe are using different methods for carbon dioxide trading, including wind farms and planting forests in other countries. Carbon dioxide emissions will still increase, even if nations reduce their emissions to 1990 levels, because of population growth and increased energy use in the underdeveloped world. As the Arctic thaws, methane, a more potent greenhouse gas than CO_2, would further increase global warming [21].

Increased temperatures and the effect on weather and sea level rise are the major consequences. Overall the increased temperature will have negative effects compared to the climate of 1900–2000. By 2100, sea levels are projected to increase by 0.2–1 m, with an increase of 2 m unlikely but physically possible. With positive feedback due to less sea ice and continued increase in carbon dioxide emissions, melting of the Greenland ice sheets would increase the sea level by over 7 m and the West Antarctic Ice Sheet would add another 5 m. Large cities on the coasts will have to be relocated or massive infrastructures will need to built to keep out the ocean. Who will pay for this, national or local governments?

2.11 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, transition to zero population growth and begin a steady-state society.

3. Place a tax on carbon.
4. 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 [22], 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 (next 15 years) 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 play for imported oil.
2. Increase substantially the use of renewable energy.
3. Reduce dependence on fossil fuels. Use of coal must include all social costs (externalities) and we need to sequester the carbon dioxide.
4. Reduce environmental impact, especially greenhouse gases.
5. Implement policies (incentives and penalties) that emphasize items 1 and 2.
6. Make use of nuclear energy. We are ambivalent about the expansion of nuclear energy.

State and local policies need to be the same. 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 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.

For a final comment, the possible futures for human society involve conservation and efficiency, transition to sustainable energy and a steady state with no growth, catastrophe, or catastrophe with some revival (Figure 2.20). As overpopulation and overconsumption are affecting the Earth, an uncontrolled experiment, the most probable future for population is catastrophe or catastrophe with some revival, especially as politicians and other decision makers primarily only respond to short term economics and concerns.

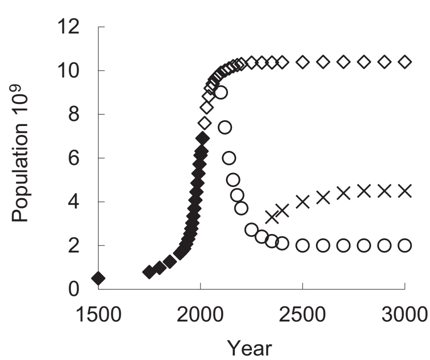


FIGURE 2.20 Possible future population paths.

GENERAL

A.A. Bartlett. 2000. An analysis of U.S. and world oil production patterns using Hubbert-style curves. *Mathematical Geology* 12(1) Available as pdf, http://jclahr.com/bartlett/20000100,%20 Mathematical%20Geology.pdf (1/5/2013).

L.R. Brown. 2009. *Plan B 4.0*. W.W. Norton: New York, London.

C.J. Campbell. 2005. *Oil Crisis*. Multi-Science Publishing: Essex, U.K.

Crossroads for Planet Earth, Special Issue. *Scientific American*, September 2005.

G. Daily and K. Ellison. 2002. *The New Economy of Nature*. Island Press: Washington, DC.

Energy for Planet Earth, Special Issue. *Scientific American*, September 1990.

T. Flannery. 2006. *The Weather Makers*. Atlantic Monthly Press: New York.

R. Heinberg. 2007. *Peak Everything*. New Society Publishers: New York.

M.T. Klare. 2004. *Blood and Oil*. Metropolitan Books: New York.

N. Lenssen. 1993. Providing energy in developing countries. In *State of the World 1993*, 101. W.W. Norton.

H.T. Odum. 1975. *Environment, Power and Society*. Wiley-Interscience: Ann Arbor, MT.

R.H. Romer. 1976. *Energy, an Introduction to Physics*. W.H. Freeman: San Francisco.

W. Youngquist. 1997. *GeoDestinies, the Inevitable Control of Earth Resources over Nations and Individuals*. National Book Company: Portland, OR.

S.A. Fouda. Liquid fuels from natural gas. *Scientific American*, 278: 92.

R.L. George. Mining for Oil. *Scientific American*, 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 the 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. 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.

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 2013 was around 7.1×10^9.
4. OM: If world population is 7×10^9, estimate how many years before the population reaches 28×10^9 at present rate of growth.
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 30×10^9 people?
7. OM: The population of the world is predicted to reach 10×10^9. 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 $4,000/kW?
10. OM: If electricity demand increases by 50% over the next 30 years for China, 50% of the new plants are to be powered by coal plants, 300 MW each. How many 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 30th 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 degrees 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 5% per year. How long will China coal last?
18. For your home, estimate the power installed for lighting. Then estimate the energy used for lighting for one year.
19. Estimate the energy saved if you converted your home lighting to LED lights. LED 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: Estimated world oil reserves are 2.1×10^{12} bbl. How long will that last at the present rate of consumption?
22. OM: Same as Problem 21, 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 250 million cars, which consume 10 million barrels of gasoline per day. Suppose the Chinese government goal has 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.

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.iea.org.

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.

Renewable Energy Data Book, US Department of Energy, Energy Efficiency & Renewable Energy. 2011. www.nrel.gov/docs/fy13osti/54909.pdf. Excellent source of information.

BP Statistical Review of World Energy. 2012. Has downloaded Excel workbook. www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

National Climate Assessment. Climate Change Impacts in the United States. https://nca2014.globalchange. gov.

REFERENCES

1. Interactions. http://hyperphysics.phy-astr.gsu.edu/hbase/forces/funfor.html.
2. K. Adler. 1986. The perpetual search for perpetual motion. *American Heritage of Invention and Technology*, Summer, 58.
3. G. Zorpette. 1999. Waiting for the supercar. *Scientific American*, April, 46.
4. A. Lovins. 1977. *Soft Energy Paths, Toward a Durable Peace*. Ballinger: San Francisco.
5. M. King Hubbert. 1969. Energy resources. In National Academy of Sciences, Ed., *Resources and Man*, pp. 157–242. W.H. Freeman: San Francisco. Also in “Energy Resources of the Earth,” *Scientific American*, 1971, 60.
6. K.S. Deffeyes. 2005. *Beyond Oil, the View from Hubbert’s Peak*. Hill and Wang: New York.
7. K.S. Deffeyes. 2001. *Hubbert’s Peak, the Impending World Oil Shortage*. Princeton University Press: Princeton, NJ.
8. J. Darley. 2004. *High Noon for Natural Gas*. Chelsea Green: White River Junction, VT.
9. B. Powers. 2012. *Cold, Hungry and in the Dark: Exploding the Natural Gas Supply Myth*. New Society Publishers: Gabriola Island, BC, Canada.
10. M.R. Simmons. 2005. *Twilight in the Desert: The Coming Saudi Oil Shock and the World Economy*. John Wiley: Hoboken, NJ.
11. Organization of Petroleum Exporting Countries. Annual Statistical Bulletin. Oil data: upstream, Table 3.3. OPEC, www.opec.org/opec_web/en/publications/202.htm.
12. World Nuclear Reactors. Energy Information Administration, USA. International Energy Statistics www.eia.gov Also Nuclear Energy Institute, www.nei.org/resources and World Nuclear Organization, www.world-nuclear.org.
13. N. Oreskes and E.M. Conway. 2010. *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warning*. Bloomsbury Press: New York.
14. NOAA National Climatic Data Center. Paleoclimatology. www.ncdc.noaa.gov/paleo/abrupt/data2.html.
15. Climate change 2013, the physical science basis, summary for policymakers, technical summary and frequently asked questions. 2013. IPPC Working Group I. www.climatechange2013.org/images/report/WG1AR5_SummaryVolume_FINAL.pdf.
16. Intergovernmental Panel on Climate Change. www.ipcc.ch/index.htm.
17. Climate change 2014. Impacts, adaptation, and vulnerability, summary for policymakers. 2014. IPPC Working Group II. http://ipcc-wg2.gov/AR5/images/uploads/WG2AR5_SPM_FINAL.pdf.
18. J. Hansen. 2009. *Storms of My Grandchildren*: *The Truth about the Coming Climate Catastrophe and Our Last Chance to Save Humanity*. Bloomsbury: New York.
19. *Global Weirdness; Severe Storms, Deadly Heat Waves, Relentless Drought, Rising Seas, and the Weather of the Future*. 2012. Climate Central, Pantheon Books: New York. Good source for high school teachers and students.

20. C. Hamilton. 2013. *Earthmasters, The Dawn of the Age of Climate Engineering*. Yale University Press, New Haven, CT.
21. S. Simpson. 2009. The peril below the ice. Scientific American, *Earth 3.0*, 18(2): 30.
22. M.T. Klare. 2001. *Resource Wars: The New Landscape of Global Conflict*. Metropolitan Books: New York.

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. Global circulation encloses eddies that enclose smaller eddies and the enclosures continue until finally the microscale is reached.

The two main factors in global circulation are solar radiation and the rotation of the Earth and Earth's atmosphere. Seasonal variation is due to the tilt of the Earth's axis to the plane of the Earth's movement around the sun. Because solar radiation is greater per unit area when the sun is directly overhead, heat is transported from the regions near the equator toward the poles.

Because the Earth rotates on its axis, and there is conservation of angular momentum, the wind will shift 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 disrupts the general flow. Also, the jet streams, the fast cores of the central westerlies at the upper levels, influence surface winds.

Local winds are due to local pressure differences and are influenced by the topography; friction with the surface due to mountains, valleys, and other features. 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 but 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. Earth's atmosphere can be considered a giant duct, and if energy is used at one location, it is not available elsewhere. Therefore, it is important to distinguish between the kinetic energy in the wind and the rates 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 is limited by the criterion of not changing the climate but the uncertainties surrounding such criteria are huge. Humans would have to substitute specific types of wind turbines for naturally occurring frictional features such as trees, mountains, and other natural features.

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 U.S. contiguous 48 states, the limit would be 2×10^{12} W (2 TW), or 62 quads/year. A similar analysis can be made for the entire world. The calculation shows that 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 available. The wind energy available represents approximately 20 times the rate of global energy consumption.

TABLE 3.1
Time and Space Scale for Atmospheric Motion

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

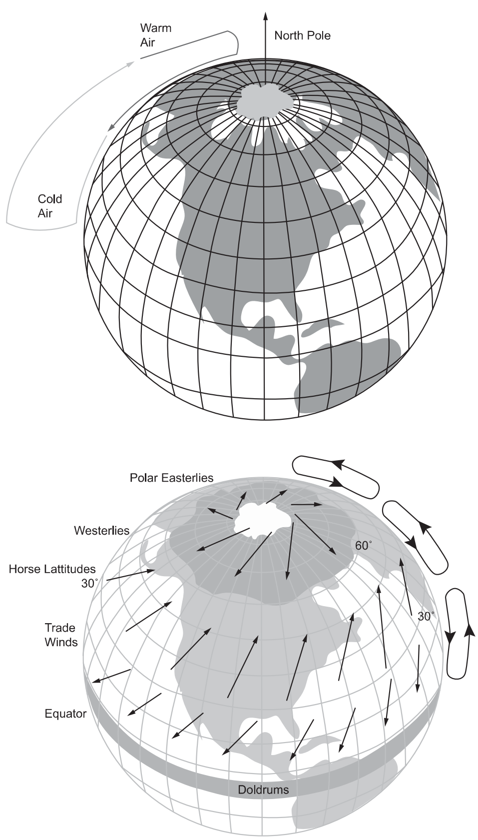


FIGURE 3.1 General atmospheric circulation in the Northern Hemisphere.

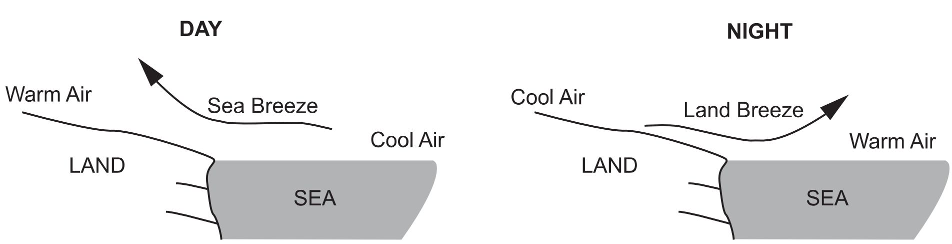


FIGURE 3.2 Sea breezes (day) and land breezes (night).

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 WIND POWER

The moving molecules of air have kinetic energy, so the amount of air molecules moving across some area during some time period determines the power locally (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:

$$P = KE/t = 0.5\ mv^2/t \tag{3.1}$$

$$\rho = m/V$$

$$V = \text{area} \times \text{length} = A \times L$$

$$m = \rho \times V = \rho \times A \times L$$

Substitute the 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

$$P = 0.5\rho ALv^2/t = 0.5\rho AL/tv^2 = 0.5\rho Avv^2 = 0.5\rho Av^3$$

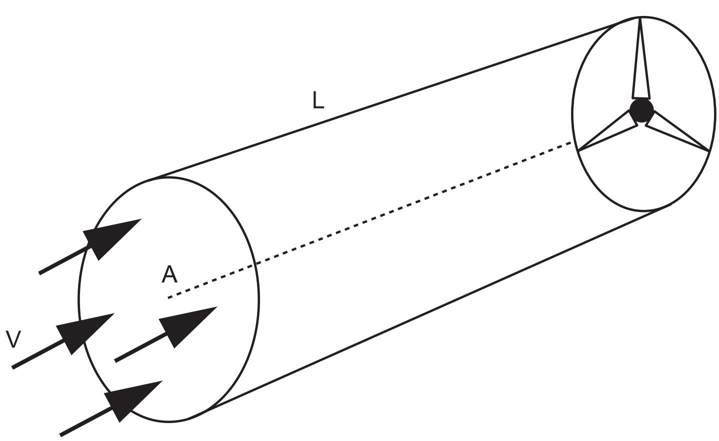


FIGURE 3.3 Flow of wind through a cylinder of area A.

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

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

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

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 eight 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, some damage to structures and trees occurs during severe storms and major damage is caused by tornadoes and hurricanes of class three and above. This is also the reason that 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/area can be calculated using the annual mean wind speed that can be estimated from the mean hourly speeds or other wind speed measurements. However, the 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 have annual average wind speeds of 6.3 m/s, but their annual average power potentials are 220, 285, and 365 W/m^2, respectively [2]. For a better estimate of the wind power potential for any extended time period, you must 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 hour 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 W/m^2. However, the power/area for the first hour is 62.5, and for the second hour is 1,687.5; 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:

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

where Pr = atmospheric pressure and VP = vapor pressure, both expressed as millimeters of mercury, and T = temperature in 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 and thus 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

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

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), Amarillo would have 10% less power for the same wind speeds. With the measurement of wind speed, pressure, and temperature, wind power/area can be calculated from Equation (3.2).

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

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

where P is in kW and time is in hours.

3.4 WIND SHEAR

Wind shear is a change in wind speed or direction over some distance (Figure 3.4) and it can even be vertical (Figure 3.5). The change in wind speed with height (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 speeds 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

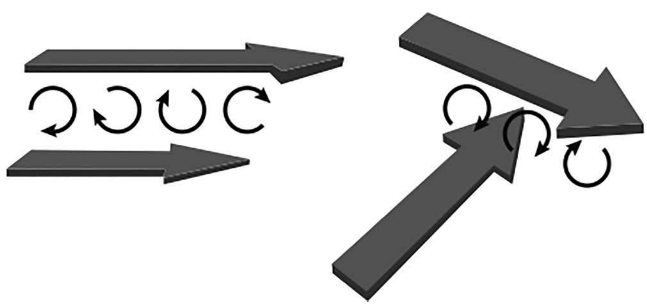


FIGURE 3.4 Left: Wind shear caused by a difference in wind speed with height. Right: Wind shear caused by a difference in wind direction.

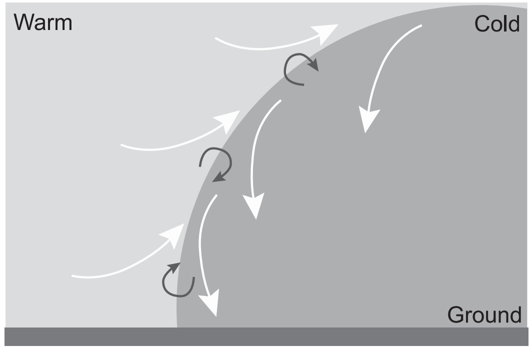


FIGURE 3.5 Example of vertical wind shear.

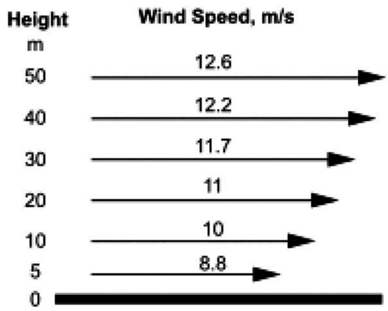


FIGURE 3.6 Wind shear, change in wind speed with height. Calculations are for known wind speed of 10 m/s at 10 m, $\alpha = 1/7$.

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. This is a convenient way to estimate power, so many wind maps show 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 and maps of wind power/area and average wind speed are available for 80 and 100 m heights.

The wind shear exponent values in continental areas will be closer to 0.20 for heights of 10 to 40 m and above, with large differences from low values during the day to high values at night. Measurements taken at heights of 10, 20, and 50 m for the northwest Texas region [3] for 12-hr periods (6–18 h spanning day and night) showed a large difference between 10, 20 and 50 m levels. Data for 16 sites in Texas and a site in New Mexico showed the same result: a change in diurnal wind speed pattern around 40 m [4]. Wind speeds were sampled at 1 Hz and averaging time was 1 hour.

The data were averaged by hour over a month, and the results 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). Other sites in the Central Plains of the United States show the same pattern [5].

Because wind speed is still increasing with height for these areas, 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 shifts in patterns between day and night wind speeds. Once data at 10 m and 40–50 m are compiled, wind shear can be used to predict wind speeds at higher levels. The higher night wind speeds mean more power; however, those hours also present less demand, so if a wind farm is selling at the market price, that energy may be worth less or even a negative value.

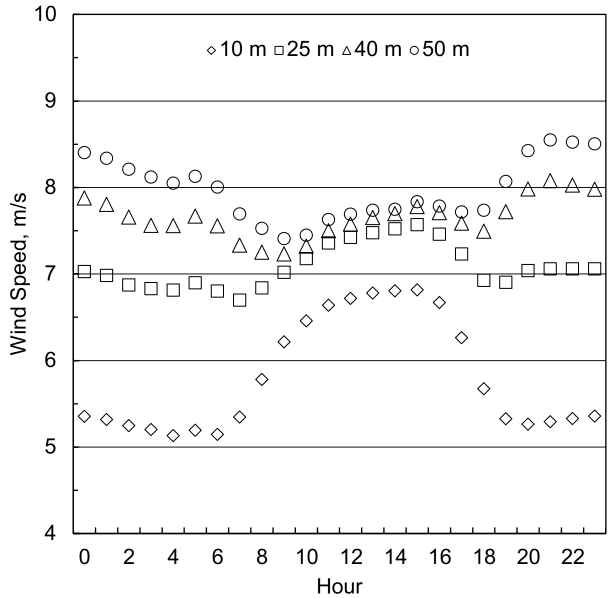


FIGURE 3.7 Annual average wind speed by time of day at 10, 25, 40, and 50 m heights, Dalhart, Texas, April 1996–2000.

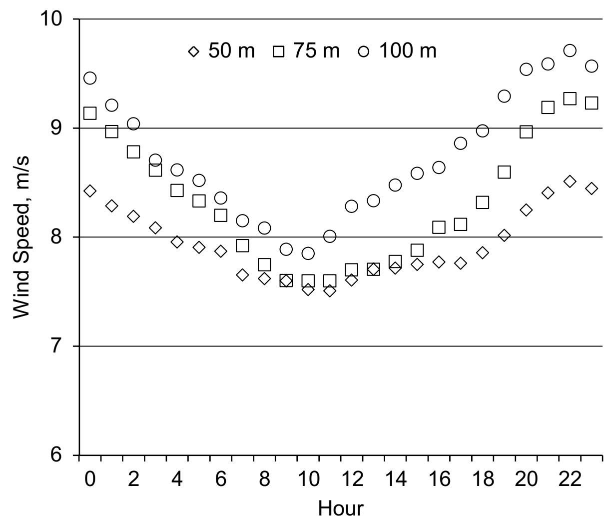


FIGURE 3.8 Annual average wind speed by time of day at 50, 75, and 100 m heights, Washburn, Texas, September 2003–2006.

The wind shear exponent changes from low values during the day to high values at night over a 24-h period (Figure 3.9). Time of day data were averaged over each month. The low values occur for more hours in the summer. Some locations, primarily mountain passes, demonstrate little wind shear (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 locations will vastly underestimate the power potential for wind farms. The other formulas for estimating wind speed with height are:

$$v = v_0 \frac{\ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H_0}{z_0}\right)} \tag{3.7}$$

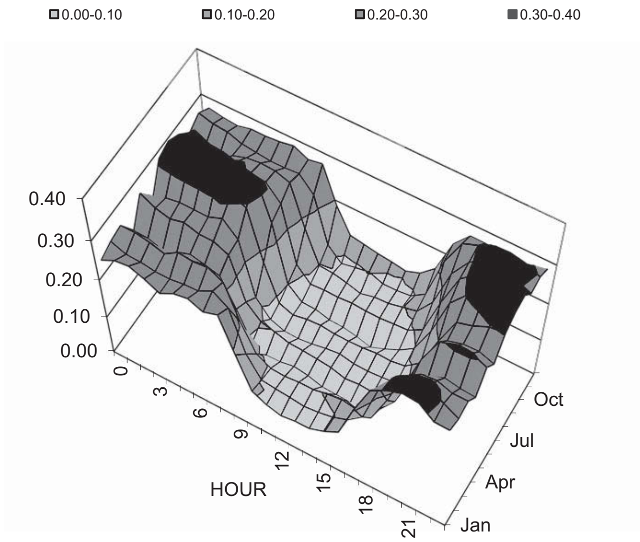


FIGURE 3.9 Wind shear exponent between 10 and 50 m for average month by time of day, Dalhart, Texas, April 1996–2000.

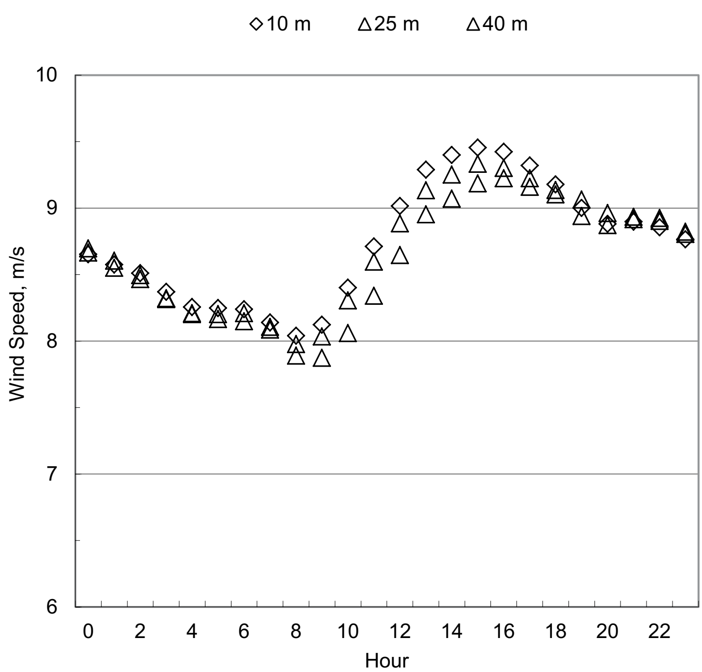


FIGURE 3.10 Annual average wind speed by time of day at 10, 25 and 40 m height, Guadalupe Pass, Texas, 1995–1999.

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

$$v = v_0 \frac{\ln\left(1 + \frac{H}{z_0}\right)}{\ln\left(1 + \frac{H_0}{z_0}\right)} \tag{3.8}$$

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 to 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 meteorology (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 $z_0 = 1.2$.

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

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 indicating percent of winds from a direction or a wind rose diagram (Figure 3.11).

Wind direction changes can also occur on a diurnal basis. However, a wind shear of change in wind direction with height is generally nonexistent or small, except for very short periods as weather fronts move through. Wind direction data (hour average wind speeds) from 16 stations in

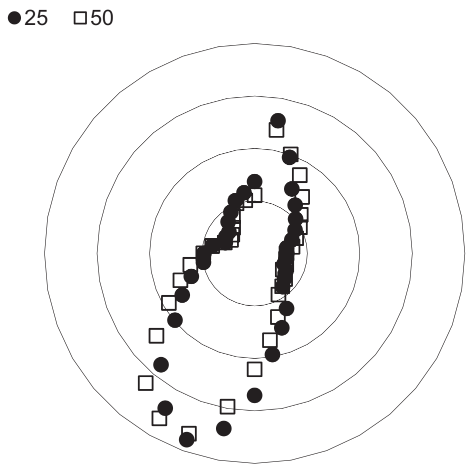


FIGURE 3.11 Annual average wind direction, 10 degree sectors, at 25 and 50 m height, Dalhart, Texas, April 1996–2000.

Texas and one in New Mexico [6] did not reveal 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 the relationship of wind speed, wind direction, and time of day for the 17 met stations, plus two tall-tower stations.

3.6 WIND POWER POTENTIAL

The most comprehensive, long-term source of data on wind speeds, pressures, and temperatures is the network of national weather stations in the United States. Other sources include the National Climatic Center in Asheville, North Carolina, Federal Aviation Administration stations, and U.S. military bases and Coast Guard installations. In the early 1960s, anemometers at national weather stations were moved from their previous locations (20–30 m heights) on airport control towers, hangers, and other structures to towers around 6 m height near runways and at least 1 km from buildings.

Wind speed data at U.S. National Weather Service (NWS) stations were recorded on strip charts and an observer estimated a wind speed over 1–2 min each hour. Hourly wind speed data along with pressure, temperature, and other climatological data were recorded on magnetic tape. The National Weather Service converted to automated surface observation systems in 1993 and 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 24 samples of 5-s each. Data on CD-ROMs, downloaded to a computer through the Internet, and monthly summary sheets can be purchased (http://lwf.ncdc.noaa.gov/oa/ncdc.html).

If the wind speeds are known, the average wind power or average wind energy per unit area can be estimated for any convenient period, usually months, seasons, or years. When more than a year of data are available, the year or month data are averaged to obtain annual values by year or month. The wind power per area is known as 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 average density, and the average power/area can be calculated for the available wind speed data. The result will be fairly accurate because the pressure and temperature will not vary over a month or year nearly as much as wind speeds vary.

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

If the observations of wind speeds are compiled into a histogram, the number of observations n_j in each wind speed bin may be converted 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 the wind speed changes due to height, 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 spreadsheet alleviates a lot of drudgery. Notice that the average wind speed (mean wind speed) is only a 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:

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

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

3.7 TURBULENCE

Winds vary by locations and times and are influenced by terrain, vegetation, and obstacles. In addition to mean wind speed, the variability of a set of data is represented by the standard deviation. For more detail, see Rohatgi and Nelson [7, chap. 9; 10]. The standard deviation for a set of wind speed data is:

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

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

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

In general, two different calculations are used: (1) the standard deviation of the average values and (2) 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, a standard deviation can be calculated for each bin. This is different from the standard deviation calculation of 1-Hz data that are averaged over 10 min or 1 h.

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

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

3.8 WIND SPEED HISTOGRAMS

A wind speed histogram shows the number of hours (or other time period used) the wind blew at each wind speed class (Table 3.5). Wind speeds were sampled at 1 Hz and averaged for 1 h. 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.

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 (%)	kWh/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		

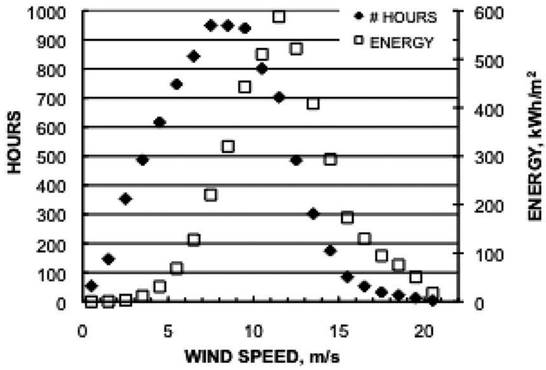


FIGURE 3.12 Annual average, comparison of wind speed and energy histograms at 50 m height, White Deer, Texas, 1996–1999.

The plots of the wind speed and energy histograms (Figure 3.12) show the relationship of wind and energy. There is little energy in low wind speeds because of the low speed, and little energy at high wind speeds because of the short durations of high wind speeds.

3.9 DURATION CURVE

Wind data can also be represented by a speed–duration curve (Figure 3.13) that plots 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 to the number of hours in a year by multiplying by 8,760. 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 h in a year for that location.

In general, whatever the wind speed is at any point in time, the behavior over the next hour should be similar. This is called persistence, calculated as $v(t + t_0) \sim v(t_0)$, where t is variable. However, a histogram does not give a time sequence of data, nor does a wind speed–duration curve indicate the lengths of calm periods. Now wind farm operators and utilities use forecasting programs for predicting wind speeds, average variations by season and time of day, durations of low wind speeds, and values for the 1–36 h ahead.

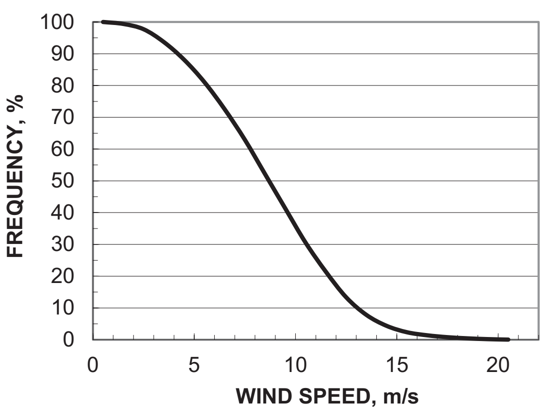


FIGURE 3.13 Wind speed duration curve at 50 m height, White Deer, Texas, 1996–1999.

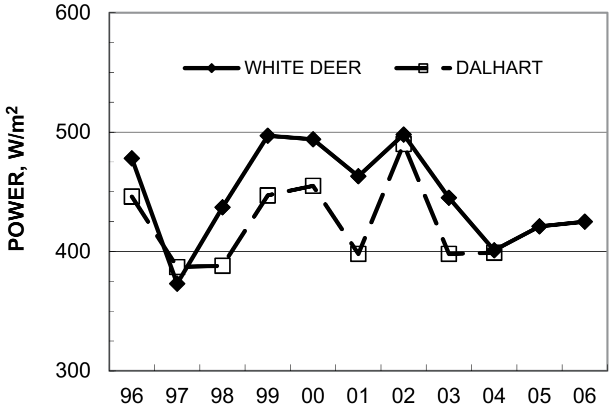


FIGURE 3.14 Annual variation of wind power potential at 50 m for White Deer and Dalhart, Texas.

3.10 VARIATIONS IN WIND POWER POTENTIAL

Because 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 W/m^2 for 1962–1977 [8]; however, variations from one year to the next can be quite large. A minimum of 2 years of data is required to obtain an estimate for annual wind power potential, and 5 years of data are needed to obtain a mean value within 6% of the long-term mean. Many researchers assume that 2 or 3 years of data suffice when combined with longer term regional data for comparison to determine wind power potential.

The annual wind power potential (Figure 3.14) for White Deer and Dalhart, Texas, shows the correlation between sites that 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 to 2 years of data would suffice for determining wind power potential at a specific location with similar surface conditions.

The seasonal variation for most of the United States constitutes high wind speeds in the spring and low wind speeds in the summer (Figure 3.15). Notice that 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 standard deviation of wind speeds for an individual month (744

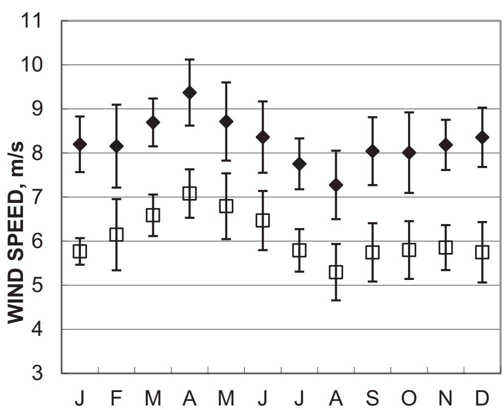


FIGURE 3.15 Annual wind speed and standard deviation by month at 10 and 50 m for White Deer, Texas, 1996–2006.

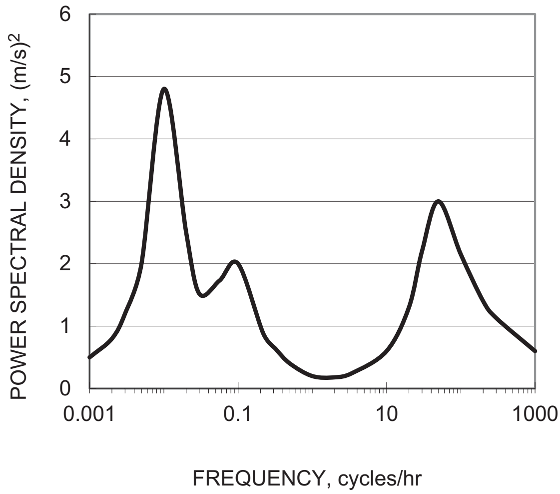


FIGURE 3.16 Example of power spectrum for wind speed. (I. van der Hoven [7]).

data points). The most notable exception to general seasonal variation occurs in the mountain passes in California between the coast and inland deserts. The windy season corresponds to heating of the deserts in the summer when 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 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 [9]. The peak at 0.01 cycle/h corresponds to a period of 100 h that represents the 4- to 5-day variation. The peak near 0.1 cycle/h corresponds to the diurnal variation.

During the investigation of power storage for a wind–diesel system, an appropriate wind speed power spectrum became a significant issue [10]. A power spectrum was developed from 13 years of hourly average data, 1 year of 5-min average and gusty day data, 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) in 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 diurnal peaks in the continental areas of the United States. The Van der Hoven spectrum is not really useful for the wind turbine industry.

3.11 WIND SPEED DISTRIBUTIONS

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

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

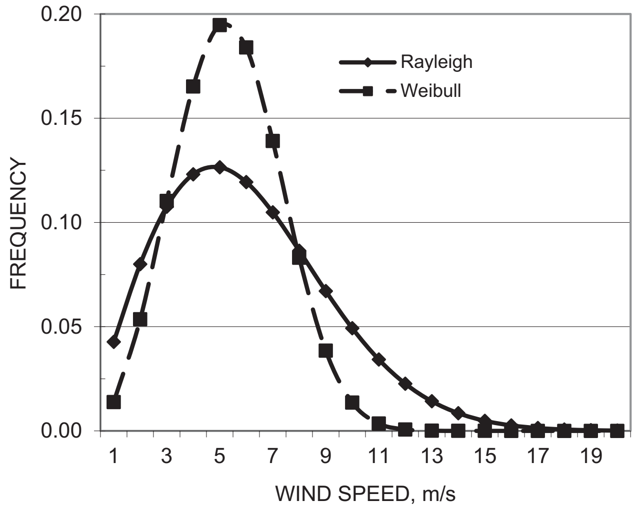


FIGURE 3.17 Example of wind speed frequency calculated using Rayleigh distribution and Weibull distribution.

where $F(v)$ = frequency of occurrence associated with each wind speed v 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 $8{,}760 \times F(v)$. The Rayleigh frequency is calculated for two different values, $v = 3$ and 9 m/s; $v_a = 8$ m/s and $\Delta v = 2$ m/s:

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

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

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 may have to be renormalized by bin value × 8,760 (sum of observations).

The Weibull distribution is characterized by 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, wind speed data are sparse. If only the average wind speed by day or month is known, the average values and their deviations are used to estimate the two parameters. Rohatgi and Nelson [7, Chap. 9] estimated the Weibull parameters by three methods: (1) a plot of c and k from log–log paper, (2) analysis of standard deviations, and (3) 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; both used a bin width of 1 m/s.

The energy pattern factor is rarely used. It is an estimate of the variability of wind speed calculated as the relationship 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, varies from 1.6 to 3.4.

3.12 GENERAL COMMENTS

Previous studies of wind behavior were performed by meteorologists who were mainly interested in weather and wanted to research turbulence and momentum transfer. Since 1975, numerous studies of wind characteristics have been funded because they pertain to wind energy potential and effects on wind turbines.

Most U.S. research was conducted by the Battelle Pacific Northwest Laboratory (PNL) and then transferred to the National Wind Technology Center (NWTC) of the 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 wind energy potential. For more data after using the national atlas, contact your state energy office or the American Wind Energy Association in the United States.

National laboratories in many countries in the European Union took the same steps, for example, the Danish laboratory in Risoe. To obtain information from other countries, the procedures are the same: contact national entities, universities, institutes, and state, national, and international wind energy associations.

Now that wind farms affect the grid, power system operators and wind farm operators require wind forecasting data [11] to improve their economics. Private companies and national laboratories have and are developing models to forecast wind resources over periods from one hour to a day ahead. Grid operators use temperature forecasts to predict demand and now use wind forecasts to anticipate wind generation levels and adjust their generation units accordingly.

Current-day and next-day graphs of forecast and actual wind power production [12] are available online for the transmission system of the Electric Reliability Council of Texas. Improved short-term forecasts allow wind farm operators make better day-ahead market decisions. Also, forecasting systems will help warn of extreme wind events and most U.S. wind farms now receive such forecasts.

QUESTIONS/ACTIVITIES

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

PROBLEMS

Use a 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 area diameters of 5, 10, 50, and 100 m. 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 20 and 50 m. Use the power law with 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 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 exponent $\alpha = 0.20$.
6. The George Bush Intercontinental Airport in Houston 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 an altitude of 3,000 m?
8. In the Great Plains, temperatures differ widely between summer (100°F) and winter (–20°F). What is the difference in air density? Assume you are at the same elevation and average pressure is the same.

   Note: For problems with wind speed distributions, remember the wind speed must be the number in the middle of the bin. If you use a bin width of 1 m/s, 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 from 0 to 20 m/s 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 from 0 to 20 m/s 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 from 0 to 20 m/s 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 speed is 5 m/s or more?
13. From Figure 3.13, what is the percent of the time the wind speed is 12 m/s or more?
14. For 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 wind power/area for $j = 5$ bin and 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 the 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 $\Delta v = 2$ m/s.
22. Go to the ERCOT site for forecast wind power data. Using the current date, note date, time, forecast, and actual wind power production.

LINKS

National Climatic Center Wind Data. http://lwf.ncdc.noaa.gov/oa/ncdc.html.
National Wind Technology Center. https://windexchange.energy.gov.

REFERENCES

1. M.R. Gustavson. 1978. Wind power extraction limits. In V. Nelson, Ed., *Proceedings of National Conference of the American Wind Energy Association*, p. 101. AWEA: Washington, DC.
2. D.L. Elliott et al. 1986. *Wind Energy Resource Atlas of the United States*. DOE/CH 10093-4. http://rredc.nrel.gov/wind/pubs/atlas/atlas_index.html.
3. E. Gilmore. 1987. Wind characteristics: Northwest Texas region, May 1978–December 1985. Report 87-1, Alternative Energy Institute, West Texas A&M University: Canyon, TX.
4. T. Han. 2004. Wind shear and wind speed variation analysis for wind farm projects for Texas. *Master's Thesis*, West Texas A&M University: Canyon, TX.
5. M. Schwartz and D. Elliott. 2006, Wind shear characteristics at Central Plains tall towers. NREL/PR-500–39989. www.nrel.gov/docs/fy06osti/39989.pdf.
6. K. Herrera. 2006. Wind direction analysis for Texas. *Master's Thesis*, West Texas: A&M University: Canyon, TX.
7. J. Rohatgi and V. Nelson. 1994. *Wind Characteristics: An Analysis for the Generation of Wind Power.* Alternative Energy Institute, West Texas A&M University: Canyon, TX.
8. V. Nelson and E. Gilmore. 1974. Potential for wind generated power in Texas. Report NT/8. Governor's Energy Advisory Council of Texas: Austin, TX.
9. I. Van der Hoven. 1957. Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour. *Journal of Meteorology,* 14: 160.
10. E.D. Eggleston. 1996. Wind speed power spectrum analysis for Bushland, Texas. In *Proceedings of Windpower Conference*, p. 429.
11. D. Lew, M. Milligan, G. Jordan et al. 2011. The value of wind power forecasting. NREL/CP-5500–50814. www.nrel.gov/docs/fy11osti/50814.pdf.
12. ERCOT. Forecasted and actual wind power production. www.ercot.com/gridinfo/csc/.

4 Wind Resource Assessment

The two aspects of wind resource assessment are: (1) determination of general wind power and (2) determination of wind power potential and predicted energy production for wind farms. Wind resource assessment for wind farms will be covered in Chapter 9.

General wind power potential was determined from available wind speed data, wind maps were then developed. In general, the old available wind speed data covered heights of 6–20 m; however, some anemometers were on tops of buildings or control towers at airports and their heights influenced 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 is the standard for world meteorological data. 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.

First maps were primarily average wind speeds, which are only an indicator of wind power. Then maps were developed for wind power per area (W/m^2) divided into classes, interactive maps, and now geographic information systems (GIS) with select and query functions. Height has also evolved from 50 m to over 100 m. Different terms are wind resource potential, wind power potential, wind energy potential, and wind capacity potential based on power/area and assumptions on turbine density (MW/km^2), area available, and somewhat on turbine specific power/area (kW/m^2). So, potential values will be for gross, technical (with exclusions), and economic assumptions on levelized cost of energy. The gross and technical estimates are enormous and will never be developed, and even the economic forecasts may be optimistic.

A world wind map that showed the wind classes at 50 m height for typical open, well-exposed sites was prepared by the Pacific Northwest Laboratory using data compiled in 1980 [1]. The assessment was made by critically analyzing available wind data and previous assessments to estimate the broad-scale distribution of wind power potential. Many data were used cautiously because of the lack of information about anemometer height and exposure.

Global pressure and wind patterns, upper air wind data, and boundary layer meteorology were also used to obtain consistent estimates of wind energy resources. Actual wind speed frequency distributions were used when available or Weibull distributions were used to estimate the wind power potential. If only mean wind speeds were available, Rayleigh distributions were used.

Most general results were known, for example, the presence of strong trade winds which are from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. At mid-latitudes (about 40–60 degrees) the flow is westerly, and strong westerlies circle the world throughout each year in the Southern Hemisphere. The flow creates strong winds at the tip of South America, the southwest coast of South Africa, the southern coast of Australia, the island of Tasmania, and New Zealand. The flow of the westerlies in the Northern Hemisphere is broken up by 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 very broad and should be viewed with caution when estimating wind power potential. Country, state, and regional maps, formulated from better data and at much higher resolution, are now available for many parts of the world. The National Renewable Energy Laboratory (NREL) maintains a map search site [2].

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 have nothing to do with world wind maps or estimations of world wind power potential.

Archer and Jacobson [3] quantified the world's wind speeds in 2000 as indications of wind power potential at 80 m height. 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 revealed class 3 (mean wind speeds ≥ 6.9 m/s) and above winds at 80 m suitable for wind farms. This is a conservative estimate; for example, India does not show any winds above class 2 and 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 wind class. Again, these maps should be used with caution as mean wind speeds are only indications of wind power potential and mean wind speeds are only shown for 1 year; however, they are considered representative of the 5-year period from 1998 to 2002.

REmapping the World, a project for renewable energy resource assessment, will provide information to individuals and to governments. The interactive map provides global wind data at heights of 20, 50, and 80 m at 15-km resolution for a single year. It estimates that 40% of the Earth's land mass has wind speeds of 6 m/s or more. The global wind map can be downloaded at Vaisala, www.vaisala.com/en.

As more data have been collected specifically on wind power potential for nations, states, and regions, digital wind maps are now available. They display 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 heights of 50 m and higher are still being collected to provide regional databases. Anemometer loan programs were available for private individuals in some states in the United States, and after some period, the data generally become public.

Computer tools for modeling wind resources have been developed by a number of groups including the National Wind Technology Center (NWTC) of the National Renewable Energy Laboratory (NREL) in the United States, WAsP developed by Risø, National Laboratory, Denmark, and private industries. Information from AWS True Power about the Northwest Wind Mapping Project describes the mapping 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 and 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 that adjusts short-term site measurements to long-term climatological norms.

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 3–7%.

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 cover the United States. However, the earlier maps did not account for 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 had fairly large potential. The problem is that most of these values were estimated from data taken at a height of 6–10 m, with the value at 50 m estimated to be double that at 10 m.

The Pacific Northwest Laboratory (PNL) oversaw a comprehensive assessment of wind energy potential. The Wind Energy Resource Atlas covered the United States and its territories [4]. 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). The atlas and the wind maps were updated in 1985 [5]. The different wind power maps show similar gross features. Regions of better wind power are in the Great Plains, along the coasts, in Hawaii, and at selected geophysical sites such as ridges, mesas, and mountain passes.

Then PNL transferred to the National Wind Technology Center (NWTC) of the National Renewable Energy Laboratory (NREL) and now information from new data and better models are available online. NREL uses geospatial data science [6] modeling to develop models and tools, which includes maps (Figure 4.1) in digital format, for professionals, developers and consumers. National wind maps are also available through WINDExchange [7]. There are wind speed maps for 80-m utility scale and maps of wind energy resource potential for 80 and 100 m. Geographic information systems (GIS) provide wind maps with selected overlays, for example, transmission lines, roads, parks, and wildlife areas, to assist in wind resource assessment. The higher resolution of the new maps allows better assessments of wind farm locations and also shows higher class winds in areas where none were thought to exist.

- Annual wind speed at 30 and 100 m, annual offshore at 90 m
- Wind resource land at 50, 80, and 100 m, offshore at 90 m, land and offshore at 80 m
- Potential wind capacity at 80 and 140 m
- Installed wind power capacity (data from American Wind Power Association)

States maps (https://windexchange.energy.gov/states) can be filtered by wind turbine height.

- 30 m residential
- 50 m community (Figure 4.2)
- 80 m land based
- 90 m offshore
- 110 m potential
- 140 m potential

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
4	200	5.6	400	7
	250	6	500	7.5
5	300	6.4	600	8
	400	7	800	8.8
6	400	7	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.

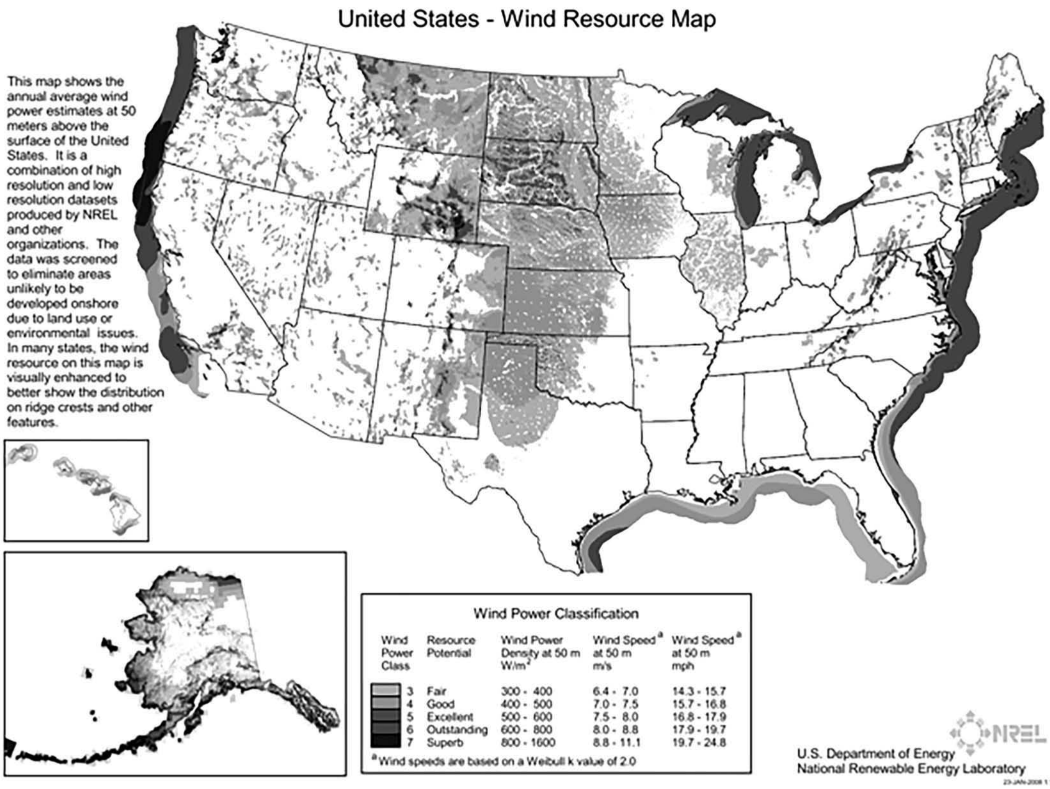


FIGURE 4.1 Wind power map for the United States. (National Renewable Energy Laboratory.)

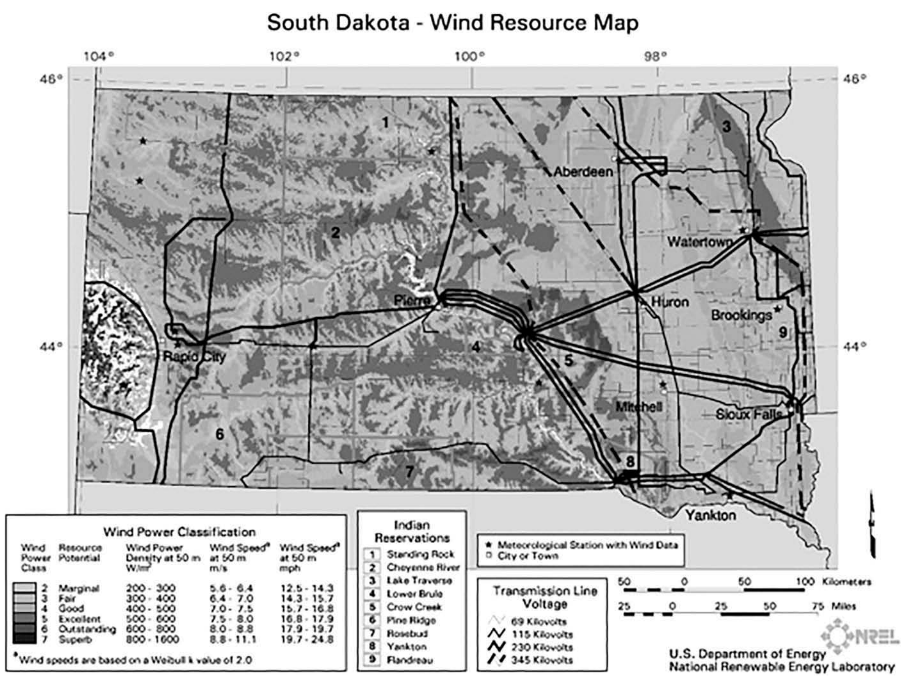


FIGURE 4.2 Wind power map with terrain enhancement for South Dakota. (National Renewable Energy Laboratory.)

WINDExchange provides Small Wind Guidebook, Wind for Schools Portal, and Wind Working Group Toolkit through openEI resources. Wind power capacity potential is estimated for 80 m by a wind turbine density of 3 MW/km^2 (8 MW/mi^2) after excluded land area. In 2017 the installed capacity of the United States was 89 GW, which compares with the potential capacity of 10,640 GW, a tremendous resource (https://windexchange.energy.gov/maps-data/321).

Wind Prospector is a powerful GIS application for resource assessment and data exploration for wind development [8]. The two main areas are (1) interactive select and query and (2) wind power analysis and wind resource data download (point or box). The GIS data layers are county & state borders, environmental concern, infrastructure, land ownership, regions & study areas, site analysis, topography, wind resource, and distributed wind resource. Within each selected layer there are sublayers, for example, under wind resource you can see wind power class (exclusions applied). Some of the layers have not been updated, for example, wind farm sites, however, for wind resource and wind potential Wind Prospector is very useful.

NWTC had a program of collecting data on tall towers, up to 100 m. The data from the 13 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 two winds that were presumed to have little potential for wind farms have now become viable if they are near large load centers.

4.2 EUROPEAN UNION

The Europeans made concerted efforts to assess wind resources beginning with the publication of the *European Wind Atlas* [9] in 1989. Part I provides an overall view of wind resources. Part II provides information for determining wind resources and siting wind turbines. It also 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 from landscape features such as coastlines, forests, hills, and buildings. Part III explains the meteorological background and analysis methods used to prepare the atlas and includes the physical and statistical bases for the models. Details of the Wind Atlas and Application Program (WAsP) are also provided.

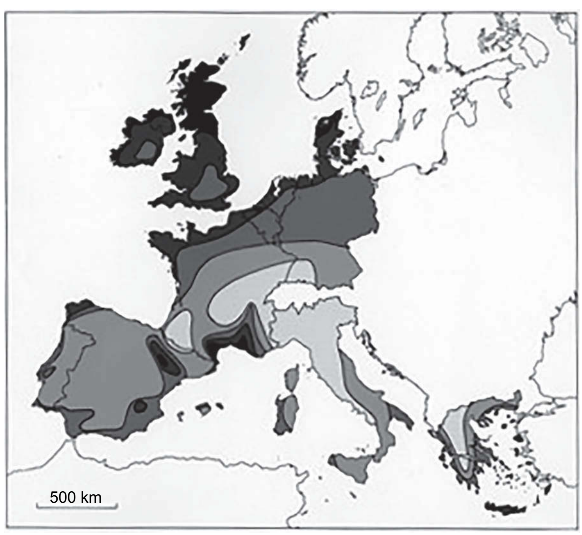


FIGURE 4.3 Europe wind resources at 50 m above ground level for five different topographic conditions. (1989 European Wind Atlas. © Riso National Laboratory, Denmark.)

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/m^2)	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2
5	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1,800
4	5.0–6.0	150–200	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

The 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. The wind power classes are somewhat different from those of the United States and cover different terrains (Table 4.2). Since the original publication, the EC expanded into the European Union (EU) and wind maps are available for more countries.

4.3 OTHER COUNTRIES

Wind maps are available for countries and regions around the world because wind energy is now included in many national energy policies. Check with national energy institutions for information available and latest data. The Global Wind Atlas [10] is a web-based application (1-km resolution) for policy makers and investors to help them identify potential wind power locations. The tool has online queries, downloadable datasets, and digital maps showing global, regional, and country wind resource potential. Other sources for wind maps are RETScreen International [11] and the Renewable Energy Data Explorer [12] has 13 international countries.

NREL geospatial toolkit [13] is a map-based software application that integrates GIS data for integrated resource assessment (maps for 24 countries). The geospatial toolkit also integrates HOMER for all countries, an optimization model for distributed power.

Examples of older maps are given in Rohatgi and Nelson [14, Chaps. 5 and 6]. China and India have installed substantial wind turbine capacity and resource assessment obviously preceded the installations.

More detailed assessments are available from measurements to provide a database for wind power by state, region, and nation and delineate possible locations for wind farms. Micrositing 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 [15,16]. A physics-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 compiled by orbital daily observations mapped to a 0.25° grid, and averages are calculated for 3 days, a week, and a month. Images of the data can be viewed on websites for the world and by region.

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 users select region, dates, and zoom factors, and also gives statistics.

The QSCAT satellite images include direction and higher wind speeds (Figures 4.4 and 4.5). They do not provide dynamic imaging. The system divides the world into regions. Ocean wind data

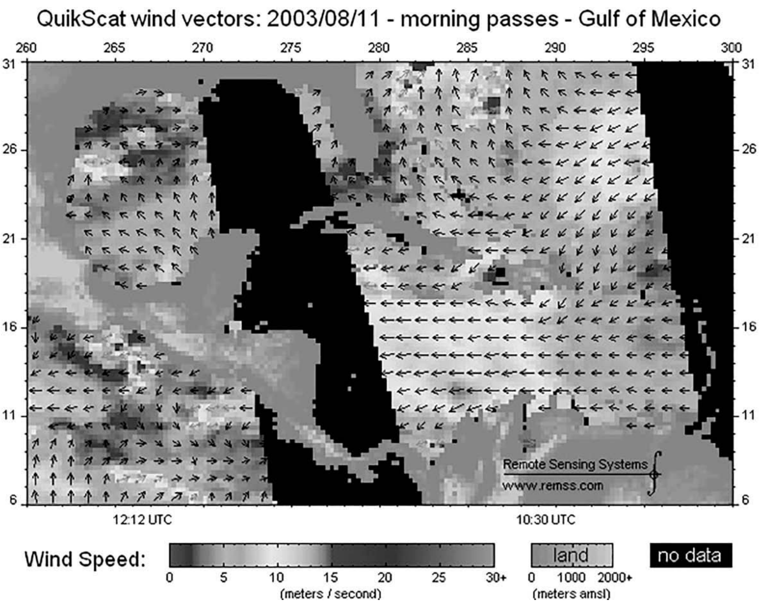


FIGURE 4.4 Daily satellite passes for the Gulf of Mexico.

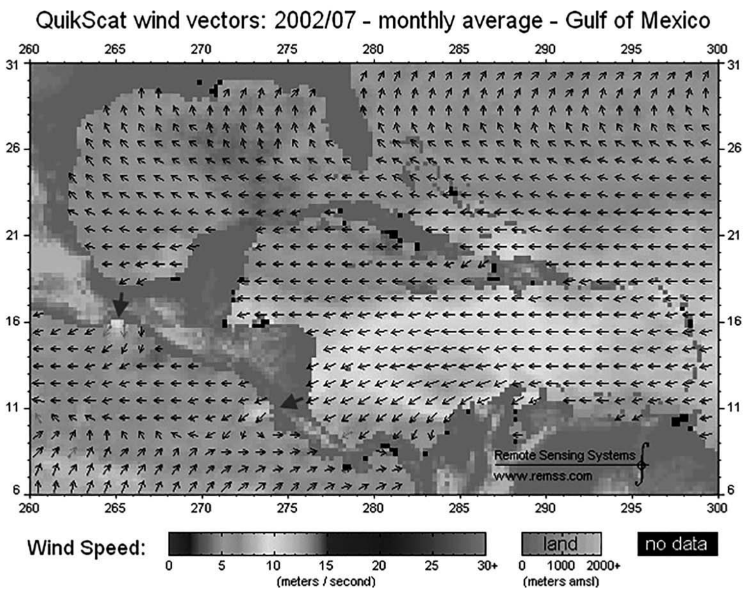


FIGURE 4.5 Average wind speeds for July 2002. Large arrows on land indicate excellent onshore wind regions. Average wind speeds = 10 m/s.

are not available within 25 km of the shore because radar reflections off the bottom of the ocean skew the data.

Notice that ocean winds 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 Tehuantepec isthmus in Mexico and the Arenal region of Costa Rica, where winds are funneled by the land topography.

In the Southern Hemisphere the latitudes of the 40s are regions of strong ocean winds. For example, for Australia and New Zealand they are know as the roaring 40s, and of course there are excellent winds for the southern coasts and islands of South America, South Africa, and India. In general, near shore and intertidal areas are not included in the estimates of offshore wind resource potential.

Geospatial wind-speed data were combined with bathymetry maps, country exclusive economic zones, wind turbine power curves, and other data sets to estimate the offshore wind resource by resource quality, depth, and distance from shore [18]. The sea winds database are at 10 m, so the power law (Equation (3.6), $\alpha = 0.11$) was applied for a 100 m height. The wind power potential was estimated using 3.5-MW wind turbines with a density of 5 MW/km^2. The global offshore wind energy potential was estimated at 192,000 TWh/yr.

4.4.1 United States

In the United States, state energy offices and wind farm developers are promoting offshore wind energy off of both coasts and in the Great Lakes. NREL's program for offshore wind resource assessment estimated the gross wind power potential at about 4,150 GW [20] for the contiguous United States and Hawaii (2009 estimate). The maps extend from coastal areas to 93 km (50 nautical miles) offshore and have a horizontal resolution of 200 m.

Offshore estimates have been updated [20], now with a coastal extension to 370 km (200 nmi), and exclusions were applied for water depth, shipping lanes and environmental considerations. The gross potential capacity was 10.8 GW with a technical resource capacity of 2.1 GW, of which 136 MW were in the Great Lakes. The energy generation potential is 7,203 TWh/yr, which is almost double the total U.S. electric consumption. Alaska is not included in the estimate because of the very large resource, low demand and inadequate transmission. A reduced turbine density of 3 MW/km^2 was used.

WINDExchange [7] has state maps of offshore average wind speed at 90 m (Figure 4.6) and wind resource potential estimates (Table 4.3). Areas with annual average wind speeds of 7 m/s and greater are generally considered suitable for offshore development. Wind potential tables present the resource broken down by annual wind speed, water depth, and distance from shore. The potential is calculated by assuming 5 MW/km^2 of water and for example, the Texas totals are 55,700 km^2 and 278 GW. Again the resource is much larger than will ever be developed.

A national offshore wind strategy was developed by the Departments of Energy and Interior [21]. The Bureau of Ocean Energy Management (BOEM) has developed national and regional guidelines for renewable energy activities [22] on the outer continental shelf, up to 321 km (200 nmi) or more. A list of the leases and a map book [23] are available. States regulate development from the coast to 4.8 km (3 mi) except for Texas. The General Land Office regulates development for a distance of 16 km (10 mi) and has leased areas for wind farm development.

Note there is considerable opposition for offshore wind farms close to the coast. The Great Lakes do not have one regulatory authority for offshore wind development, as each state and Ontario institutes their own policies, plus there are U.S. Federal agencies such as Fish and Wildlife Services.

TABLE 4.3
Texas Offshore Wind Resource Potential (No Exclusions) by Average Wind Speed Class within 93 km (50 nmi)

	Wind Speed (m/s) at 90 m				
	7.0–7.5	**7.5–8.0**	**8.0–8.5**	**8.5–9.0**	**Total**
Area (km^2)	2,019	24,823	16,556	12,273	55,671
GW	10.1	124.1	82.8	61.4	278.4

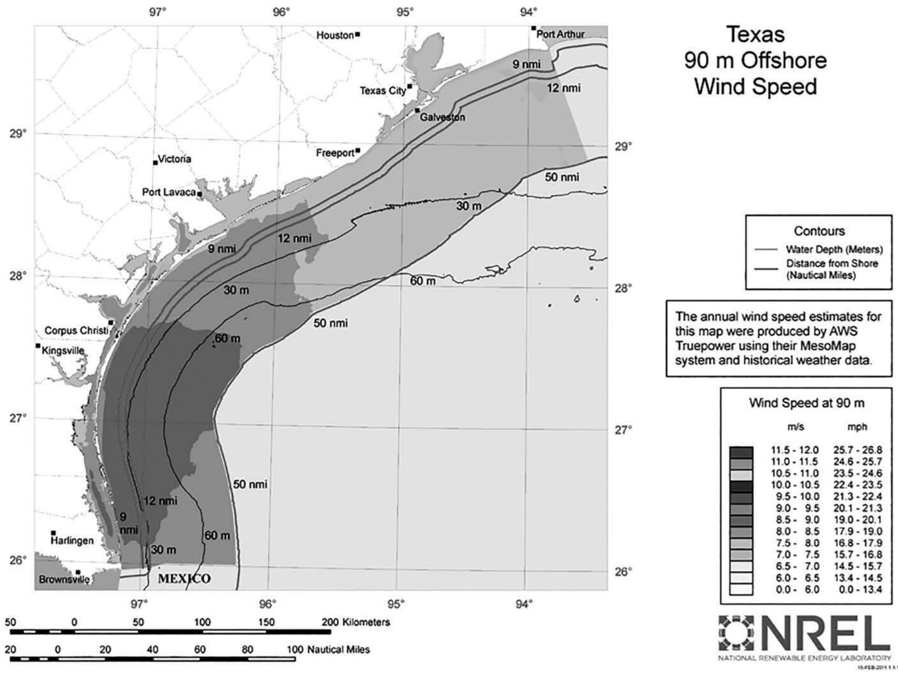


FIGURE 4.6 Offshore wind speed for Texas, 90 m height. (EERE, WINDExchange.)

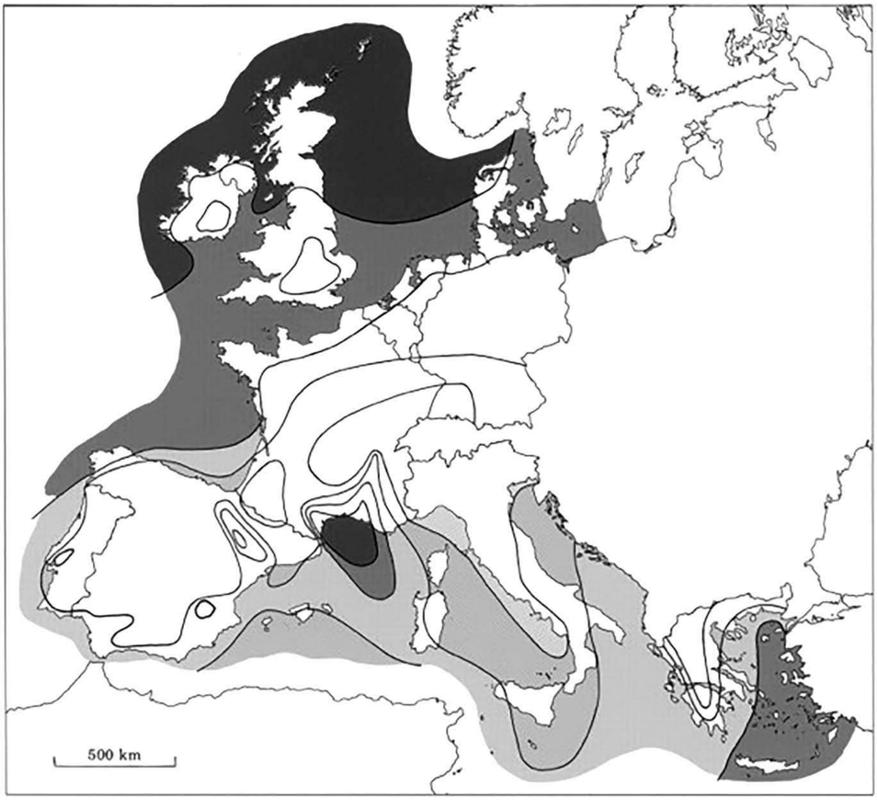
4.4.2 World

The *European Wind Atlas* also has offshore wind data (Figure 4.7). The economical offshore wind resource [24] in the Baltic, North Sea, and Atlantic basins (France, Ireland, U.K.) could provide 25% of total electric demand for Europe by 2030 (64 GW installed, average €54/MWh). Zones excluded are the Norwegian Exclusive Economic Zone (EEZ) in the North Sea and the Russian EEZ in the Baltic Sea. A wind farm density of 5.26 MW/km^2 and a wind turbine specific rating of 368 W/m^2 were used. The economically potential capacity is the resource potential at or below a reference levelized cost of energy.

The offshore technical power potential is estimated at 800 GW for South Korea, 600 GW for China, 10 GW for the Taiwan Straight, 27 GW for India, 7 GW for the Gulf of Thailand, and 3 GW for the Bay of Bangkok. To estimate the potential annual energy production, use a capacity factor of 35–40% and the number of hours in a year. Facilitating Offshore Wind in India (FOWIND) is focusing on determining the offshore resource in the Gulf of Khambhat, Gujarat, and off of Tamil Nadu. India plans to auction 5 GW of offshore wind power projects in 2018.

4.5 INSTRUMENTATION

An anemometer is a device for measuring airflow. Devices that measure wind speed include pitot tube, cup, vane, propeller, hot wire, hot film, sonic, and laser Doppler anemometers. More common (and less expensive) devices are cup and propeller anemometers. However, their response times to changes in wind speed are slower. Wind turbines also have response times to changes in wind speed, so cup anemometers are adequate for determining wind energy potential. The advantages of sonic and hot wire anemometers are that they have no moving parts or response times in contrast to mechanical sensors. However, their higher cost has prevented much penetration into the wind resource assessment market.



Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}
(darkest)	> 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
(lightest)	< 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 in open sea. (Map from European Wind Atlas. © 1989, Riso National Laboratory, Denmark.)

An anemometer can measure the amount of wind that has passed (wind run). Based on the wind run, the average wind speed can be calculated for a specific period. An anemometer can also measure the fastest mile (maximum wind speed).

Microprocessors sample, store, and even analyze data in real time. Also, personal computers alleviate most of the problems in analyzing large amounts of data.

Digital instruments and digitized analog inputs typically have sample rates of 0.1–1 Hz (hertz = number/s). 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 times of occurrence can also be recorded and stored.

Microdata loggers were designed specifically for wind potential measurement and recording time sequence data (averaging time is selectable) on chips. The chips can store data from a number of channels, and data loggers can be queried by telephone (cell or direct), radio link, or satellite, so data are transmitted directly to a base computer now that Internet connection is available. More detailed information on instrumentation and measurement can be found in Rohatgi and Nelson [14]. Also see the *Wind Resource Assessment Handbook* [25] 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. Wind speeds can be measured to 500 m (sodar) and even out to several kilometers (lidar). Lidar instruments can be mounted on the top of the wind turbine to measure wind conditions in front of (forecasting) and behind the turbine (turbulence). Sodar and lidar can be used for wind resource assessment, micrositing, wind shear, turbulence, ramp event forecasting, and power curve testing and nacelle anemometer correlation. Lidar can map 3D wind fields at ranges of 50 m to kilometers.

Case studies and validation reports for the Triton Wind Profiler (sodar) are available from Vaisala (www.vaisala.com/en/products/instruments-sensors-and-other-measurement-devices/weather-stations-and-sensors/triton). A short-term study [26] 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 varied by several orders of magnitude, and that contributed to the observed levels of uncertainty. The mean differences were around 0.14 m/s.

The three general types of instrumentation for wind measurements are: (1) instruments used by national meteorological services, (2) instruments designed specifically for determining wind resources, and (3) instruments for high-sampling rates to measure gusts, turbulence, and inflow winds and for determining power curves, stress, fatigue, and other parameters of wind turbines.

The data collection by meteorological services is the most comprehensive and long term; however, in much of the world, the available data are almost worthless for determining wind power potential. The reasons are that (1) most stations are in cities and airports that are generally less windy; (2) sensors are mounted on buildings and control towers; (3) the quantity of data actually recorded is small (one data point per day or monthly averages); and (4) 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.

Costs for various types of instruments for measuring wind speed range from $400 hand-held anemometers and $1,200 data loggers with cell phones or Wi-Fi; sensors for multiple levels would add at least another $2,000. Companies sell instruments that sample at rates of 0.1–1 Hz and display their outputs on analog devices (meters and recorders) or digital devices (stored on chips). Instruments will record and analyze time sequence data. Wind speeds and directions can be stored for selected time intervals, power can be calculated, and options to measure selected events such as maximums, gusts, and times 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; 60 m (with gin pole), $18,000; and to 80 m (with gin pole) $40,000. Guyed lattice towers can be obtained for higher heights. Pole towers of 50 and 60 m are normally used because they can be raised and lowered with gin poles, are tall enough to gather higher nighttime wind speeds, and are lower than the Federal Aviation Administration (FAA) height requirement of (61 m or 200 ft). The substantial cost for met towers over 60 m is a disadvantage; and the cost for a met tower of 150 m (the height to the top of a rotor on a large turbine) is very high.

In many countries, mechanical anemometers were the normal measuring instruments but they require considerable maintenance and frequent calibration. The power from a cup anemometer drives a 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 high at a national meteorological station in Jujuy, Argentina (Figure 4.8) to determine daily average wind speed. Due to height and blockage by trees and buildings, the wind power potential was vastly underestimated.

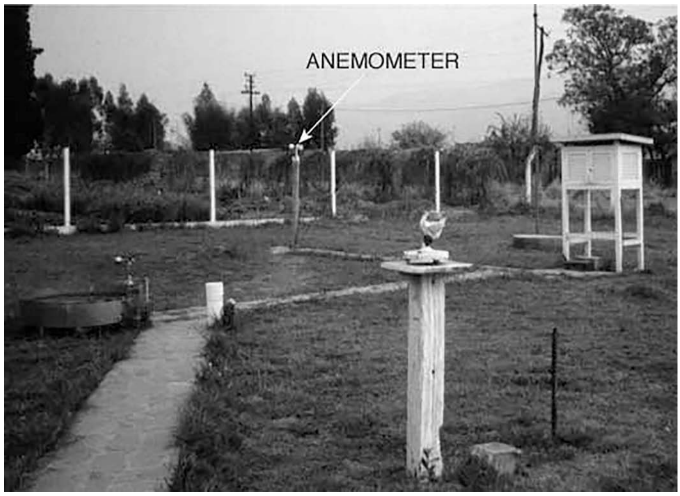


FIGURE 4.8 Meteorological station in Jujuy, Argentina. Arrow indicates anemometer.

Data from Mexicali Airport, Mexico [27], reveal a trend in wind speed data over time (Figure 4.9). The number of 1-hr observations was fairly consistent from 1973 to 1999 when the airport operated. The downward trend indicates degradation of the anemometer from failure to maintain and recalibrate it or less exposure of the instrument because of increased vegetation or other obstructions. The wind power changed 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 a cup housing and one or two coils for pick-up of the signal (Figure 4.10) that approximates 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 analog signal problems of attenuation and amplification). The accuracy of cup anemometers in wind tunnels is estimated at ±2% [28].

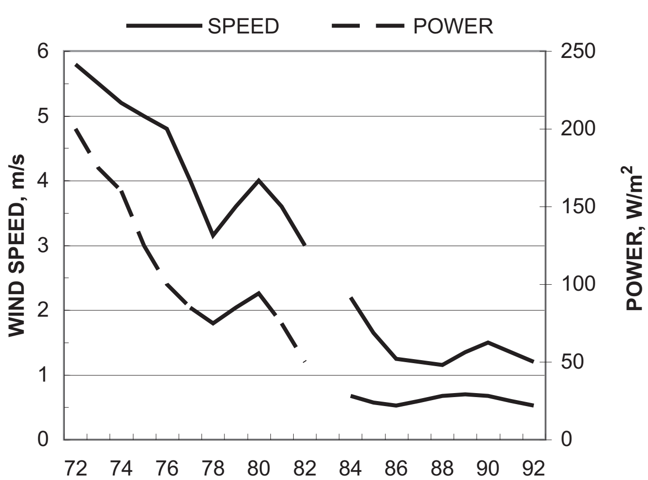


FIGURE 4.9 Wind speed data for Mexicali Airport, Mexico.

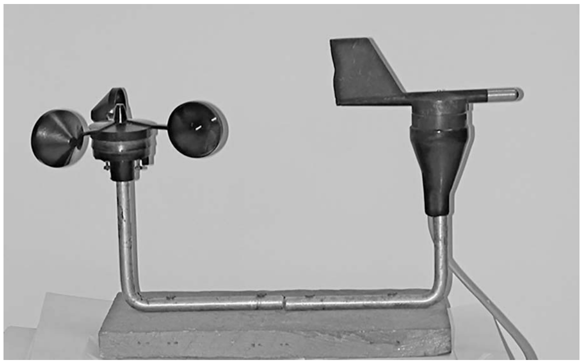


FIGURE 4.10 Maximum cup anemometer and wind vane. Anemometer is about 15 cm across.

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 and the sampling rate can be increased to 5 Hz.

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

Propellers are usually made of 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 will measure the three components of wind.

FIGURE 4.11 Propeller anemometers for measuring in three directions. (Photo courtesy of R.M. Young.)

4.5.2 Wind Direction

Wind direction is measured by a wind vane counterbalanced by a weight fixed on the end of a rod. However, the vanes of propeller anemometers form part of the propeller's axis and require minimum force to initiate movement. The threshold wind speed for this force is usually about 1 m/s. Normally, the vane motion is damped to prevent rapid changes of direction. Wind vanes generally produce signals by contact closures or by potentiometers. The accuracy of potentiometers is higher than that achieved by 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 high precision but low accuracy.

Accuracy, however, may be a function of time or may depend on maintenance. Anemometers are calibrated in wind tunnels where the airflow is steady. Another method of calibrating anemometer performance for wind resource assessment (known as scale and offset) uses controlled velocity via a boom mounted on a truck. Generally, calibrated anemometers produce signals that are accurate to within 0.5–2.0% of the true wind speed. Under normal use in the atmosphere, good anemometers should be accurate to 2–4%.

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 a change from one value to another value, similar to ascending a stairway one step at a time. Larger and heavier cup anemometers usually have distance constants of 3–5 m. For light-weight and smaller cup anemometers, such as those used to measure turbulence, the distance constant is typically about 1 m. The time constant is the period 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 a signal is sampled and may include the time for recording data. Because a large amount of data requires large storage, wind speeds are averaged over a longer period and these values, along with standard deviations, are stored. Typical values for wind power analysis are sample rates of 1 Hz and averaging time of 10 min, though 1-hr 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 at a distance of two- to three-tower diameters to reduce the effect of the tower on airflow. Solid towers should be mounted six tower diameters away. Met towers must be located away from obstacles such as trees and buildings.

The time and money spent for measuring wind resources depends on whether the plan is for a wind farm or a small wind turbine. The difference between class 3 and class 4 and above wind sites determines economic viability for wind farms. Individuals who install small wind turbines tend to overestimate wind resources before their turbines are installed and later bemoan the lack of wind.

FIGURE 4.12 Flagging of trees. Left: Tree on plains, Canyon, Texas (6 m/s average wind speed 10 m height). Right: Tree at South Point, Hawaii (10 m/s average wind speed).

Instrumentation for measuring turbulence and wind inflow for wind turbine response involves multiple anemometers and a higher sampling rate. A system for characterizing turbulence [29] developed and tested by Pacific Northwest Laboratory consisted of two towers and nine anemometers and data sampling at 5 Hz. The propeller vane anemometers for horizontal measurements were replaced by cup anemometers due to problems of maintenance and errors in wind speed measurement.

4.5.5 Vegetation Indicators

Vegetation can indicate regions of high wind speed in areas where no measurements are available. Deformation or flagging of trees [18, p. 96] is the most common indicator (Figure 4.12). In some cases, the flagging of trees is a more reliable indicator of wind resource than the data available.

For example, the Arenal region of Costa Rica has high winds that were measured (average for 12 stations) at 11 m/s [30]. A meteorological station near Fortuna in the Arenal region was erected to collect hydrology data. The mechanical anemometer height is less than 2 m because the researchers were originally interested in determining evaporation, and the station was located near trees. Wind speed data indicated no wind power potential, but flagged trees in the area indicated high wind speeds. The Griggs and Putnam Index [31] for flagging coniferous trees (Figure 4.13) is related to annual mean wind speed [32] by:

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

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 wind (Figure 4.14).

$$D = A/B = C/45 \text{ deg}$$

The relationship is used for both coniferous and hemispherical crowned trees.

For coniferous trees (Figure 4.14), *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

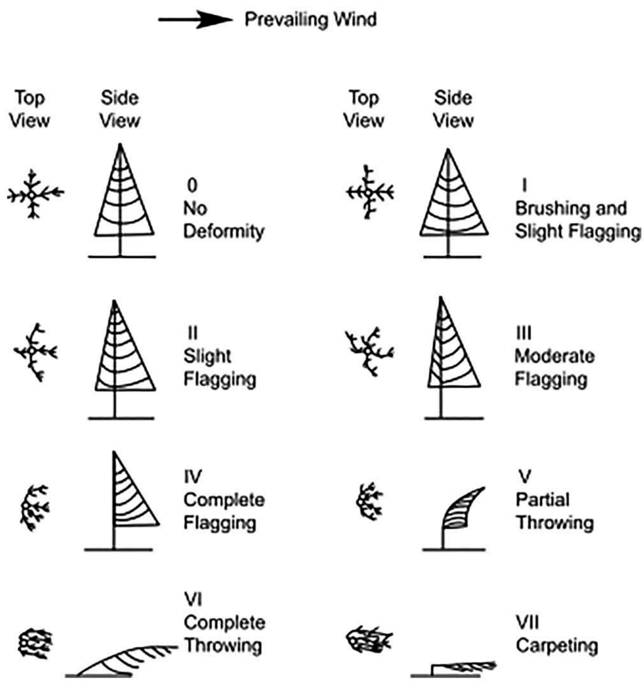


FIGURE 4.13 The Griggs-Putnam Index of tree deformation.

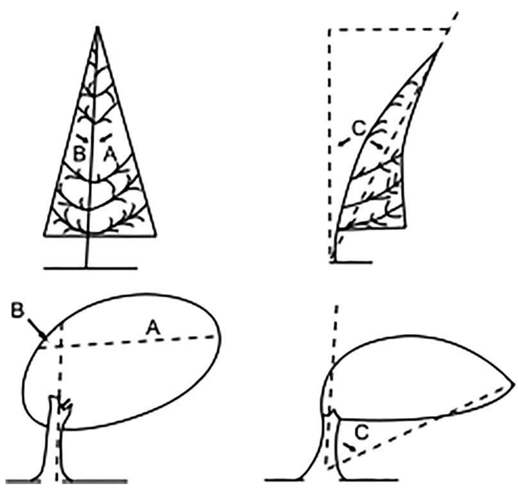


FIGURE 4.14 Estimation of wind speed by tree deformation.

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 *A/B* ratio assumes that $1 \le A/B \le 5$. 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, 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,

$$\bar{\mu} = 0.96D + 2.3$$

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

The use of trees as indicators of wind speed is subject to a number of practical limitations. Of greatest concern is the exposure of a tree to the wind. The deformation should be viewed perpendicularly to the prevailing wind direction so that the full effects of flagging and throwing are considered. 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 other trees. However, isolated trees or those in small, widely spaced groups should be favored as wind speed indicators. If several locations are to be compared, 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 the chips are retrieved or the loggers send information to a base personal computer. The BASE program monitors telephone lines, answers calls, and determines the site calling and 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.).

Time sequences generate large amounts of data. For example, suppose you want to measure wind speeds, wind directions, pressures, temperatures (1 Hz sampling rate), average values, and statistics stored every 10 min. That would occupy around 130 KB of data per month. Chips are available to store 2 or more years of data. You still need to retrieve the data at least monthly in order to check on problems. Data generated by phones or satellite connections should be retrieved once per week.

Logistic problems must be resolved to ensure high data recovery, and the quality of the data must be analyzed. Calibration and replacement of sensors must be part of a routine maintenance program. For example, anemometers should be replaced once every 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%. Sensor problems arise from equipment failure and inadequate data collection 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 may be higher for sites with very harsh conditions, for example, hail, lightning, dust and sand circulation, and extended periods of high winds.

Generally, two anemometers and one wind vane per level are installed in systems with two or more levels. If one anemometer is down, data can be collected by the second anemometer. If both are not operating, it is possible to estimate values based on data from another level and past wind shear values, so 95% data recovery is feasible.

Wind farm developers want an average wind speed (10 min or 1 h) so they can predict energy production. Available data analysis programs are fairly flexible. Monthly average, minimum, and maximum data for each sensor are available and selected graphs and tables can be generated.

Example of Summary Reports Available by Month from an Analysis Program

Comparison of hourly wind speeds (two anemometers at same height or at different heights)
Frequency distributions (calculate wind power/area; see Figure 4.15)
Frequency distribution graph
Diurnal wind speed graph
Average turbulence intensity (upper level, use prevailing wind anemometer)

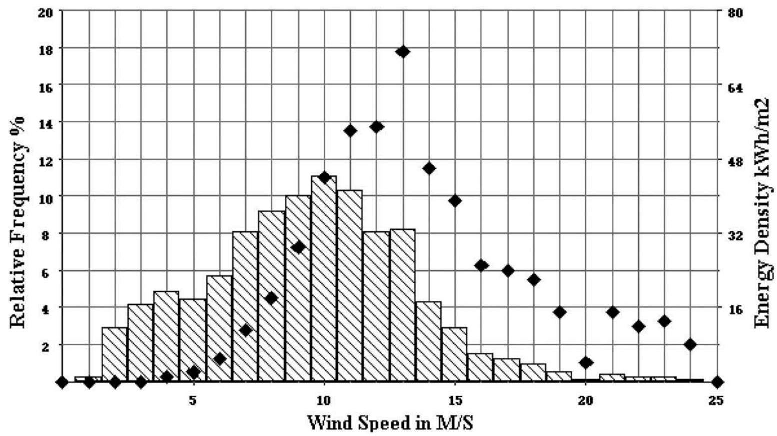


FIGURE 4.15 Example graph, frequency distribution plus energy, from analysis program, 50 m height, White Deer, Texas, April 1998.

Data can be placed in spreadsheets for further analysis since most data loggers allow export. Another benefit is that data analysis is not tied to proprietary programs whose manufacturers may have trouble updating, especially if subcontractors developed the software programs.

4.7 WIND MEASUREMENT FOR SMALL WIND TURBINES

For a very small wind turbine (100 W to 3 kW), anemometers, data loggers, and analyses may cost more than the wind turbine. In one sense, a wind turbine is an anemometer and the energy produced is the measurement. It is wise to depend on historical and regional data to determine the 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 other owners about the performance of other small wind turbine installations in the region. For a wind turbine of 10–50 kW, the investment is fairly large—$60,000–$250,000. Inexpensive digital weather stations that include data loggers are now available for $300–$600 and the data loggers can be plugged into personal computers for analysis.

These instruments are not suitable for collecting long-term data for wind resource assessment or for wind farms. If maps indicating sufficient winds are available and wind farms have already been installed in an area, there is no need to collect wind data before installing same size turbines. However, use caution when installing wind turbines within cities, even in windy areas, as the winds will be less than those indicated on wind maps.

Maps

Canada: www.windatlas.ca/index-en.php

Database of wind characteristics: www.winddata.com

NREL (U.S.): www.nrel.gov/wind/resource-assessment.html

Wind Atlases of the World: www.wasp.dk/dataandtools#wind-atlas__world__wind-atlases-of-the-world

Ocean Wind Data

College of Marine Studies, University of Delaware—Annual and monthly values: www.ocean.udel.edu/windpower/

European Wind Atlas: www.wasp.dk/dataandtools#wind-atlas__european-wind-atlas

Galathea 3: www.galathea3.dk/dk.html
Ocean surface winds: http://manati.orbit.nesdis.noaa.gov/doc/oceanwinds1.html

Data Logger, Sensor, and Tower Information
www.campbellsci.com
www.ekopower.nl
www.nrgsystems.com
www.secondwind.com
www.wilmers.com
www.rohnproducts.com (towers)

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/area?
5. What region of Nicaragua has the best wind power potential? Use 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 (Ref. [22]).
7. Go to www.windmap.org (2/27/2013). 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. Use 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. How far should an anemometer be placed away from a tall tower 13 cm in diameter?
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. No tower is needed for a laser system that measures wind speed. What is the reason for not employing a laser system?
14. You want to measure wind speeds and directions at three levels (10, 25, and 50 m) at six sites (dispersed across your state) for 2 years. Estimate the cost for equipment and workers to handle installation, data collection, and data analysis. You may choose any type of data logger, tower, data retrieval, and analysis.
15. Compare the amount of storage needed for (a) 1 hr average and standard deviation (sample rate 1 Hz) for 16 channels for 1 year and (b) 1 min average and standard deviation (sample rate 5 Hz) for 16 channels for 1 year.

16. How many years of data are required to establish a database to which shorter term data for wind farms can be referenced? In other words, how many years of data are needed to generate a wind map for a large region or state?
17. Estimate the cost for installation of a 50-m guyed pole tower. Consider difficulty getting to the site when estimating travel costs.
18. Estimate the costs to install a 50-m guyed lattice tower (e.g., Rohn 25G or 45G); include travel cost based on difficulty getting to the site. Will you use a crane or attached gin pole for installation of the lattice tower?
19. Estimate the cost of installation of a 100-m guyed lattice tower. Include travel costs based on difficulty getting to the site. A crane will be used for installation. Also, FAA regulations require lights so the additional cost of transmitting power to a remote location must be considered.
20. Compare wind resource instruments (cost, sample rate, data storage, and data analysis) from two different manufacturers.
21. Are there any shareware programs for wind resource analysis?

REFERENCES

1. N.J. Cherry, D.L. Elliott, and C.I. Aspliden. 1981. Worldwide wind resource assessment. In *Proceedings of Fifth Biennial Wind Energy Conference and Workshop*, Vol. II, p. 637.
2. NREL MapSearch. https://maps.nrel.gov.
3. C.L. Archer and M.Z. Jacobson. 2005. Evaluation of global wind power. *Journal of Geophysical Research* 110, 12110. www.stanford.edu/group/efmh/winds/global_winds.html.
4. D.L. Elliot and W.R. Barchet. 1977. *Synthesis of National Wind Energy Assessments*. BNWL-2220 WIND-5/UC-60. Battelle, Pacific Northwest Laboratory: Richland, WA.
5. D.L. Elliott et al. 1986. *Wind Energy Resource Atlas of the United States*. Pacific Northwest Laboratory: Richland, WA DOE/CH 10093-4. http://rredc.nrel.gov/wind/pubs/atlas.
6. National Renewable Energy Laboratory, geospatial data science. www.nrel.gov/gis/.
7. US DOE, EERE. WINDExchange. https://energy.gov/eere/wind/windexchange.
8. NREL, Wind Prospector. www.nrel.gov/gis/wind.html.
9. I. Troen and E.L. Petersen. 1989. *European Wind Atlas*. Risoe National Laboratory: Denmark. www.wasp.dk/dataandtools#wind-atlas__european-wind-atlas.
10. Global Wind Atlas 2.0. https://globalwindatlas.info.
11. RETScreen International. Energy resource maps. Windows only apt. www.retscreen.net/ang/energy_resource_maps.php.
12. NREL, REexplorer. www.re-explorer.org.
13. NREL, International Activities, geospatial toolkit. www.nrel.gov/international/geospatial_toolkits.html.
14. J. Rohatgi and V. Nelson. 1994. *Wind Characteristics: An Analysis for the Generation of Wind Power*. Alternative Energy Institute, West Texas A&M University: Canyon, TX.
15. Remote Sensing Systems. Geophysical graphic images and binary data files on FTP server. ftp.ssmi.com/ssmia; climatological data sets (three-day, weekly, and monthly averages) for each geophysical parameter and satellite. www.remss.com.
16. Jet Propulsion Laboratory, Physical Oceanography DAAC. Ocean winds. https://earthdata.nasa.gov/about/daacs/daac-podaac.
17. Wind Europe, offshore wind in Europe. https://windeurope.org/about-wind/statistics/offshore/.
18. D. Arent, et al. 2012. Improved offshore wind resource assessment in global climate stabilization scenarios, NREL?TP-6A20–55049. www.nrel.gov/docs/fy13osti/55049.pdf.
19. M. Schwartz, et al. 2010. Assessment of offshore wind energy resources for United States. NREL/TP-500-45889. www.nrel.gov/docs/fy10osti/45889.pdf.
20. W. Musial, et al. *2016* Offshore wind energy resource assessment for the United States. NREL/TP-5000-66599. www.nrel.gov/docs/fy16osti/66599.pdf

21. U.S. DOE & U.S. DOI, 2016. National offshore wind strategy. www.boem.gov/National-Offshore-Wind-Strategy/.
22. BOEM. Renewable energy programs. www.boem.gov/Renewable-Energy/.
23. BOEM. 2017. Outer continental shelf renewable energy leases, map book. www.boem.gov/Renewable-Energy-Lease-Map-Book/.
24. Wind Europe. 2017. Unleashing Europe's offshore wind potential. https://windeurope.org/wp-content/uploads/files/about-wind/reports/Unleashing-Europes-offshore-wind-potential.pdf.
25. *Wind Resource Assessment Handbook*. 1997. NICH Report SR-440-22223. www.nrel.gov/docs/legosti/fy97/22223.pdf.
26. N.D. Kelley, B.J. Jonkman, and G.N. Scott. 2007. Comparing pulsed Doppler LIDAR with SODAR and direct measurements for wind assessment. In *Proceedings of Windpower Conference*. www.esrl.noaa.gov/csd/projects/lamar/references/kelley2007.pdf.
27. M.N. Schwartz and D.L. Elliott. 1995. Mexico wind resource assessment project. In *Proceedings of Windpower Conference,* p. 57.
28. J.L. Obermier. 2000. Single variable comparison of calibrated results for NRG maximum 40 anemometers. In *Proceedings of Windpower Conference*.
29. L.L. Wendell et al. 1991. Turbulence characterization for wind energy development. In *Proceedings of Windpower Conference,* p. 254.
30. T. de la Torre. 1993. International developments: new wind power projects and wind electric power development in Costa Rica. In *Proceedings of Windpower Conference,* p. 429.
31. P.C. Putnam. 1948. *Power from the Wind*, p. 84. Van Nostrand Reinhold: New York.
32. E. W. Hewson and J. E. Wade. 1979. A handbook on the use of trees as indicators of wind power potential. Report RLO-2227. U.S. Department of Energy.
33. Global Wind Energy Consortium. 2017. Offshore wind. www.gwec.net/wp-content/uploads/2017/05/Global-Offshore-2016-and-Beyond.pdf.

5 Wind Turbines

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

5.1 DRAG DEVICES

In a drag device, the wind pushes against the blades or sails (Figure 5.1). Drag devices are inherently limited in efficiency because the speed of the device or blades cannot exceed the wind speed. The wind pushes on the blades of a drag turbine, forcing the rotor to turn on its axis.

Examples of drag devices are cup anemometers, vanes, and paddles that are shielded from the wind or change parallel to the wind on half the rotor cycle (Figure 5.2). Clam shells that open on the downwind side and close on the upwind side are also examples of drag devices. No drag wind turbines have been produced commercially because they are inefficient, and the blades require a lot of material. However, drag devices are popular with inventors and homebuilders because they are easy to construct (Figure 5.3). Invariably, inventors become irate when they are told that the inefficient aerodynamics and amounts of material required for blades limit the commercialization of drag devices.

5.2 LIFT DEVICES

Most lift devices use airfoils similar to propellers or airplane wings for blades but other concepts have also 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. 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. The ratio of amount of power per material area for a lift device 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.

A single 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 will save on material but a counter weight is needed for balance. Most modern wind turbines have two or three blades because of other considerations, and most large turbines in the commercial market have three blades.

The MBB Monopteros and Flair designs were single-bladed wind turbines built in Germany. A one-blade (5-kW) unit was built by Riva Calzoni in Italy. The Monopteros had full-span pitch control and the rotor was upwind. MBB and Riva Calzoni collaborated on a 20-kW one-blade 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. Notice the large number of blades on the Honeywell unit in Figure 1.7. Some modern wind turbines have been built 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 for construction and problems arising from force at high wind speeds even if the rotor is not turning. An advantage of the Savonius wind turbine is the ease of construction.

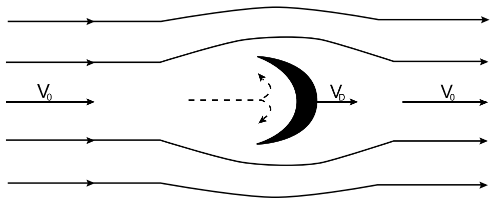


FIGURE 5.1 Drag device. An example is a sailboat moving downwind.

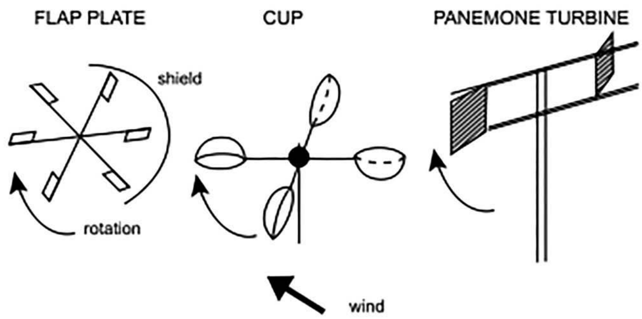


FIGURE 5.2 Diagrams of drag wind turbines.

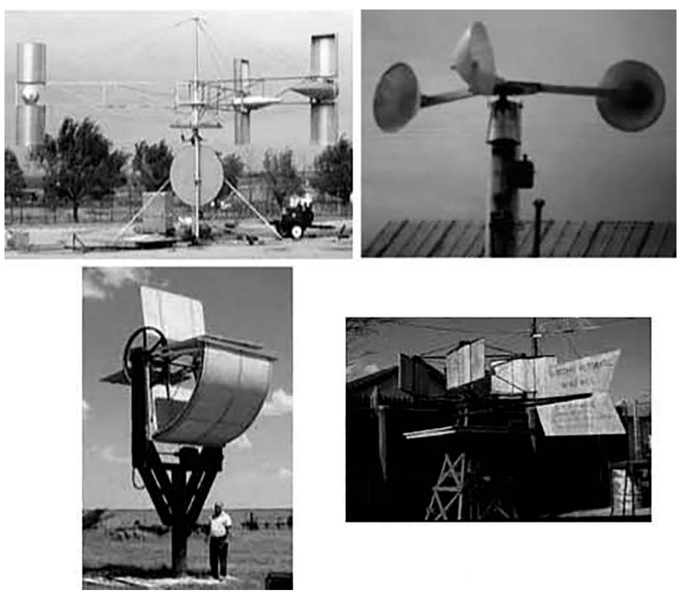


FIGURE 5.3 Examples of drag devices. Top left (clockwise): (1) Around 10-m diameter, with flywheel which was supposed to store energy and reduce variation in power. (2) Cups 1.2-m diameter. Inventor predicted power output at 4 kW. (3) Panemone device. Blades move parallel to wind when moving upwind. (4) Shielded plywood sheets, 1.2 by 2.5 m. Notice the large wheel for speed increase to the generator. Inventor predicted output at 4 kW.

5.3 ORIENTATION OF ROTOR AXIS

Wind turbines are further classified by the orientation of the axis of the rotor to the ground: horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT; Figures 1.10 and 5.6). The rotors on

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 was 3-m high by 1.75-m diameter) test at Kansas State University. (Photo courtesy of Gary Johnson.)

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

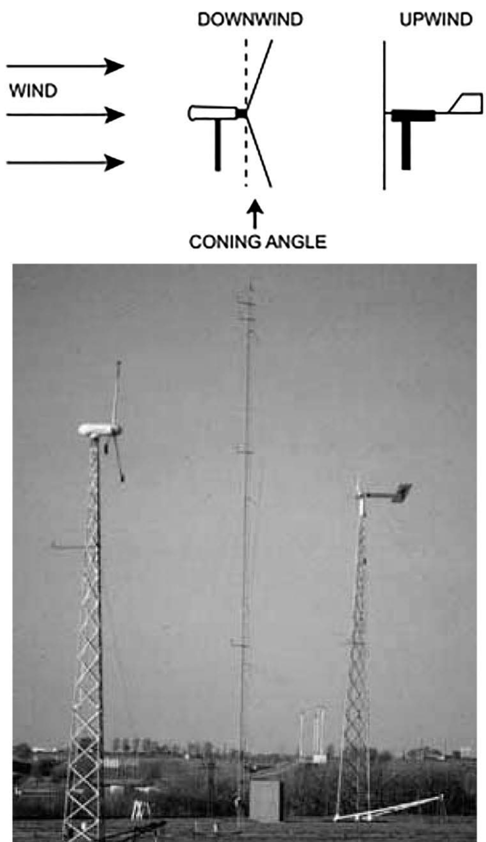


FIGURE 5.7 Diagrams of downwind unit with coning, passive yaw control, and upwind unit with tail for yaw control. Photos of downwind turbine (Enertech, 6.5 m diameter, 5 kW) and upwind turbine (Hummingbird, 6 m diameter, 5 kW) at Alternative Energy Institute Wind Test Center, Canyon, Texas.

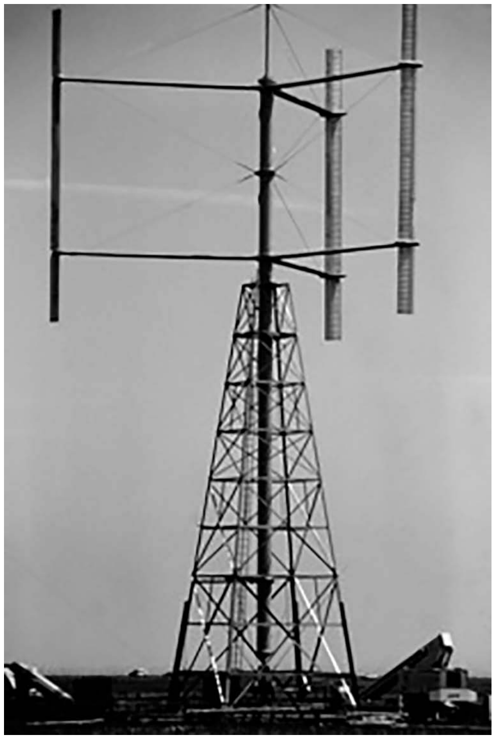


FIGURE 5.8 Giromill, 40 kW (rotor dimensions, 18-m diameter, 12.8-m height) at National Wind Technology Center of National Renewable Energy Laboratory.

HAWTs must be kept perpendicular to the flow of the wind to capture maximum energy. This rotation of the unit or rotor about the tower axis (*yaw)* is accomplished by tails on upwind units (small turbines up to 10 kW although some 50-kW units had tails), by *coning* on downwind units (Figure 5.7), or by electric motors or wind-propelled fan tail rotors to drive the unit around the yaw axis. *Coning* means the blades are at an angle from the plane of rotation.

VAWTs have the advantage of accepting wind from any direction. However, the Darrieus wind turbine is not reliably self-starting because the blades have to be moving faster than the wind to generate power. An induction or other type of motor or generator is used for start-up to get the blades moving fast enough to generate positive power. A giromill (Figure 5.8) may have articulated blades that can change angle on the rotational cycle and may be self-starting. Another advantage of VAWTs is that the speed increaser and generator can be at ground level. The two primary disadvantages are: (1) the rotor is closer to the ground and (2) cyclic variation of power occurs on every revolution of the rotor.

5.4 SYSTEM DESCRIPTION

A 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, the choice is electrical energy, so the conversion system is a generator.

Blade configuration may be one of three variations: (1) nonuniform platform (blade width and length), (2) twist along the blade, (3) 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.

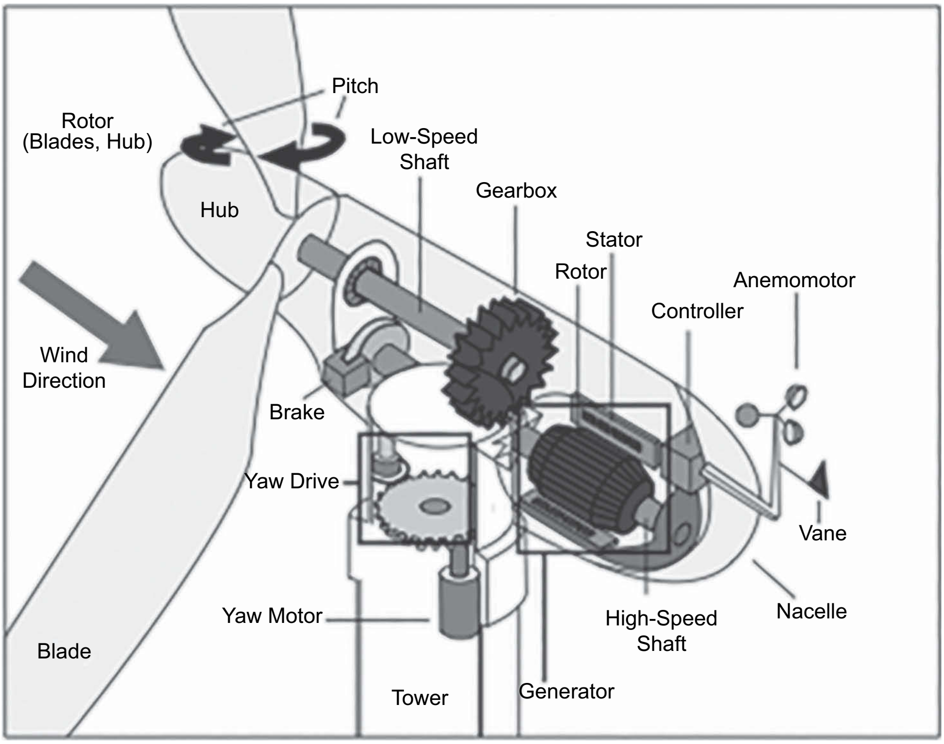


FIGURE 5.9 Major components for large wind turbine.

Components for a large unit mounted on a bedplate are shown in Figure 5.10. Most large wind turbines that 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 should have the same pitch for operational conditions, however some large wind turbines have cyclic pitch control between top and bottom of swept area to improve blade efficiency.

For units connected to a utility grid, 50 or 60 Hz, the generators can be synchronous or induction type connected directly to a grid, or a variable-frequency alternator or direct current generator connected indirectly to a grid through an inverter. Most direct current (DC) generators and permanent magnet alternators on small wind turbines do not have speed increasers. There are large wind turbines that have no gearbox; they have 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 of extra length for absorbing twist. After a certain amount of twist, the excess must be removed by yawing the turbine or via 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).

5.5 AERODYNAMICS

The moving blades of a 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.

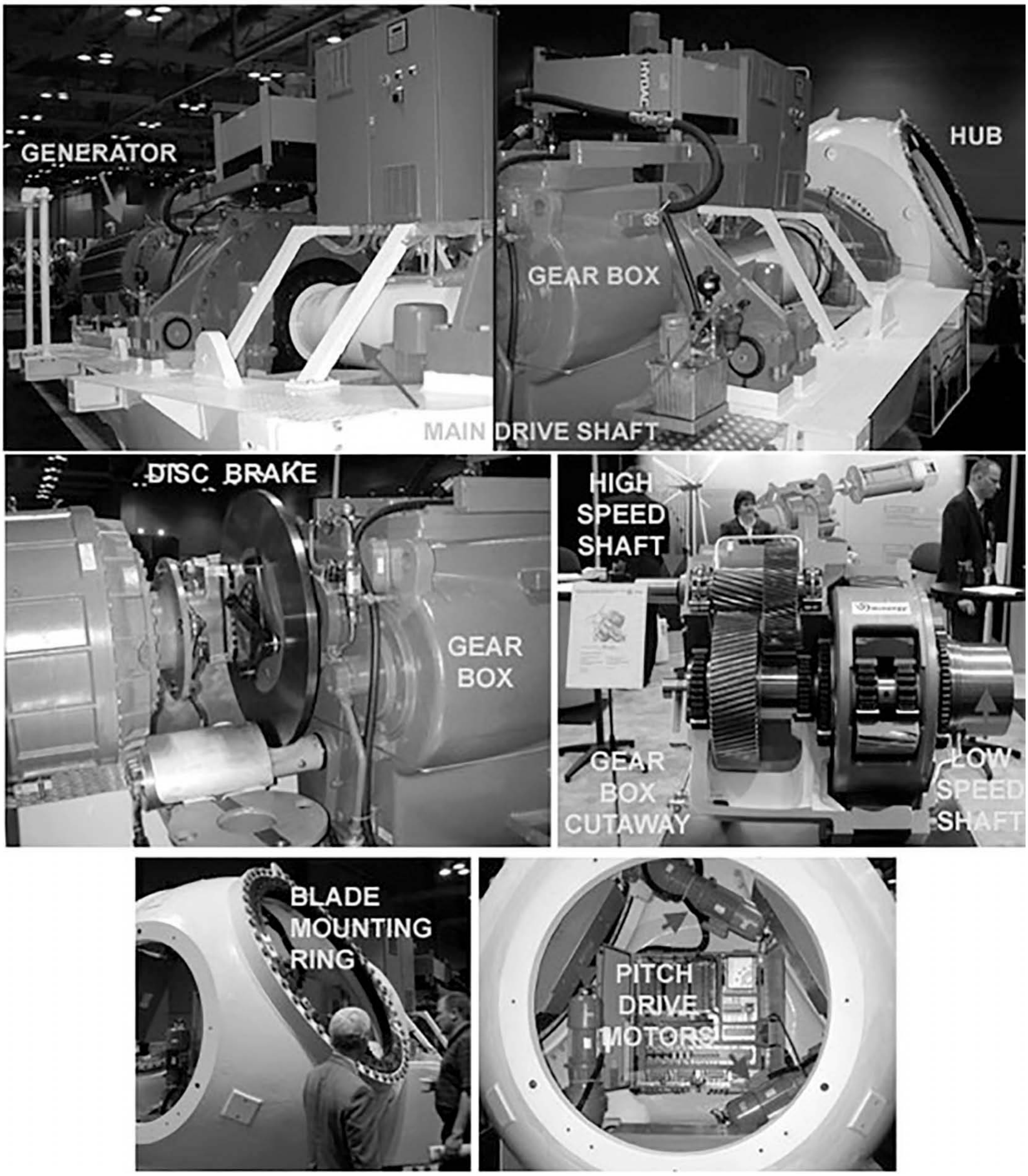


FIGURE 5.10 Suzlon, 64-m diameter, 1,000 kW, induction generator 4/6 pole. Winergy cutaway gearbox.

Note: Θ is the angle expressed in units of degrees or radians. A radian is the angle at which 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 $v = \omega \times r$, 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 fewer revolutions per minute (rpm) by the rotor. That is why small diameter rotors complete many revolutions per minute and large diameter rotors make few revolutions.

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

Based on conservation of energy and momentum, the maximum theoretical efficiency for the capture of wind power and wind energy is 59%. The highest experimental efficiencies for systems converting wind energy to electricity are around 50%.

Lift and drag forces of airfoils are measured experimentally in a wind tunnel as functions of the *attack angle* (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 that depends on the angle of attack makes the rotor turn about the axis (Figure 5.12). The relative wind experienced by the blade has two parts: (1) the vector sum of the motion of the blade and (2) the motion of 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

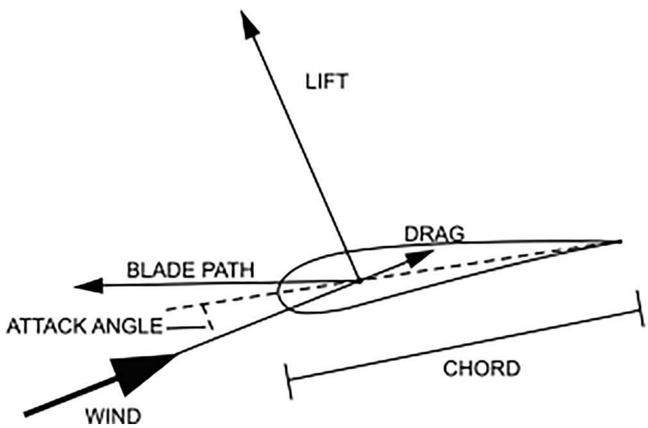


FIGURE 5.11 Forces on blade, lift and drag, due to airflow of relative wind.

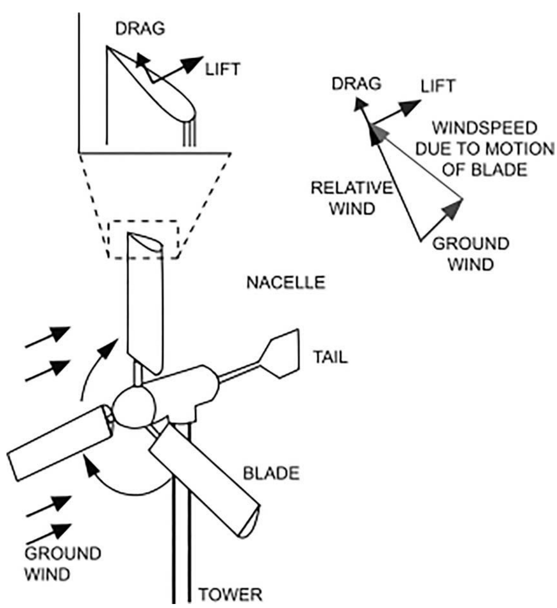


FIGURE 5.12 Wind produces forces on the blade. Relative wind is the vector sum of the blade speed plus the ground wind. Rotor is perpendicular to ground wind.

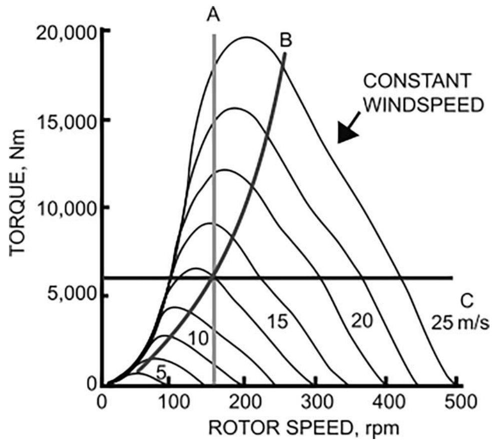


FIGURE 5.13 Theoretical curves of torque versus rpm for different wind speeds.

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). Although rotor efficiency decreases above the point of maximum power coefficient for fixed-pitch blades, the power output of the wind turbine can remain high because available power increases as the cube of the wind speed.

Computer programs are available for estimating the aerodynamic performances of both HAWTs and VAWTs. Inputs include airfoil lift and drag versus attack angle, radius, twist and pitch of blades, and solidity. Wind speeds or tip speed ratios can be varied to determine power, forces, moments, and other parameters for each blade section and for 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. The number of blades, airfoil, and other parameters 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 ratios (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 the wind contains too much power and the wind turbine is controlled to capture less power, and in cases of 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 that high-solidity rotors like farm windmills have high starting torques at low winds and tip speed ratios around 1, and are thus too inefficient for generating electricity.

5.6 CONTROL

Because wind power increases so rapidly, all wind turbines must have ways 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 or hydraulic
   b. Air brake
   c. Electrical (resistance, magnetic)

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

For control in high winds, most small wind turbines and farm windmills have tails to yaw the wind turbine out of the wind (*furling* the rotor). For high speed wind control, the rotors of some wind turbines are rotated about the horizontal axis rather than yawed about the vertical axis. The results are the same; the intercept area is 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 wind) during shutdown. When the brake is released, the feather position provides starting torque, and the pitch is changed to the run position (pitch angle at tip around 0°) as revolutions increase. The blades are kept at the same pitch (run position) over a range of wind speeds. For high wind speeds and overspeed control, the blades are moved to the feather or *stall* position (blades perpendicular to wind, negative pitch) to shut the unit down. The pitch can be changed to maintain 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, the tip speed ratio over this range is constant and the unit operates at higher efficiency.

Fixed-pitch blades allow two possible operations: (1) constant tip speed ratio (variable rpm) providing maximum efficiency and (2) constant rpm. The blade must have enough twist to produce torque for start-up, or the induction motor or generator can start the rotor at the cut-in wind speed. Constant rpm operation with induction generators means that the maximum efficiency is reached only at the design wind speed. Above rated power, the output is controlled by the reduced aerodynamic efficiency (stall control).

Part of the control system can be electronic, generally a microprocessor or microcomputer (Figure 5.14). In constant rpm operation with an induction generator, the unit is connected to the

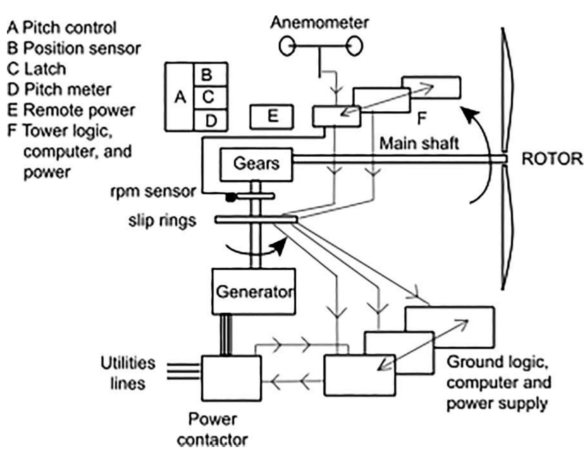


FIGURE 5.14 Block diagram of system with pitch control.

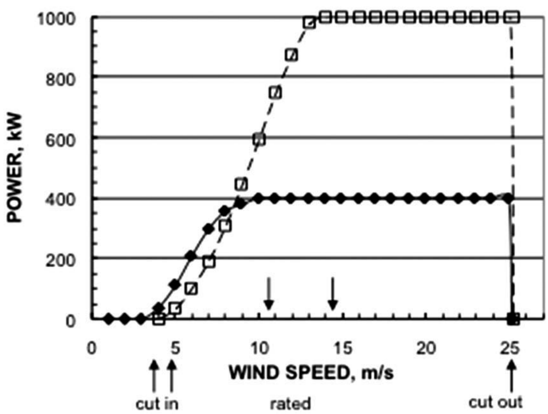


FIGURE 5.15 Power curves of rotor with two different generator sizes.

utility line after the rpm exceeds the synchronous rpm of the generator. In reality, an induction generator does not operate strictly at constant rpm due to a small change in rpm (slip) with power output. Doubly fed induction generators have large rpm ranges of around 50%, and are used because of the increased aerodynamic efficiency of large wind turbines with blades in the run position.

5.6.1 Normal Operation

A *power curve* (plot of power versus wind speed) describes the normal operation of a wind turbine (Figure 5.15). Notice that the difference in power output at low wind speed is due to differences 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 (based on size of generator) at the rated wind speed, and continues to produce 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 when determining energy production is the rotor swept area because 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 had two generators and utilized the smaller generator at lower wind speeds to increase overall efficiency. Although a larger generator is probably desirable in the best wind regimes, the optimum size for a rotor radius for a specific wind regime is still being determined.

Manufacturers now offer different size generators (with different power ratings) for the same rotor diameter or the same size generator for different rotor diameters. The goal is to maximize the energy production, the economic return. Jay Carter, Sr. designed and built a wind turbine for both medium and good wind regimes. The adjustment was made simply by changing the sizes of the induction generators (30 kW, six poles and 50 kW, four poles).

5.6.2 Faults

Wind turbines are shut down for faults such as loss of load, vibration, loss of phase, and current or voltage anomalies. Each of these safety features could save the unit, but the most important feature is a method of controlling the rotor during 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, production 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 sized rotors may have different sized generators:

$$AEP = CF \times GS \times 8,760 \tag{5.2}$$

where AEP = 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 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 capacity factors calculated for individual wind turbines. However, if a wind farm is composed of different wind turbines, the differences should be considered. 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 rotors.

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 11–13 m/s. If the rated power is above that range or a wind regime is below class 3, the capacity factor should be reduced accordingly.

Example 5.1: Wind Turbine Specifications

Rated power = 25 kW at 10 m/s
Rotor diameter = 10 m
Estimated capacity factor = 0.25
AEP = 0.25 × 25 kW × 8,760 h/year = 55,000 kWh/year
For a poor wind regime, AEP 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 for a wind turbine in a medium wind regime. Wind farms are located in good to excellent wind regimes and capacity factors should be 32–45%. Capacity factors up to 50% were reported for a wind farm located in the Isthmus of Mexico. The Wildorado Wind Ranch near Amarillo, Texas has a capacity factor of 45%.

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 areas for different types of wind turbines can be calculated from the dimensions of the rotor (see Figure 1.10).

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

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

$$AEP = CF \times Ar \times WM \times 8.76 \tag{5.3}$$

where Ar is the area of the rotor (m^2); WM is the power/area from a wind map (W/m^2); and 8.76 is the conversion factor that yields an answer in kWh/year. Again, the capacity factor reflects the annual average efficiency of a wind turbine; around 0.20–0.40.

Example 5.2

Use the wind turbine in Example 5.1, and from the wind map:
WM = 200 W/m^2
Area = πr^2 = 3.14 × 25 m^2 = 78.5 m^2
AEP = 0.25 × 78.5 m^2 × 200 W/m^2 × 8.76 kWh/year = 34,000 kWh/year

Notice the large difference in the answers for the two examples. The difference may arise from two factors: (1) generator size is too large for rotor size, or (2) 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 a wind speed at 1 m/s intervals and then calculate the annual energy production at standard density using the power curve for their wind turbines 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 a location should be determined 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. Based on the graph, a wind speed of 8.2 m/s means that 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, a good estimation of energy production can be calculated from the histogram and the power curve for a wind turbine. Manufacturers 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

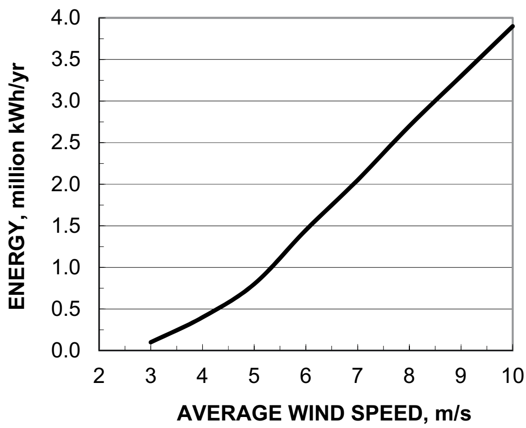


FIGURE 5.16 Estimated annual energy production based on annual average wind speed.

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 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

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

Wind Speed (m/s)	Power (kW)	Bin (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

long-term regional data are available. Two to three years of wind speed data, averaged to an annual histogram, will suffice.

Wind speed histograms and power curves must be corrected for height and adjusted for air density due to location of the data compiled for the power curve. When a 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 production of 3,061,000 kWh/yr to 2,750,000 kWh/year.

Availability is the time that a wind turbine is in operational mode, and it does not depend on whether the wind is blowing. Availability relates to the reliability of a wind turbine and reliability is affected by 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 but availabilities of 98% have been reported for later units that have good programs 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. You would expect more operation and maintenance (O&M) problems with more years of operation.

Calculation of estimated energy production is simple using spreadsheets or by writing a program to perform the calculation from a histogram and power curve. The data will be in tabular form and can be graphed using spreadsheets or generic plot programs.

5.9 INNOVATIVE WIND POWER SYSTEMS

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

The West German government funded the construction of a 200-m tall tower in Spain in the 1980s [5]. A 240-m diameter greenhouse at the bottom provided the hot air to drive the air turbine rated at 75 kW and located inside the tower. A private entrepreneur in California [6] constructed a Magnus type wind turbine 17 m in diameter with a purported rated capacity of 110 kW (Figure 5.18). The unit was later moved to the wind test site of Southern California Edison located in San Gorgonio Pass. A small wind turbine with spirals on the cylinders was built. (Figure 5.19). A built-in motor spins the cylinders when wind makes the rotor rotate due to the Magnus force on the cylinders. The unit is 11.5 m in diameter and rated power is 12 kW.

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. Windstalk is based on the idea of wheat or reeds moving in the wind and would also make use of a public place (https://atelierdna.com/portfolio/windstalk/). The Vortex wind turbine is based on oscillations due to the alternating vortices around a tubular tower (https://vortexbladeless.com/). Note on the 500-kW VAWT wind test bed (Figure 10.15), a spiral staircase was used to eliminate these vortices.

The Solar Energy Research Institute (SERI), later renamed the National Renewable Energy Laboratory (NREL), was the lead agency in innovative concepts (Table 5.2), and reports on projects funded by SERI are available in conference proceedings [8–10]. The U.S. Department of Energy (DOE) discontinued funding for this program after a few years.

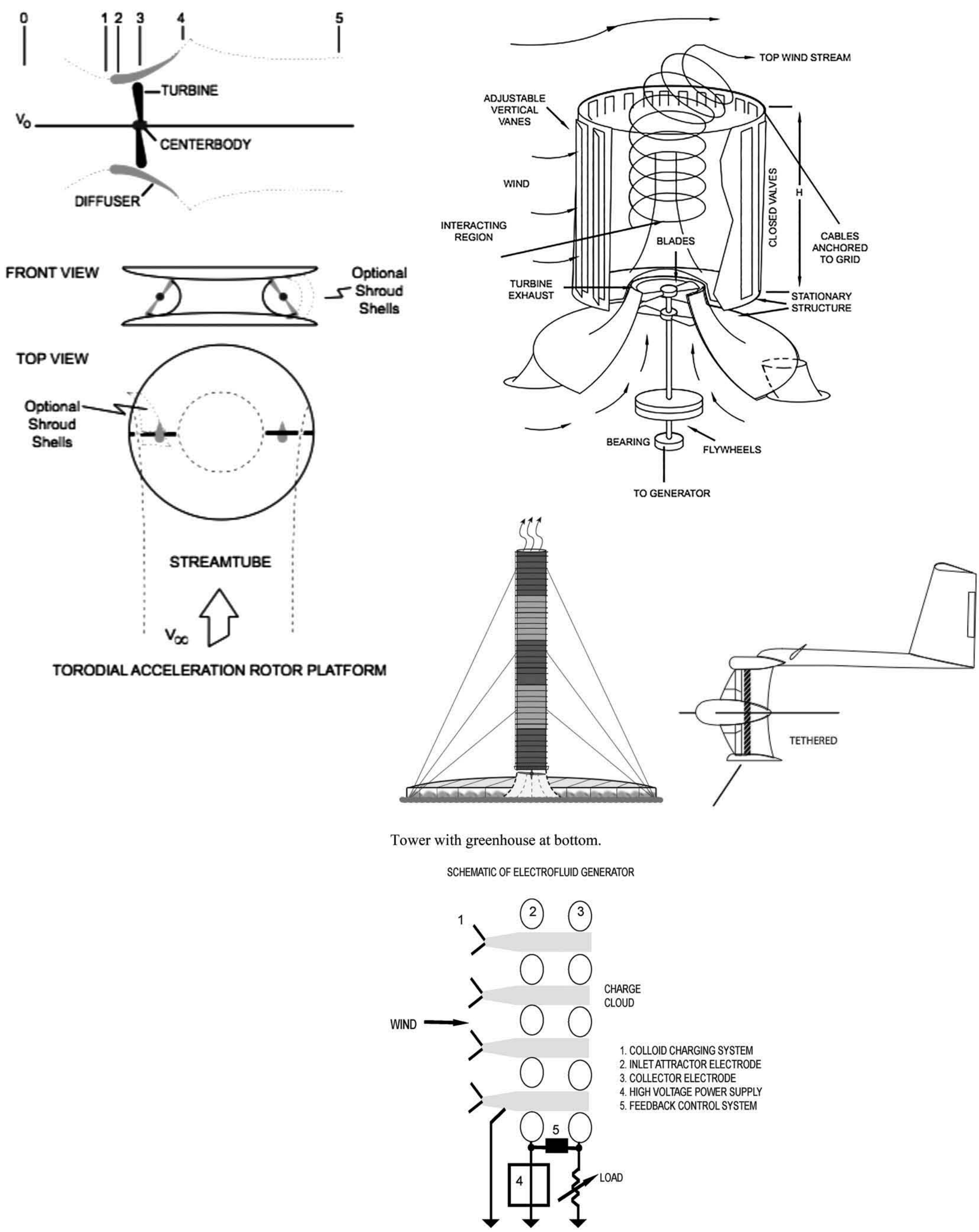


FIGURE 5.17 Examples of innovative wind turbines.

Winglets or tips (dynamic inducers) on the ends of the blades [11] that reduce the drag from the tip vortex were tested by Aerovironment and the University of Delft, the Netherlands. The results were inconclusive due to the variability of 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 wind speed variability is not a major factor, winglets can reduce drag and increase lift, as they do on some airplanes.

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 courtesy of MECARO [Japan] and Charlie Dou.)

A simple sail wing consisting of a pipe spar and a trailing edge cable was designed and built by Sweeney [12]. Some advantages are its light weight and ease of repair. Patent rights were purchased by Grumman, which 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 within a short time. The same sail wing design was used on a prototype project by the Instituto de Investigación Electricas in Mexico.

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

The idea of a confined vortex (tornado) was invented by T.J. Yen. The U.S. Department of Energy (DOE) funded theoretical and model studies of the concept. Another concept was using unconfined vortices produced along the edges of a delta wing and placing two rotors at those locations. Again, the DOE funded model studies. Existing structures could be modified or new buildings could incorporate features to increase wind speed that would be captured by a wind energy conservation system (WECS). Because wind speed increases with height, a large amount of energy could be obtained by placing rotors in low-altitude jets by use of tethered balloons or airfoils.

Another idea is to use lift translators with horizontal or vertical axes. This concept is similar to the idea of railroad cars with wings, except that cables hold the sails or airfoils and the wind turbine resembles a moving clothes line. Both concepts need wind from a predominant direction because the large units cannot be oriented. A number of foundations were constructed, and a few lift translators were built during the early 1980s in California, but they were never operational.

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

Numerous designs and several wind turbines utilizing different combinations and unusual blade shapes were built. A few examples are Darrieus or giromill wind turbines with Savonius rotors on the inner shafts for start-up torque (Figure 5.20), wind turbines with double rotors (some rotors close together, some farther apart), multiple vertical or horizontal rotors on a single shaft, double-bladed giromills, and blades with nontraditional shapes (e.g., helical curves) 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 utilized enclosures to increase wind speed or were designed to be incorporated into tall buildings.

Because of the stronger and more consistent winds at higher altitudes and thus better energy production, prototypes of tethered systems are being developed and tested [13]. Such systems are also referred to as airborne wind energy systems (AWES). One system used a helium filled balloon (Figure 5.21) while others used kites, propellers, drones, and wings and propellers (Figure 5.22). Most operating heights are from 200 to 500 m. For kites the rising portion of flight loop powers the generator on the ground.

The Noah wind turbine had two five-blade rotors (Figure 5.23) placed close to one another. The wind rotors counter-rotated, with one connected to the stator and the other to the rotor of a generator so no gearbox was needed. The wind turbine had a unique overspeed control consisting of a counterweight that tilted the rotor assembly to the horizontal position and then had to be reset manually.

FIGURE 5.20 Wind/PV streetlight, rotor is a Darrieus (1-m diameter) and Savonius for starting (wind = 300 W, PV = 120 W).

FIGURE 5.21 Protoype 10.5-m diameter tethered balloon filled with helium. Skystream wind turbine in center, diameter 3.7 m, 2.1 kW. (Photo courtesy of Altaeros Energies.)

Another system utilized multiple rotors on a coaxial shaft [14]. The line of the rotors was 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 (2.4-m diameter, two rotors, 3.7 m apart) to 4 kW. One unit contained 13 two-bladed rotors, each with a diameter of 0.5 m, and rated at 400 W. For a number of rotors on a single shaft, the almost ultimate wind turbine is the Sky Serpent (Figure 5.24).

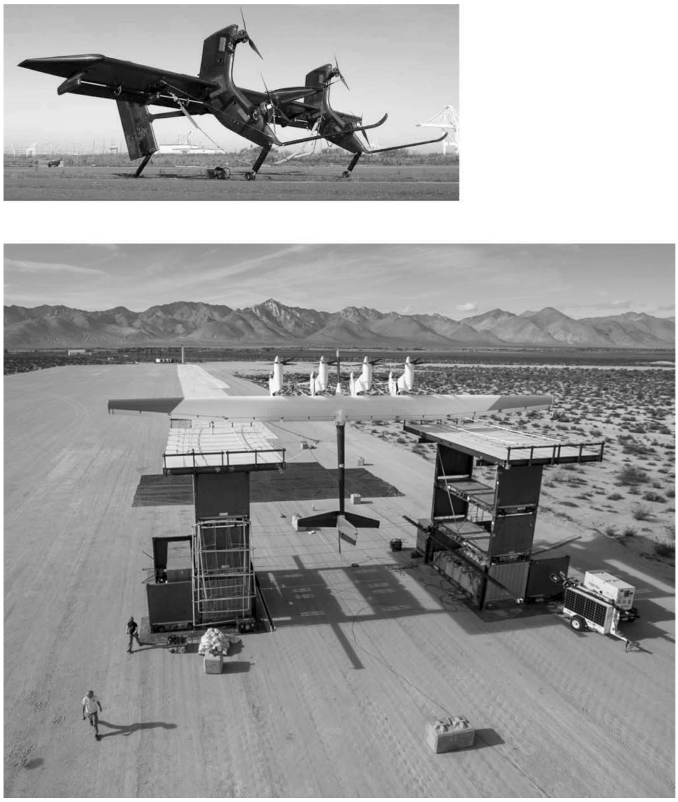


FIGURE 5.22 Tethered wing prototypes. Top (2012): Wingspan 8 m, four wind turbines, diameter ~ 0.75 m, power 30 kW. Bottom (2017): Wingspan 26 m, eight wind turbines, diameter ~ 2 m, power 600 kW. (From Makani Power, https://x.company/makani/technology/.)

FIGURE 5.23 Wind turbine with double rotor.

FIGURE 5.24 Doug Selsam with his Sky Serpent**,** 25 rotors on single shaft with a 3-kW generator. (Photo courtesy of Doug Selsam.)

Lagerway built a unit with two conventional wind turbines (25 kW each) mounted on a horizontal cross-beam at the top of a tower. The company also built another that resembled a tree. It had two more levels accommodating a total of six wind turbines.

A shroud, diffuser, duct, or even a building can increase wind flow and thereby increase the output of a wind turbine [15]. Prototypes have been built and tested and a few models are available on the market (Figure 5.25). It is generally cheaper to use longer blades than to construct a shroud or modify a building or terrain to enhance wind speed. Also, should wind turbines on a building be fixed in place or able to rotate around the structure to the highest wind speed locations?

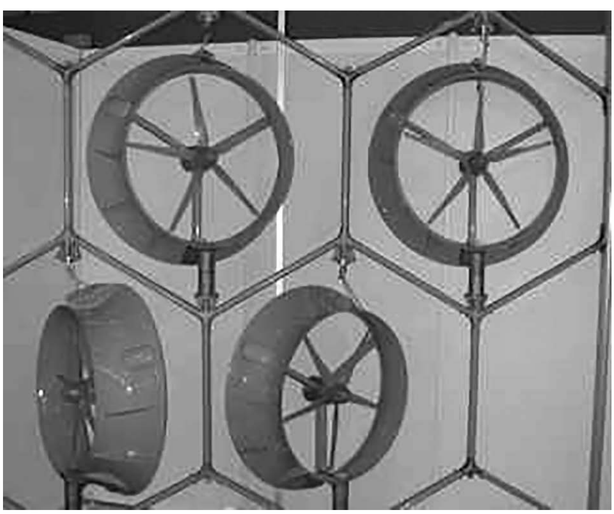


FIGURE 5.25 Small shrouded wind turbines, rotor diameter 0.68 m, rated 200 W. Can be mounted in clusters, each rotates independently. Company has larger shrouded turbine, rotor diameter 9.8 m, rated 50 kW.

FIGURE 5.26 Wind amplification turbine system at Progressive Field, Cleveland, Ohio. Dimension of the wind system, height = 6.4 m, diameter = 6.7 m, inner spiral diameter = 4.6 m. Each wind turbine is 2-m diameter, rated power = 1.6 kW. (Photo courtesy of Majid Rashidi.)

A helical structure (instead of a toroidal acceleration rotor platform) was developed at Cleveland State University [15]. The structure (Figure 5.26) has four fixed wind turbines and the whole structure is rotated in yaw to keep the turbines perpendicular to the wind. An aluminum frame (1.4 metric tons) is covered with white plastic pieces to form a helix, and the wind system rises around 12 m above the upper concourse of Progressive Field, the Cleveland Indians' ballpark. The unit is expected to generate around 40,000 kWh per year

Other ideas for innovative wind turbines appear regularly on the Internet. For example, a reciprocating wind turbine (Wind Harverster) with two horizontal airfoils operates like a teeter-totter. Another reciprocation wind turbine is based on biomechanics or biomimicry of the hummingbird. This unit consists of flapping wings that move in a figure-eight pattern. The prototype has swept area of 3.6 m^2 and runs at 450 rpm at rated power of 1 kW (www.tyerwind.com/technology/). In addition, prototypes of V-shaped VAWTs have been built.

5.10 APPLICATIONS

The kinetic energy of the wind can be transformed into mechanical, electrical, and thermal energy. Historically, the transformation was mechanical, and the end use was grinding grain, powering ships, and pumping water [17,18].

The applications can be classified as wind-assist and stand-alone systems. A wind-assist system, the wind turbine works in parallel with another source of energy to provide power. The advantages of such systems are that power is available on demand, no storage is required, and power source

and load are better matched. Stand-alone systems provide power only when the wind is blowing and the output is variable unless a storage system is connected. Wind–diesel is an application where the wind turbine is primarily a fuel saver, which is a wind-assist system. Another emerging application is a hybrid system for powering villages and telecommunications equipment.

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 directly through induction generators and synchronous generators, or indirectly by variable-frequency alternators and DC generators connected through inverters. The utility line and generating capacity of a power station act as a storage system. For stand-alone systems, battery storage is the most common option.

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

5.10.2 Mechanical Energy

The major use for windmills has been the pumping of water. Farm windmills are well designed to pump small volumes of water at low wind speeds. Because a farm windmill has a large number of blades (vanes), it will start under a load because it has a large torque. However, many blades require a lot of material and the units are 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 [19,20]. 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. It is difficult to match the power output of the wind turbine with the power needed by the irrigation pump. Calculated maximum efficiencies were very low, about 10% for both types of pumps.

Airlift pumps have the advantage of employing 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. Koenders Windmills makes an airlift pump (www.koenderswindmill.com) and two U.S. companies manufactured a wind-powered airlift pump to compete with farm windmills; both are now out of business.

For maximum efficiency, the submergence (depth of pump below water level) should be equal to the lift. Wells with little water at large depths present problems 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 to serve as a wind-assist system for pumping water. The other power source could be an electrical motor or internal combustion engine. Both systems have been tested.

5.10.3 Thermal Energy

Thermal energy can be obtained directly by churning water or another 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 [21–23]. Conversion of electrical to thermal energy by resistance heating has been tested a few times [24], and one company marketed such a wind system.

5.10.4 Wind Hybrid Systems

A large market exists for wind-assist to diesel-generated electricity systems for isolated communities, businesses, farms, and ranches [25]. About 1.1 billion people live 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 needing energy of 20–200 kWh per day [26,27]. Hybrid systems have also been installed in very remote locations such as military facilities and telecommunications systems. For telecommunications, the emphasis is on continuous power, so redundancy is important to achieve high reliability.

NREL established a site dedicated to hybrid systems for village power. The Renewables for Sustainable Village Power (RSVP) project database covered about 150 projects (50 involved wind) in over 30 countries. Project information included basic concepts, technological requirements, economic and financial data, host country descriptions, lessons learned, pictures and graphics, and contact information. The database is now archived and is not available online.

A large number of hybrid projects have been installed since 2004. For example, China now has over 700 village installations (16-MW capacity) powered by mini hydro, photovoltaic, or wind–photovoltaic hybrid systems [28]. Alaska has 63 MW of wind–diesel systems and China has also installed a few wind–photovoltaic–diesel systems [29].

5.11 SUMMARY

Applications will be considered in more detail after we learn more about design and construction of wind turbines. Electricity generation is the most used application of wind power. The problem of load matching when pumping water for irrigation must be a design consideration.

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 in a good wind resource area.
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 four, five, or six) from the 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 the European wind map.
6. For a giromill, H = 10 m, D = 12 m, estimate annual energy output for two different regions from the U.S. wind power map.
7. From the 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 to convert rpm to rad/s).
   a. Wind turbine operating at 160 rpm (line A).
   b. Wind turbine operating at maximum power coefficient (line B).
   c. Wind turbine operating at constant torque (line C) of 6,000 Nm.

9. From Figure 5.13, the wind speed is 12.5 m/s (where lines A, B, and C cross). What is the torque? What is the rpm measure? What is the power?
10. Calculate the wind speed frequency distribution for the data in the Table 5.1.
11. Calculate the annual energy production for a mean wind speed of 8.2 m/s and average air density of 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 are the cut-in and rated wind speeds for the 1,000-kW unit?
13. Refer to Figure 5.15. What are the cut-in and rated wind speeds 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 caused by fault on the utility line, how much time is available for shutdown of the wind turbine?
17. For innovative wind systems, what are two or three major problems with tethered wind turbines?
18. A wind amplification system (Figure 5.26), is expected to produce 40,000 kWh per year. Use a wind map and area of the wind energy conversion system to estimate annual energy production. Is the result larger or smaller than the estimate given? In your opinion, is the cost for the extra structure economical? Justify your answer.
19. What is the estimated increase in energy per year for tethered systems?

LINKS

Altaeros Energies (tethered wind). www.altaerosenergies.com
Bergey Windpower http://bergey.com (wind–CAD performance models; can download spreadsheet, bergey.com/documents/2012/03/excel-10-grid-intertie.xls
Makani Power (tethered wind). https://x.company/makani/
Sky Windpower (tethered wind). www.skywindpower.com
Amphx Power (tethered wind). www.ampyxpower.com
Kite Power Systems (tethered wind). Has video of two kites in the sky. www.kps.energy
Mother Nature Network, nine ingenious wind turbine designs. www.mnn.com/earth-matters/energy/photos/9-ingenious-wind-turbine-designs/wind-harvester

REFERENCES

1. E. F. Lindsey. 1974. Windpower. *Popular Science*, July, 54.
2. B. Kocivar. 1977. Tornado turbine. *Popular Science*, January, 78.
3. V. Chase. 1978. 13 Wind machines. *Popular Science*, September, 70.
4. J. Schefter. 1983. Five wild windmills. *Popular Science*, June, 76.
5. B. Juchau. 1983. A 650-foot power tower. *Popular Science*, July, 68.
6. J. Schefter. 1983. Barrel-bladed windmill: Power from the Magnus effect. *Popular Science*, August, 70.
7. G. Lorente. 1982. Nuevo concepto de generador elctro-eólico. *Metalurgia y Elctricidad*, 532, 51.
8. SERI (Solar Energy Research Institute). 1980. In *Proceedings of Second Wind Energy Innovative Systems Conference*, Vols. I and II, pp. 635–638 and 938–1051.
9. SERI (Solar Energy Research Institute). 1981. In *Proceedings of Fifth Biennial Wind Energy Conference and Workshop*, Vol. I, p. 415.
10. American Solar Energy Society. 1983. In *Proceedings of Sixth Biennial Wind Energy Conference and Workshop*.
11. D. Scott. 1983. Tip-vane windmill doubles output efficiency. *Popular Science*, September, 78.
12. S. Kidd and D. Garr. 1972. Electric power from windmills? *Popular Science*, November, 70.
13. A. Cherubini, et al. Nov 2105. Airborne wind energy systems: A review of technologies. *Renewable and Sustainable Energy Reviews*, 51: 1461–1476.
14. D. Selsam. www.selsam.com.

15. Y. Ohya, T. Karasudani, T. Nagai et al. 2011. *Development of shrouded wind turbines with wind-lens technology*. Poster presented to European Wind Energy Association. www.riam.kyushu-u.ac.jp/windeng/img/aboutus_detail_image/EWEA2011_poster.pdf.
16. Cleveland State University. Wind Amplification Turbine System. www.csuohio.edu/sustainability/wind-amplification-turbine-system.
17. V. Nelson, N. Clark, and R. Foster. 2004. *Wind Water Pumping*. CD, Alternative Energy Institute, West Texas A&M University: Canyon, TX. Contact: kstarcher@wtamu.edu.
18. V. Nelson, N. Clark, R. Foster et al. 2005. *Bombeo de agua con energía eólica*. CD, Alternative Energy Institute, West Texas A&M University: Canyon, TX. Contact: kstarcher@wtamu.edu.
19. R. E. Chilcott and E. B. Lake. 1966. Proposal for the establishment of a 10-hp windmill water pumping pilot plant in Nevis, West Indies. Brace Research Institute Publication I.45.
20. T. A. Lawand. 1968. The evaluation of a windmill water pumping irrigation system. Brace Research Institute Publication I.58.
21. W. W. Gunkel et al. 1981. Wind energy for direct water heating. Report DOE/SEA-3408–20691/81/2 available from NTIS.
22. D. H. Lacey and W. W. Gunkel. 1980. Operating performance and observed performance of a SEWCS for direct water heating. In *AWEA, Proceedings of National Conference*, V. Nelson, Ed., p. 96.
23. M. Rolland and D. Cromack. 1980. Wind-driven fluid devices for water heating. In *Proceedings of National Conference*, V. Nelson, Ed., p. 93.
24. M. Edds. 1980. UMASS wind furnace performance and analysis. In *AWEA, Proceedings of National Conference*, V. Nelson, Ed., p. 142.
25. R. Hunter and G. Elliot, Eds. 1994. *Wind–Diesel Systems: A Guide to the Technology and Its Implementation*. Cambridge University Press: Cambridge, U.K.
26. L. Flowers et al. 1993. Decentralized wind electric applications for developing countries. In *AWEA, Proceedings of Windpower Conference,* p. 421.
27. L. Flowers et al. 2000. Renewables for sustainable village power. In *AWEA, Proceedings of Windpower Conference*.
28. C. Dou and J. Graham, Eds. 2005. *China Village Power Project Development Guidebook*. CD, in Chinese and English.
29. C. Dou, Ed. 2008. Capacity building for rapid commercialization of renewable energy in China. Chemical–Industrial Press: Beijing.

6 Design of Wind Turbines

6.1 INTRODUCTION

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

Someone made the comment that you could use brooms for turbine 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 developed for wings on planes and sailplanes were later used for wind turbine blades.

In wind turbine history, aerospace engineers thought that the design and construction of wind turbines would simply involve 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 highly variable loads and must include control mechanisms for shedding power in high winds.

A lot of research and development, primarily by universities and national laboratories, and later by the manufacturers of wind turbines, created today's wind industry. The design of wind turbines requires a broad cross section of knowledge of aerodynamics, mechanical engineering, electrical engineering, electronics, materials and industrial engineering, civil engineering, and meteorology. The design process is iterative from first concept to final design, and it is easier to fix problems at the design stage than deal with 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. Since early measurements were made for use with airplanes, a lot of airfoil data [1] are available from national laboratories. 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 past stall (beyond a stall point, an airplane loses lift, stalls, and falls). Lift and drag data for attack angles up to 180° were available only for a few airfoils. Airfoils exhibiting large ratios of lift to drag were developed for sailplanes.

Choices of airfoils for wind turbines depend on the ratio of lift to a drag and a number of other factors. Because the requirements are different for wind turbines, airfoils were designed specifically for wind turbines starting in the late 1980s. A major change was designing 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 performances of wind turbines. This theoretical performance can be checked against the measured outputs of models in wind tunnels, truck testing for small-diameter units, or field testing (atmospheric) of wind turbines. At one time, larger turbines mounted on railroad flat cars were used for controlled speed testing.

Overall efficiencies of the rotor, drive train, and energy converter (generator, etc.) must be tested. Complete analyses covering design of wind turbines, primarily rotors and structures, can be found in more advanced texts [3–13]; however, a knowledge of basic physics is useful for a qualitative understanding of rotor performance.

6.3 MATHEMATICAL TERMS

The momentum of a particle equals the mass times the velocity. Boldface indicates a vector that has both magnitude and direction. In two dimensions, two components are required to define a vector; in three dimensions, three components are required. In an analytical representation, a vector can be represented by its components along two axes (perpendicular and orthogonal for this presentation).

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

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

$$M\boldsymbol{R} = m_1\boldsymbol{r}_1 + m_2\boldsymbol{r}_2 + \cdots + m_i\boldsymbol{r}_i \tag{6.2}$$

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

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

Torque makes a particle turn around some point and 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 increasing the force.

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

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

If a mass is attached to a rod that is free to rotate about its end (Figure 6.1) and a force is applied, the torque will make the mass rotate, and power will be available. The amount of power is the product of the torque and angular velocity [Equation (6.5)] and the power is available at the shaft. Most operations of transferring shaft power utilize large ω because of structural considerations.

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

Also, a rotating object will have rotational kinetic energy.

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

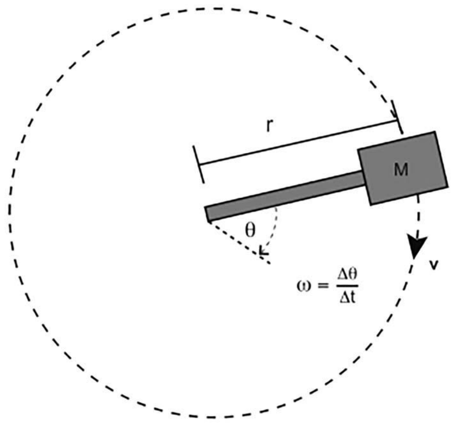


FIGURE 6.1 Mass rotating about a point.

where the speed of the rotating mass depends on the radius $v = \omega r$. 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 value, no direction). Also note that no work (gain or loss of energy) is done if the force is perpendicular to the motion. An example is the motion of the moon around the Earth.

$$W = \mathbf{F} \cdot \Delta\mathbf{r} = \mathbf{F} \cdot (\mathbf{r}_j - \mathbf{r}_i) \tag{6.8}$$

The dot between the vectors means only the parallel component of the **F** is used ($W = \mathbf{F} \cos\theta\ \Delta\mathbf{r}$), where $\Delta\mathbf{r}$ = final position–initial position, and θ is the angle between **F** and **r**. We then divide both sides of Equation (6.8) by time:

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

Thus, the power is

$$\mathrm{P} = \mathbf{F} \cdot \mathrm{v} \tag{6.9}$$

6.4 DRAG DEVICE

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

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

where C_D is the drag coefficient. Drag coefficients for different shapes are given in *Marks' Handbook* [14], but the simplest procedure is to use $C_D = 1$ for round pipes and wires and flat plates perpendicular to the wind. Flat plates at an angle to the wind will experience some lift and drag like airfoils, and C_D data are available.

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

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

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

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 is improved by reducing the drag coefficient and decreasing speed. Automobile manufacturers are doing everything possible to decrease drag coefficients, even by small increments.

The power coefficient for a drag device can be calculated from the relative wind speed experienced by the device and the device speed. The relative velocity of the wind as measured by a sensor mounted on the drag device is $v_r = v_0 - u$ where v_0 is the wind speed and u is the speed of the device. The power per unit area from Equation (6.9) is

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

Notice that at $u = 0$ and $u = v_0$, the power is zero. In other words, no power is output if a drag device is not moving, and a 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 $C_{P(\max)} = 4/27 = 0.15$ 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 coefficients greater than 1 and 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 no commercial drag devices for generating electricity are available.

6.5 LIFT DEVICE

A lift device can produce about 100 times more power per unit surface area of blade than a drag device. See Rohatgi and Nelson [15, chap. 6] for more details.

Example 6.1

Suppose we have a two-blade wind turbine. Each blade is 5 m long and 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.

An example of a lift device is a sailboat—a lift translator (Figure 6.2) whose sails form an airfoil. Notice that a sailboat moving downwind (drag device) moves much slower than a sailboat moving perpendicular to the wind (lift device). Using lift translators to generate power has been proposed. The problems are the large speeds of the devices because lift devices can move faster than the wind, proximity to the ground, and the need for a predominant wind direction. Some lift translators were built, but never operated successfully.

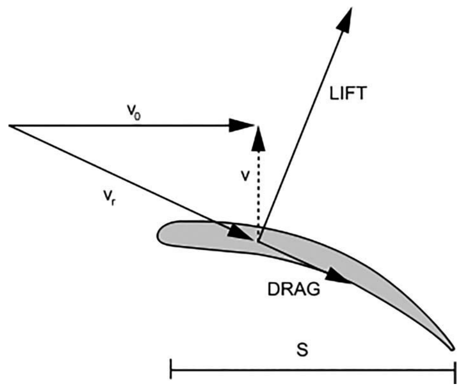


FIGURE 6.2 Lift translator. Direction of motion v is perpendicular to the ground wind v_o. S is length of the cross sectional area of blade or sail.

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, or screw), and a pressure drop occurs across the disk (Figure 6.3). The thrust (force) loading *T* is uniform across the disk and no friction or drag force is present. At large distances behind and in front of the disk, the wind speed and pressure will have the same values. As stated earlier, the pressure *p* is the force/area.

The concept of conservation of momentum is: 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

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

Using 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, the pressure decreases; the two are

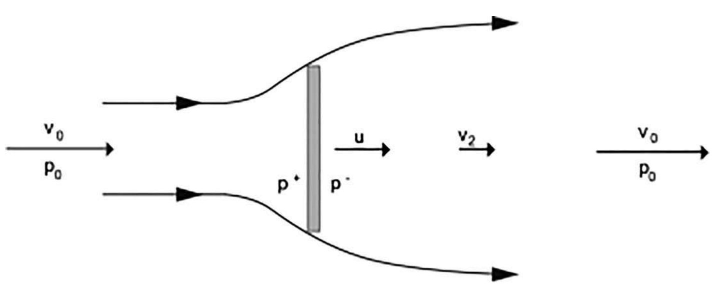


FIGURE 6.3 Wind speeds and pressures at infinity, at disk, and behind disk.

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 we set Equation (6.13) equal to Equation (6.15):

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

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 the ratio to which 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 because all the mass would pile up at the rotor. The power is equal to the change in kinetic energy from upstream to downstream: $P = \frac{\Delta KE}{t} = \frac{KE_{us} - KE_{ds}}{t} = 0.5\frac{m}{t}v_0^2 - 0.5\frac{m}{t}v_2^2 = 0.5\rho Au\left(v_0^2 - v_2^2\right)$ 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 area is for the drag device that reaches a maximum around 0.22 at a speed ratio of 0.3. The maximum for the lift device is around 15 at a 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 coefficient of 1.5. For the lift device, the ratio of lift coefficient to drag coefficient was 10. Thus, the lift device can easily produce 50 times the power/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.

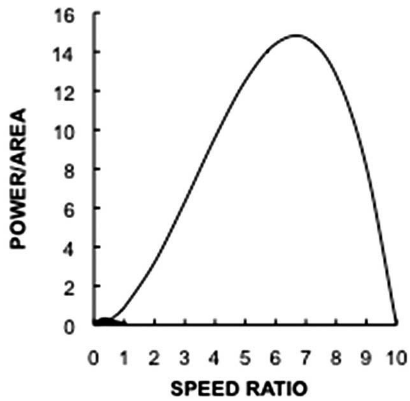


FIGURE 6.4 Comparison of power/area for a translating drag device (small solid curve) and a translating lift device versus speed ratio of the device to the wind.

6.5.1 Maximum Theoretical Power

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

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

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 from 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 instead of drag devices; the maximum power coefficients are 50% versus 20%, respectively. However, a farm windmill that has some of the same characteristics as a drag device (large solidity, low tip speed ratio) is well designed to pump low volumes of water.

6.5.2 Rotation

Angular momentum is

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

Angular momentum, like momentum, is always conserved. Based on the concept of conservation of angular momentum, a rotating disk will impart rotation to the wake in the opposite direction of the disk (Figure 6.5). From the conservation of energy concept,

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

The torque acting on the rotor makes it rotate and power can be extracted. 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 wake = ω).

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

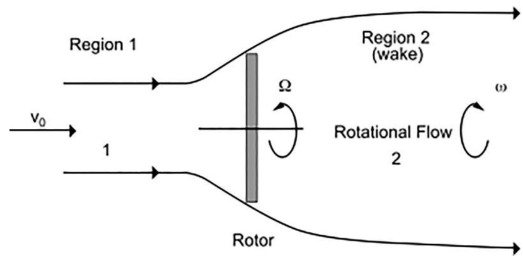


FIGURE 6.5 Rotor imparts a rotation to the wake.

A similar analysis, as previously described, can determine the power extracted when 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 rotor velocity is a function of the radius, so the values must 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 that act at the quarter chord of the airfoil are represented by a (tangential) force that makes the blade rotate and a (perpendicular) force trying to push the rotor over. If these lift and drag forces are calculated for a blade, the tangential and perpendicular forces are calculated and the rotor performance can be predicted. If the angle between the blade path and the wind at the blade is Φ (Figure 5.9), the tangential and perpendicular forces are

$$F(\tan) = L\ \sin\Phi - D\ \cos\Phi$$

$$F(\text{per}) = L\ \cos\Phi + D\ \sin\Phi \tag{6.23}$$

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

A number of computer programs can predict aerodynamic performance of wind turbines [16]. These are based on the momentum (or strip) theory that assumes that each element of a 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,

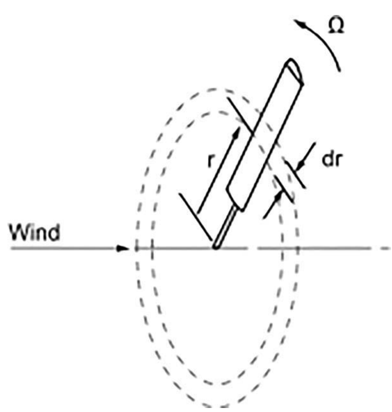


FIGURE 6.6 Blade element.

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 calculate total performance.

Drag and lift coefficients versus angle of attack and Reynolds number are available for many airfoils. In general, the coefficients are given for attack angles near zero to a few degrees past stall. Stall occurs when lift decreases and drag increases steeply. The problem in calculating performance predictions is using the correct inflow angle to the blade because the angle depends on the wind speed at the blade.

The relative wind speed must be corrected for the actual speed at the blade using 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, lift and drag data for the angles 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 of the programs are the treatment of unsteady aerodynamics in the region of dynamic stall and the use of two-dimensional 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 Darrieus wind turbines. A number of performance models for the Darrieus rotor have been formulated [3,17–19]. In general, symmetrical airfoils are used, so lift and drag data are needed from 0 to 180°. The operation of a vertical axis wind turbine at an attack angle of 90° also means no lift, so the torque and power are negative and a cyclic variation occurs on every revolution [20].

From observations of the flow field of a Savonius rotor, an analytical model was developed for the analysis of performance [3]. Two major discernible features of the flow field are: (1) counter-rotating vortices are shed from the vane tips when a vane is approximately at right angles to the flow, and (2) 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 blades and larger power output than the predictions from the performance codes using steady-state data for lift and drag. Dynamic stall may occur during operation in high winds due to gusts on constant pitch blades or on 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. After 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. Westinghouse wind turbines installed in Hawaii and rated at 600 kW had this problem as power spikes to 800 kW occurred during shutdown. The solution was to change the blade pitch in the run position to lower the rated power, so when a spike occurred during high wind shutdown, the loads and power were not too high. Now lift and drag data for some airfoils are available that show dynamic stall for changing attack angles. These data can be used for performance prediction.

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 [21]. Blades with pressure taps were used for an unsteady aerodynamics experiment [22] that included a test of an extensively instrumented wind turbine in the giant (24.4 × 36.6 m) NASA Ames wind tunnel. Results from computer models at high wind speeds under stall were significantly different; power predictions ranged from 30 to 275% of the measured values. Hence aerodynamic performance prediction programs are used as design tools, not final answers.

Aerodynamic performance prediction programs are available for personal computers, and include menu-driven interactive editing and graphical displays to facilitate use as design tools. The inputs to PROP93 program [23] include blade characteristics (number, length and hub cut-out, platform, twist, 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 of PROP93 in metric or English units may be directed to a screen, printer, or data file. 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 steady-state programs do not predict the high loads seen in the field from gusts or from 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 6.8–6.10) are for a Carter 25 wind turbine, NACA 2300 series airfoil. Smoother graphs would be obtained by using 20 data stations. These blades had large twist and larger chord toward the root and 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, starting torque is insufficient and the rotor needs to be motored for start-up. Variable pitch 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 [24] 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 used for the global post-stall method for predicting post-stall 3D airfoil characteristics to be used with 2D airfoil data.

PROPID [25] is a personal computer program for the rotor design and analysis of horizontal axis wind turbines, and the executable program is available online [26]. The strength of the method is

TABLE 6.1
Sample Output from PROP93

Propprint 3

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	$V_{0\ m/s}$	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.

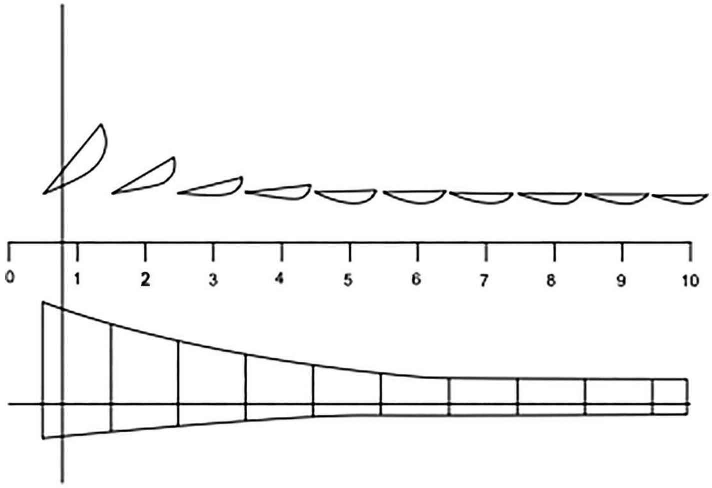


FIGURE 6.7 Twist and planform for Carter 25 wind turbine blade. Blade is divided into 10 sections for analysis. The station is at the midpoint of the section.

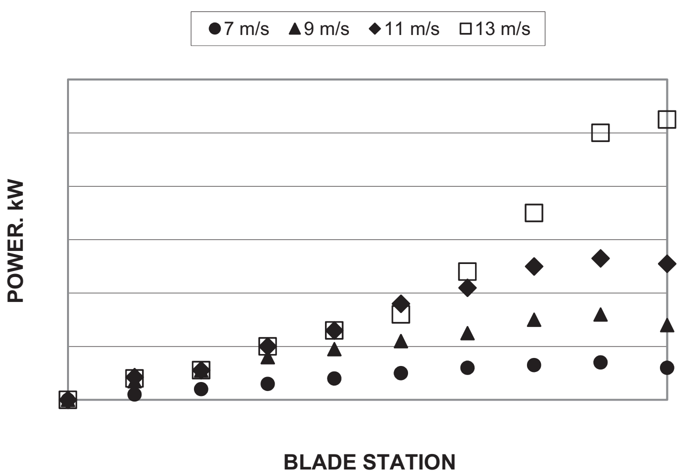


FIGURE 6.8 PROP93: Prediction of power output for one blade by blade station for four wind speeds. Tip speed ratio = 6.1.

its inverse design capability. PROPID is based on the PROPSH blade element/momentum code, and includes a 3D post-stall airfoil performance synthesization 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 (AEI) also fabricated test blades for the Carter 25, which used new airfoils designed specifically for wind turbines by the National Renewable Energy Laboratory (NREL) [27].

The criteria for the design of thin airfoils were high lift to drag for the inboard blade portion, restraining 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 splines under tension [28,29].

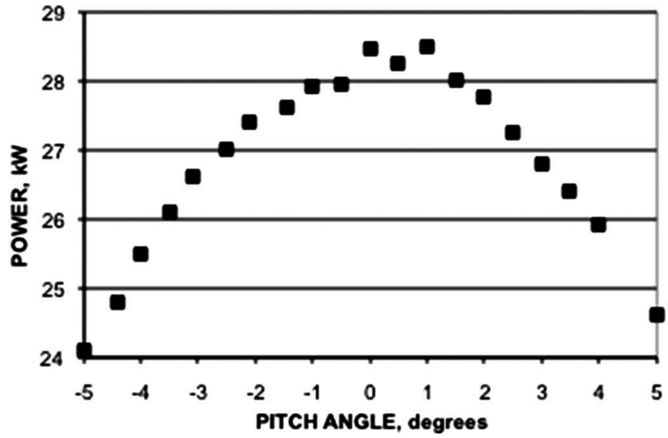


FIGURE 6.9 PROP93: Prediction of rotor power output for different pitch angles at 10 m/s. Carter 25 wind turbine is a fixed-pitch, constant rpm machine.

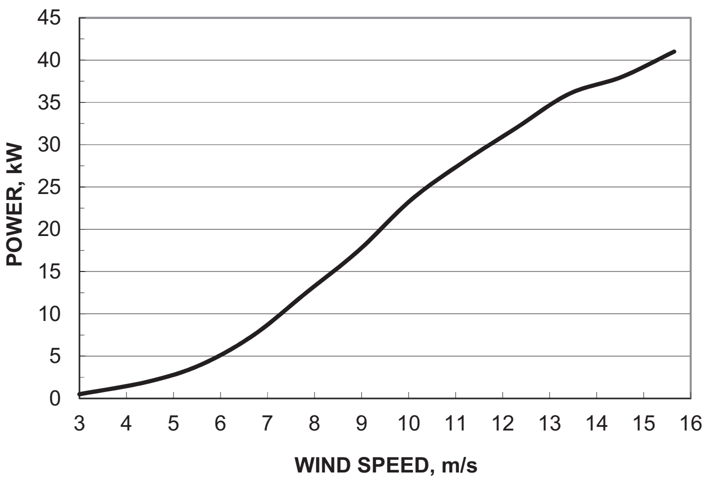


FIGURE 6.10 PROP93: Theoretical power curve for Carter 25 rotor, tip speed ratio = 6.1.

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 a blade cannot be constructed practically. Therefore, the program permits various input constraints 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 with the proper twist (Figure 6.12). The blade templates were then used to construct a plug, from which top and bottom molds were constructed. After fabrication of the skins, the blades were attached to a Carter 25 spar and hub and tested in the field in a side-by-side comparison with a production unit [30,31]. Data were collected at low, medium, and high wind speeds for clean, medium, and heavy surface roughness conditions.

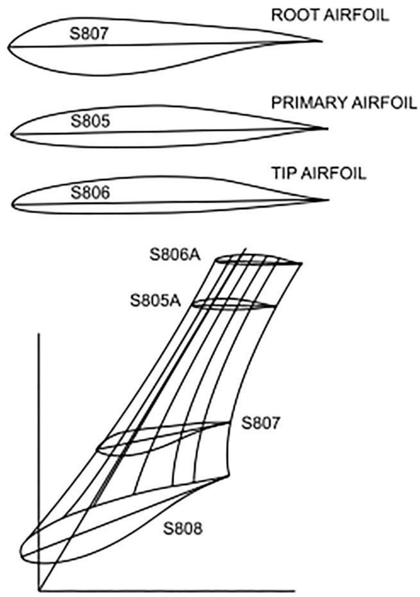


FIGURE 6.11 Thin airfoil series for wind turbine blade, and their input placement for 5-m blade.

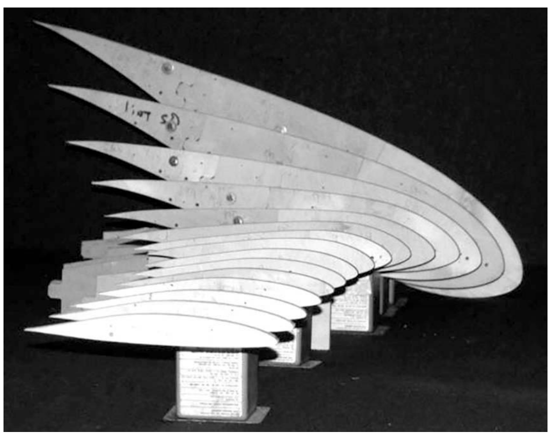


FIGURE 6.12 Blade templates using new thin airfoils for Carter 25 wind turbine, fabricated by AEI. There are three different airfoils, and thus there are different shapes along with different chords and twists at the ten stations.

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 edges. 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. However, the new airfoils were much less sensitive to surface roughness at medium and high wind speeds.

Essentially the same amount of power can be obtained from one blade rotating fast, more blades rotating more slowly, or the same number of blades with different chord lengths. Performance prediction programs show that 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 a unit by increasing the rated wind speed.

In the past, many wind turbines were built with the same 10-m diameter and their rated powers were 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 new standard (Small Wind Certification Council) for small wind turbines in the United States is rated power at 11 m/s.

The design engineers of wind turbines follow a number of rotor parameters to select: airfoil, planform, solidity, number of blades, radius, tip speed ratio (variable or fixed), and others. The most efficient blade from an aerodynamic view is generally more difficult to construct from a practical and manufacturing standpoint. Early blades (and propellers) were made from wood, and a commonly used airfoil was the NACA 4400 series because its bottom side was flat. Other airfoils with better lift to drag such as the NACA 23000 series and the LS1 airfoil were used. These airfoils had cambers curved on the bottom sides that made them somewhat more difficult to construct.

An aerodynamically efficient blade will have the largest twist and chord at the root that then decreases toward the tip; however, because of other considerations, the inner part of the blade is designed generally to achieve 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 had 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 determined by the solidity of the rotor. In general, the blade tip speed is limited to roughly 70 m/s since the blade tips cause excessive acoustical noise at higher tip speeds. For an offshore wind turbine, noise is not an important issue. Besides the rotor design there is the design of the rest of the system; hub that may include components for adjusting blade pitch; drive train and gearbox in most cases; generator; yaw control; tower; and control system.

6.7 MEASURED POWER AND POWER COEFFICIENT

A common specification is the power output of the wind turbine versus wind speed depicted by a power curve. The curve generally includes all efficiencies from wind to electrical output in addition to rotor efficiency. Since all wind turbines must control power output at high wind speeds, efficiency decreases at some point. 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 a band of values, not a line.

The experimental power and power coefficient curves (Figure 6.13) apply to 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 that includes drive train and generator is possible because this unit has an almost optimal blade (taper, twist, and thickness).

Besides the tip and hub losses of the blades, a further reduction of the power coefficient will occur due to the inefficiencies of the mechanical system (drive train, coupling) and the generator. Under optimum design conditions, the modern two- or three-bladed rotors at tip speed ratios in the range of about 4–10 will have power coefficients of about 0.4–0.5 (Figure 6.14). The power coefficients for farm windmills and 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—lower than those for the horizontal axis wind turbines. This is one reason vertical axis wind turbines are not commercially available for wind farms.

The three methods of regulating output are passive stall in which the wind turbine operates at fixed rotational speed with fixed pitch blades; active stall in which the wind turbine operates at fixed

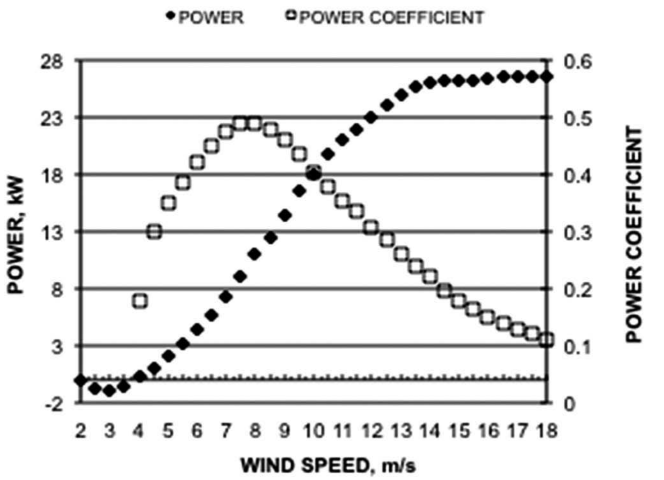


FIGURE 6.13 Experimental power and power coefficient for a Carter 25, rated 25 kW, 10-m diameter. Notice_at 3 m/s the turbine uses power (energy for the field coils of the induction generator).

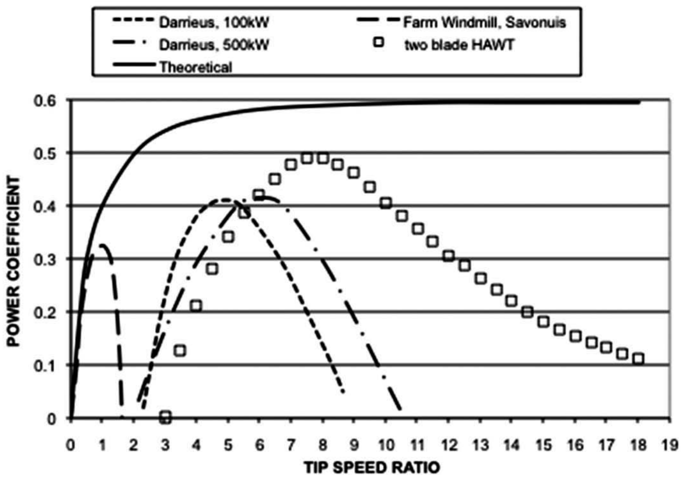


FIGURE 6.14 Experimental power coefficients for different rotors compared to the theoretical value: farm windmill [32], Savonius [33], 100 kW Darrieus [34], 500 kW Darrieus [19], horizontal axis wind turbine, Carter 25 (data from Figure 6.13).

rotational speed with adjustable pitch; and variable pitch in which 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 (pitch motors located in the hub; variable pitch tips; and ailerons (flaps on airplane wings) to control aerodynamics even though pitch is not adjustable. The variable pitch tips and ailerons have pitch motors in the blades. The most common method for large wind turbines is full-span control, although wind turbines have been built with the other two methods. The MOD-2 and MOD-5, large prototype turbines funded by U.S. government, had tip controls.

Ailerons are moved to the low-pressure side of a blade to reduce lift, in contrast to flaps on airplanes that are moved in the opposite direction to increase lift. A NASA–DOE program investigated

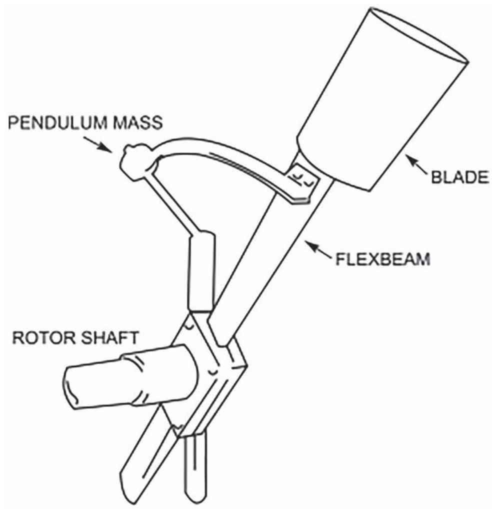


FIGURE 6.15 Passive control with flexbeam and pendulum weights, unit was constant rpm operation. Injection mold blade for 300-W unit has carbon filaments.

ailerons both theoretically and experimentally for application to medium and large wind turbines [35]. Zond built and installed 12, 500-kW units with aileron control near Fort Davis, Texas, as part of the Utility Wind Turbine Verification Program [36]. However, after 4 years of operation they were dismantled; one reason was maintenance problems with the ailerons. Finally, the control system for the Italian Gamma 60 1.5-MW wind turbine with fixed pitch blades was yawing the rotor and that presented the problem of differences in lift on the blades on each cycle.

Efforts have been made to develop passive pitch control techniques that adjust the blade pitch angle without need for actuators [37]. 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) attached in the middle to the drive shaft. The twist was sufficient 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. Also, the weights provided control at high winds by twisting the blades toward stall. One problem was that the flexbeam moved toward a different set twist over time and that reduced the starting torque.

The Proven wind turbine had a exible hinge (delta-3) near the root of the blade [38]. As rotor rpm increased, the blades were forced outward. The blade pitch changed toward stall and the blades coned, thus reducing the rotor swept area. 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 carved from single pieces of wood or from wood blocks glued together from several pieces. The material properties of wood are good: strength, exibility, 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 excessive.

One type of larger blade was constructed like an airplane wing with a spar, ribs, and a covering. The spar is the load-bearing element 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, for example, aluminum, fabric, or metal covers on ribs and spars (like an airplane wing). Other examples are a sail wing made of fabric attached to a leading edge spar; a laminated wood composite shell; berglass-reinforced plastics (FRPs) and carbon bers; pultruded FRPs; extruded aluminum (blades for vertical axis wind turbines); and small turbine blades made from injection molds.

Pultruded blades are made by pulling the berglass and other parts through a die and applying epoxy at the same time; then the blades are cut to length. Extruded blades are made by pushing the material through a die. Blades for Darrieus wind turbines are bent to curvature after extrusion. Cross sections of some blades illustrating different manufacturing processes are presented in Figure 6.16.

A blade on a wind turbine goes through more fatigue cycles in 1 year than airplane wings undergo in their lifetimes. Therefore, fatigue is the major concern of wind turbine manufacturers and operators because wind loads are large and variable. The fatigue properties of metal blades built for wind turbines are not satisfactory and many failures resulted. Carbon laments are used in blades because they are stronger, even though they are more costly than glass laments. The limitation on pultruded FRP blades is the constant chord with no twist. FRP blades incur additional costs for

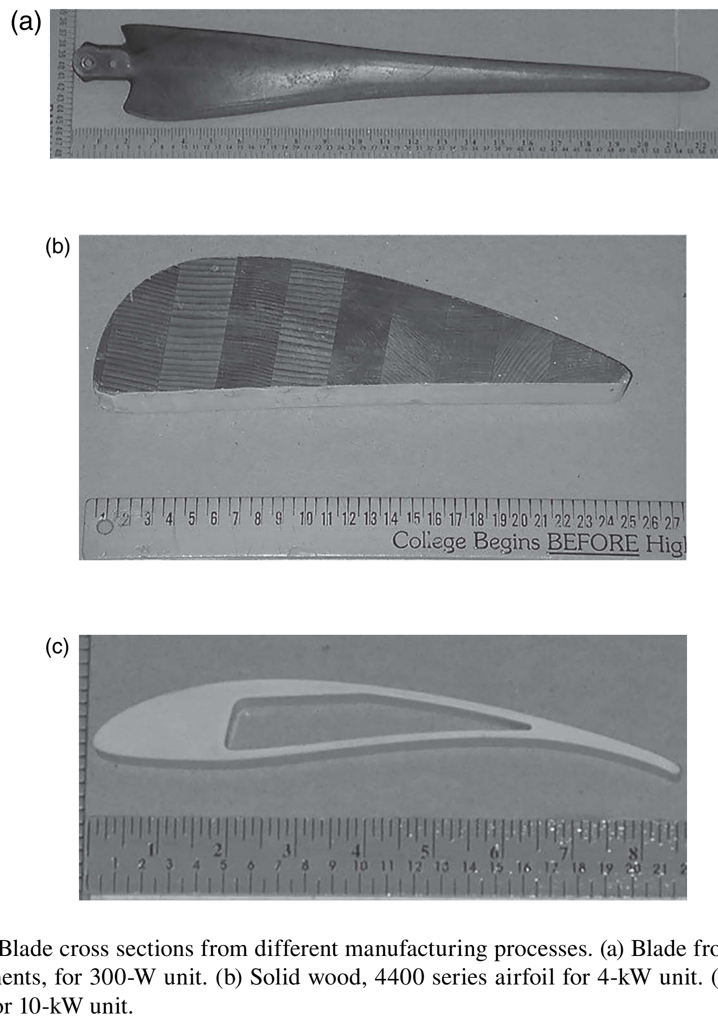


FIGURE 6.16 Blade cross sections from different manufacturing processes. (a) Blade from injection mold, has carbon filaments, for 300-W unit. (b) Solid wood, 4400 series airfoil for 4-kW unit. (c) Pultruded FRP, special airfoil, for 10-kW unit.

(Continued)

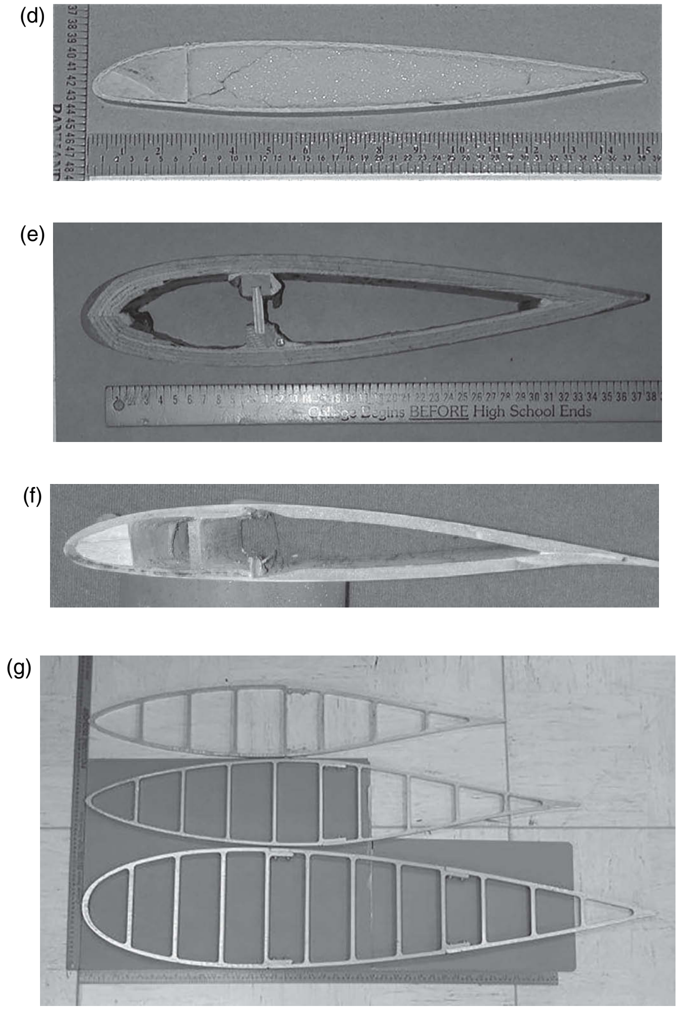


FIGURE 6.16 (CONTINUED) Blade cross sections from different manufacturing processes. (d) Pultruded FRP, airfoil 23012, for 25-kW unit. Notice lead weight in nose and foam to keep skins from flexing. (e) Laminated wood composite blade for 50-kW unit. (f) FRP, airfoil LS1, for 300-kW unit. Hand layup in three molds, top and bottom skins are attached to nose (D-spar with lead weight in nose). (g) Extruded aluminum for 500-kW VAWT, 34-m test bed. Bottom (chord 1.2 m) from three pieces. The other from two pieces (top chord 0.9 m).

master molds and there is a trade-off between automated winding of laments and hand layup. Molds are expensive and dies for the extruded aluminum blades are even more expensive.

The material for blades is predominantly FRPs, for both spar and blade skin, which also supports the load. Large wind turbine blades are constructed very differently from 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 Wind Power, the world's leading supplier of blades [39].

The aeroelastic blade incorporates the coupling of blade bending and twisting so that rotors can be larger in diameter, while still staying within the turbine load envelope for the nacelle, tower, and foundation.

Small wind turbine manufacturers have also switched from wood to FRP blades. Composite wood laminate blades (6.5 m long) have been successful on 50-kW units.

FIGURE 6.17 Blade cross sections for megawatt wind turbines.

The Sandia National Laboratory concentrates research on the aerodynamic and structural designs of wind turbine blades [40]. Topics include adaptive structures, thick airfoils, material and fatigue, manufacturing issues, design tools and applications, and sensors and nondestructive inspection. Reports in all of these areas are listed online. Another aspect of its program is a joint project with NREL to collect experimental inflow and turbine response data for a long-term inflow and structural test. One of the instrumented wind turbines is a GE 1.5-MW unit.

Vortex generators have been used to improve aerodynamic efficiency. Novel ideas for improving efficiency of blades include dimples (like golf balls), scales (like sharks), and bumps on leading edges (like tubercles on whales). There is always a trade-off between increased efficiency and construction costs for novel airfoils. The simple solution is to increase the blade length a little on conventional blades to collect the same energy.

Presently, MHI-Vestas makes a 164-m diameter (80-m blade) 9.5-MW unit, Siemens [41] produces a 167-m diameter (81.5-m blade) 8-MW unit, and LM Wind Power has made a 88.4-m blade (see videos, www.lmwindpower.com/en/products-and-services/blade-types/longest-blade-in-the-world) for a 180-m diameter, 8-MW wind turbine. Wind turbines of 10–20 MW will require blades of 85–130 m length. Carbon fiber, maybe even carbon nanotubes, will eventually replace FRPs.

One of the main concerns is developing a procedure and mechanism for shutdown caused by overspeed. If a load loss arises when a utility transmission line goes down due to an ice storm or during high winds while a wind turbine is operating at rated power, the power of the rotor has to be controlled within 5–10 s. If the condition produces too much power to control even with the application of a mechanical brake, the unit will self-destruct or a few high wind speed shutdowns will stress the drive train to the point where it must be replaced. For light-weight blades on wind turbines operating at constant rpm, rotor control period is 4–5 s.

AEI and the U.S. Department of Agriculture's Agricultural Research Service installed and tested over 80 prototype and first-production wind turbines, from 50 W to 500 kW. Most units had failures 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 remedy is to move upwind and wait a while.

The USDA program for wind energy was terminated in 2012. AEI moved its test center in 2010, which was adjacent to the campus, to WTAMU's Nance Ranch and the Regional Wind Test Center had space for testing 20 small wind turbines, however AEI was terminated in 2015. Testing of large and small wind turbines is now available at the WTAMU-UL Advanced Wind Turbine Test Facility.

If a mechanical brake is part of a system for overspeed control, it should be installed on the low-speed shaft. If the brake is on the high-speed shaft and the drive train fails, the brake is useless. The failure does not have to be mechanical. 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 but the gust was short. The software ordered the brake to release, 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. Due to the high power, the brake soon burned up and the rotor was in the runaway condition. Within a short period, one blade broke loose and cut the guy wires and the unit fell.

The blades should have the same pitch setting or a cyclic forcing function will affect the drive train and other components. For large wind turbines with large wind shear between the top and bottom of the rotor area, cyclic pitch can be used to improve performance. One extreme case was a 40-kW wind turbine whose three blades had dihedral spars. The system was to change its position to feather for shutdown and change rapidly to feather for overspeed. An attachment mechanism connecting 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. Along with the wear problem caused by the yaw, the unit did not produce much power yawed out of the wind.

Another concern is yaw rate, especially for flexible blades. A rotor has angular momentum, and when the brake is applied, a wind turbine will tend to rotate about the yaw axis. The rate of yaw, which is motor driven on large turbines, is limited. On some smaller turbines the rate of yaw is limited by a yaw damper. The rate is limited because a change in angular momentum produces 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 caused by 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 may be large enough to cause the blades to strike the tower. In the worst case, the blades break off at the roots.

Another example of fast yaw rate is for small wind turbines with flexible blades, downwind, with coning. Suppose a 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, the condition is unstable and eventually the wind direction will change or the wind speed will increase enough for the rotor to suddenly change from the upwind to a stable downwind condition. This very fast yaw rate exerts large flat forces on the blades that will bend the blades. The solution is using 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. The association also maintains data on testing wind turbine blades [42]. One problem with fatigue testing of large blades by vibration is the long time required to reach enough cycles so that fatigue becomes noticeable.

Nondestructive testing by acoustic emission is one way to monitor the progression of fatigue and may even predict where failures will occur [43]. 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 and provided assessments 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 changes in those properties indicate 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 has a facility for static and dynamic load testing of blades that includes nondestructive techniques such as photoelastic stress visualization, thermographic stress visualization, and acoustic emission. A facility for testing blades up to 90 m long is now available in the United States [44]. A facility in the United Kingdom can test blades up to 100 m in length and blade test facilities are available in other countries. New blade designs (12 m long for a constant rpm 100-kW unit) using carbon filaments for more strength at less weight were fabricated and tested [45]. All the blades survived the specified test loads and two designs exceeded them significantly.

In the final analysis, the important factor is energy produced by a wind turbine at the most economical cost per kilowatt-hour. A rotor design study considered four basic configurations: upwind three blades, upwind two blades, downwind three blades, and downwind two blades [46]. The cost of energy was estimated with improvements and compared to baseline turbines of 750 kW, 1.5 MW, and 3.0 MW. Two conclusions were drawn: (1) the cost of energy would be reduced by up to 13%—a small saving relative to the magnitude of the load reduction, and (2) more than 50% of the cost of energy was unaffected by rotor design and system loads.

6.8.2 Other Components of 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 the 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 a wind load 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. Now for the large wind turbines for offshore installations, direct drive and permanent magnet alternators are common.

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 [47] for input into a multibody dynamics code (commercial). FAST (fatigue, aerodynamics, structures, and turbulence) factors 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 are 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 was actually used as a method of overspeed control for a 300-W wind turbine. The blades were constructed of carbon filaments formed in an injection mold, so the high strength allowed flutter. In all other cases, a blade that enters flutter will generally fall in a short time.

All wind turbines and blades have natural frequencies (modes) of vibration. The models predict the modes or the modes can be found experimentally. During operation, especially constant rpm operation, major modes must be avoided, 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 drive train problems, thereby reducing costs by preventive maintenance.

Wind turbines are set on various types of towers—pole, guyed pole, pole or guyed pole with gin pole, so operation and maintenance functions 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. Lattice towers were common 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. To date, the record hub height is a 178-m (584 ft) tubular tower constructed by Max Bögl Wind for a 3.4-MW wind turbine (https://electrek.co/2017/11/02/worlds-tallest-wind-turbine-built-in-germany/).

Towers must be strong enough to support the weight at the top and resist the movement of the wind forces trying to push the tower over. Movement during operation at rated power in high winds can be quite large. Among the several types of foundations, a lot of rebar and concrete are required for large wind turbines. Examples of foundations are piers and bells (at the bottom) for each leg of lattice towers and various types of anchors, primarily piers for guyed pole towers. Foundation types for large turbines on tubular towers are piers, piers with concentric cylinders, or pads on the ground (Figures 6.20 and 6.21). Piers can be drilled in suitable ground (not rock) with augers. A hole for a pier 5.5 m in diameter and about 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; the inner can is backfilled with dirt. Also, the rods can be stressed after the concrete is poured to obtain a stronger foundation.

Wind turbines with downwind rotors will experience a reduction of wind speed due to tower shadow and a cyclic driving force. One result is the generation of repetitive sounds as the blades pass behind the tower. Repetitive sounds are more annoying than the normal chaotic noises generated by passing wind. For most wind turbines, noise attenuates to an acceptable level not too far from the turbine. However, the MOD-1, 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) by replacing the generator.

FIGURE 6.18 Small (1.8-kW) wind turbine mounted on 10-m pole tower, no guy wires, with gin pole. Note the swept blades.

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. Finished pad will require 32 metric tons of rebar and 270 cubic meters of concrete.

FIGURE 6.21 Finished pad foundation for 2.3-MW wind turbine. Note copper wire for grounding.

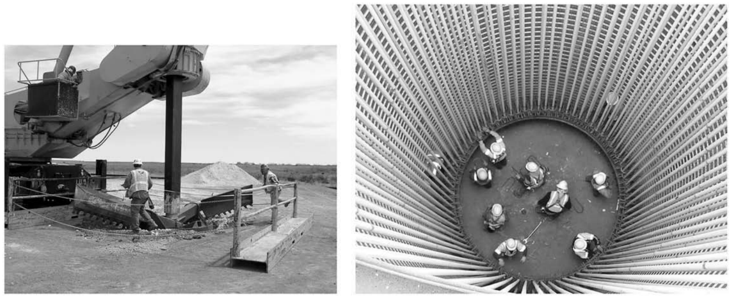


FIGURE 6.22 Pier foundation, concentric cans, for a 3-MW wind turbine. Right: The bolt rods are in place and starting to attach rebar. Notice two men are on other side of bolt rods.

6.9 EVOLUTION

Since 1970, the design of modern wind turbines evolved from the extremes of large utility scale wind turbines and small wind turbines. Large wind turbine development was funded primarily by governments, and only prototypes were built and tested. Small wind turbines were built in large numbers by private manufacturers for an emerging commercial market. There are a number of books and chapters in books on the history and evolution of wind turbines. Paul Gipe's *Wind Energy for the Rest of Us* [48] has two chapters with a number of color photos.

In the United States, NASA–Lewis began with the MOD-O design, a two-blade, downwind 100- to 200-kW turbine that progressed to the design of the two-blade, 7-MW MOD 5. This design was reduced to 3.2 MW, and one prototype that had steel blades, teetered hub, upwind, and tip pitch control was built. The tip pitch control was driven by motors in the blades that created maintenance problems. The Hamilton-Standard WTS-4 was a 4-MW 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 connected to hydraulic drives on the ground to drive the generator. The losses in the hydraulic drive were high, and the unit reached a power output of only 1.1 MW rather than the designed 3 MW. The unit was mounted on a tripod truss tower that rotated on a track; the tower was yawed for control.

Several large prototype systems were built in Europe. 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; the Tvind, three blades, variable pitch, upwind, 2 MW; and the Tjaereborg, three blades, upwind, 2 MW.

In Sweden, four 2- to 3-MW 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 to transfer 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 MW. Other megawatt prototypes were built in Italy, The Netherlands, Spain, and the U.K. The largest VAWT was a 4-MW Darrieus unit built in Canada.

A table of wind energy systems exceeding 500 kW through 1993 describes 35 units [7, Table 3-2]. Divone described the evolution of modern wind turbines from 1970 to 1990, with emphasis on description and operational notes of large units [7, Chap. 3].

At the other extreme were wind turbines rated from 20 to 100 kW and designed for the commercial market. All sorts of designs were built and sold. Common types in the United States were two blades, fixed pitch, teetered hubs, downwind; three blades, fixed pitch, downwind; and three blades, variable pitch, downwind. 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 [49].

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

The technical data on wind turbines in commercial operation in the United States [7, Appendix C] through the mid-1980s covered the total number of installed units of a given configuration. As a result of the growth of the wind farm market in California and later in the 1990s in Europe, evolution continued toward larger wind turbines. By 2008, the predominant wind turbines were megawatt size, three blades, rigid hub, variable pitch (full-span control), variable and constant rpm operation, upwind.

As a result of the evolution, 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 (300-kW) units but was unable to continue in business.

A Vestas, 90-m diameter, 3-MW wind turbine was installed near Gruver, Texas (Figure 6.23). For installation, an 800-metric ton crane was needed. Twenty trucks were needed to haul the crane to the site and another ten were required to transport the turbine and tower. The nacelle weighed 70 metric tons; the rotor, 41 metric tons; and tower, 160 metric tons. The 80-m tall tower consisted of four sections on a foundation that required 460 m^3 of concrete including a small pad for the transformer.

The sizes of commercial wind turbines (2013) increased from 4 to 8 MW (164-m diameter) and are primarily designed for offshore use. Designs for 10- to 20-MW (200-m diameter) systems are being developed, but transportation will probably require delivery of the turbine in sections and assembly on-site.

6.10 SMALL WIND TURBINES

Generally small horizontal axis wind turbines are kept facing into the wind by tails. The control mechanism to reduce power in high winds is to offset the rotor axis from the pivot point axis of connection to the tower (Figure 6.24). The result is more force on one side of the rotor that tries to move the rotor parallel to the wind. However, the wind force on the tail keeps the rotor perpendicular to the wind. In high winds the unequal force on the rotor is greater than the force of the tail; therefore, the rotor moves parallel to the wind. The tails of very small rotors may be fixed.

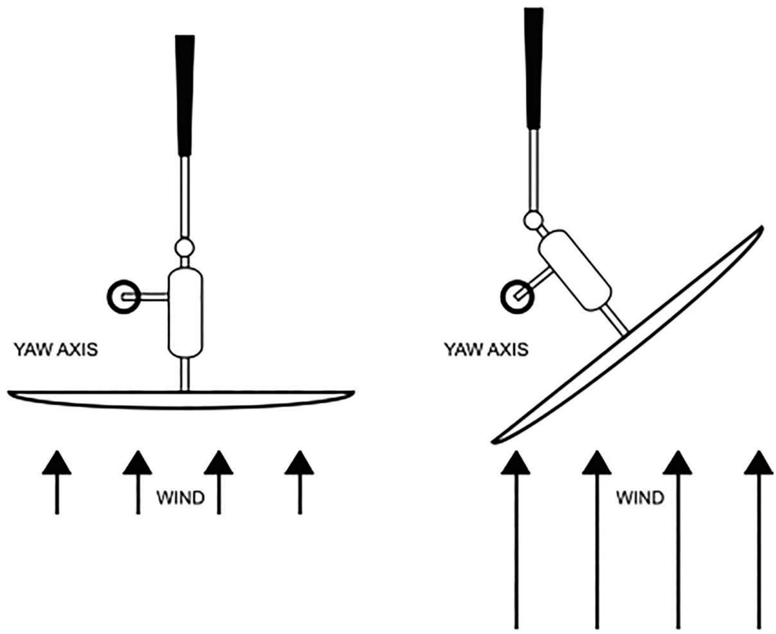


FIGURE 6.24 Furling diagram of rotor axis offset from tower (yaw axis) with hinged tail.

During medium to high winds with rapid changes in direction, a small turbine may make a complete 360-degree revolution around the yaw axis.

Most wind turbines have hinges for their tails. During high winds, the rotor moves to a position closer to parallel to the tail (furling) [50–52]. When the winds decrease, the tail returns to a position perpendicular to the rotor by a force exerted by springs or gravity. Dampers, like shock absorbers, can keep the furling and restoration to normal operation from happening too rapidly. A farm windmill uses springs with adjustable lengths to restore force. One mechanism that uses gravity is installing the tail hinge at a slight inclined angle to the vertical plane.

Performance was measured for a 2-kW wind turbine for water pumping. Changes in the offset of the rotor axis to the yaw axis, length of tail boom, area of tail, and pitch angle were analyzed [53]. Four different tails and two different yaw axis offsets were tested because furling behavior was critical to the performance [54]. Overall, nine configurations including two sets of blades with different pitch angles were tested to try to improve 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 and 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 a gravity restoring mechanism. Another horizontal pivot was unique in that the rotor was downwind and the tail with flat plate and fins hung down (moderate winds to 13 m/s). In high winds, the force on the rotor and also on the flat part of the tail moved the tail and rotor, the alternator to the horizontal position, and caused vertical furling (Figure 6.25). There is no hinge on the tail and the restoring force is gravity.

Small wind turbines are usually mounted on pole and lattice towers. Very small wind turbines are mounted on almost any structure—buildings and even on short poles (stub masts) mounted on sailboats.

In the 1980s, small wind turbines were made by a large number manufacturers. The viable numbers in the United States and Europe were reduced to a few. New subsidies after the turn of the millennium increased the number of manufacturers in the United States and Europe and then there were a large number of vertical axis designs. However as in the past, only a few will

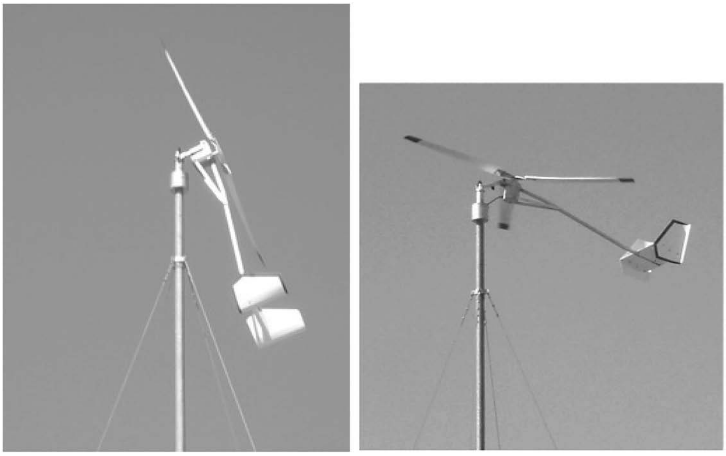


FIGURE 6.25 Rotor axis offset from horizontal pivot point for control. Left: Run position at wind speeds below 13 m/s. Right: Furled position in high winds.

be long-term commercial operations. The dramatic decline in the cost of photovoltaic systems impacts the small wind turbine market.

PROBLEMS

1. A blade is 12 m long and weighs 500 kg. 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. The struts are 4 m long and 2.5 cm in diameter. Rotor speed is 180 rpm. Use numerical approximation by dividing struts 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 diameters = 0.5 m. Struts are at the top and bottom, 2 m long from torque tube to blades, diameter = 5 cm, rotor speed = 80 rpm. $C_D = 1$. Calculate numerically (see Problem 2) or use calculus.
4. (a) 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. (b) 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 a 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; and (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 rpm for maximum C_P compared to the same size rotor with higher solidity?
9. (a) For those who know calculus, calculate the value of axial interference factor for which C_P is a maximum for a lift device and show that this gives a maximum $C_P = 59\%$. (b) 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 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 to 18, the 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, two-blade rotor; mass of one blade = 500 kg, hub radius = 1.5 m, and 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 has to be in 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 to 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, three-blade rotor, mass of one blade = 3,000 kg, hub radius = 1.5 m, and 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 per 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, and weight = 500 kg, calculate the angular momentum if the rotor operates 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 and 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 a utility grid, how long can overspeed shutdown take?
32. For megawatt-size wind turbines, what is the most common configuration?
33. Go to a website of any manufacturer of small wind turbines. Note the type of blade construction and material.
34. List two methods of nondestructive testing and briefly describe them?
35. For offshore wind turbines, 6 MW and larger, what are the common configurations?

REFERENCES

1. I.A. Abbott and A.E. Von Dolnhoff. 1959. *Theory of Wing Sections Including a Summary of Airfoil Data*. Dover: New York.
2. S.J. Miley. 1982. *A Catalog of Low Reynolds Number Airfoil Data for Wind Turbine Applications*, RFP-3387. Department of Aerospace Engineering, Texas A&M University: College Station, TX.
3. R.E. Wilson, P.B.S. Lissaman, and S.N. Walker. 1976. *Aerodynamic performance of wind turbines*. ERDA/NSF/04014-76-1, UC-60. Available from NTIS.
4. D.M. Eggleston and F.S. Stoddard. 1987. *Wind Turbine Engineering Design*. Van Nostrand Reinhold: New York.
5. D. Le Gouriérès. 1982. *Wind Power Plants, Theory and Design*. Pergamon Press: Oxford, U.K.
6. L. L. Freris, Ed. 1990. *Wind Energy Conversion Systems*. Prentice Hall: Englewood Cliffs, NJ.
7. D. A. Spera, Ed. 1994. *Wind Turbine Technology*. ASME Press: New York.
8. NTIS. Wind Energy Conversion Reports. C00–4131-Ti: Methods for Design Analysis of Horizontal Axis Wind Turbines; Aerodynamics of Horizontal Axis Wind Turbines; Dynamics of Horizontal Axis Wind Turbines; 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; Free Wake Analysis of Wind Turbine Aerodynamics; Aerodynamics of Wind Turbine with Tower Disturbances.
9. E. H. Lysen. 1983. *Introduction to Wind Energy*. Consultancy Services: Wind Energy for Developing Countries: Amersfoort, Netherlands.
10. T. Burton, D. Sharpe, N. Jenkins et al. 2001. *Wind Energy Handbook*. John Wiley & Sons: New York.
11. J.F. Manwell, J.G. McGowan, and A.L. Rodgers. 2002. *Wind Energy Explained*. John Wiley & Sons: New York.
12. M.O.L. Hansen. 2008. *Aerodynamics of Wind Turbines*. 2nd ed. Earthscan: London.
13. J. Pramod. 2011. *Wind Energy Engineering*. McGraw-Hill: New York.
14. E.A. Avollone, T. Baumeister III, and A. Sadegh, Eds. 2002. *Marks' Standard Handbook for Mechanical Engineers*, 11th ed. McGraw-Hill: New York.
15. J.S. Rohatgi and V. Nelson. 1994. *Wind Characteristics: An Analysis for the Generation of Wind Power*. Alternative Energy Institute, West Texas A&M University: Canyon, TX. Contact kstarcher@wtamu.edu.
16. J.L. Tangler. 1983. Horizontal axis wind system rotor performance model comparison: A compendium. RFP-3508, UC-60, Rockwell International and Wind Energy Research Center (now National Wind Technology Center).
17. R.J. Templin. 1974. Aerodynamic performance theory for the NTC vertical axis wind turbine. LTR-LA-160, National Research Council of Canada.
18. R.J. Maraca et al. 1975. Theoretical performance of vertical axis windmills. NASA TM TMS-72662, NASA Langley Research Center.
19. J.H. Strickland. 1975. *The Darrieus Turbine: A Performance Prediction Model Using Multiple Stream Tubes*. SAND 75-0431. Sandia National Laboratory: Albuquerque, NM.
20. R.E. Akins, D.E. Berg, and W.T. Cyrus. 1987. *Measurements and Calculations of Aerodynamic Torques for a Vertical Axis Wind Turbine*. SAND 86-2164. Sandia National Laboratory: Albuquerque, NM.
21. S. Schreck and M. Robinson. 2007. Wind turbine blade flow fields and prospects for active aerodynamic control. NREL/CP-500-41606. www.nrel.gov/wind/pdfs/41606.pdf.
22. D. Simms et al. 2001. Unsteady aerodynamics experiment in the NASA Ames wind tunnel: A comparison of predictions to measurements. NREL/TP-500-29494.
23. J. McCarty. 1993. PROP93: Interactive editor and graphical display. In *AWEA*, *Proceedings of Windpower Conference*, p. 495.
24. J. Tangler and J.D. Kocurek. 2005. Wind turbine post-stall airfoil performance characteristics guidelines for blade-element momentum methods. NREL/CP-500–36900. Presented at *43rd AIAA Aerospace Sciences Meeting*. www.nrel.gov/docs/fy05osti/36900.pdf.
25. M.S. Selig and J.L. Tangler. 1994. A multipoint inverse design method for horizontal axis wind turbines. In *AWEA*, *Proceedings of Windpower Conference*, p. 605.
26. M.S. Selig. PROPID for horizontal axis wind turbine design. www.ae.illinois.edu/m-selig/propid.html.
27. J.L. Tangler and D.M. Sommers. 1993. NREL airfoils families for HAWTS. In *Proceedings of Windpower Conference*, p. 117.

28. B.C. Andrews. 1993. Optimal design of complex wind turbine blades. *Master's Thesis*, West Texas A&M University (includes user's manual): Canyon, TX.
29. B. Andrews and K. Van Doren. 1988. A method for geometric modeling of wind turbine blades. In *Proceedings of Seventh ASME Wind Energy Symposium*, p. 115.
30. K.L. Starcher. 1995. Atmospheric test of special purpose thin airfoil family. *Master's Thesis*, West Texas A&M University: Canyon, TX.
31. K.L. Starcher, V.C. Nelson, and J. Wei. 1996. Test results of NREL 10m, special-purpose family of thin airfoils. In *AWEA*, *Proceedings of Windpower Conference*, p. 261.
32. J. van Meel and P. Smulders. 1989. *Wind Pumping: A Handbook*. World Bank Technical Paper 101, p. 30.
33. M.H. Khan. 1978. Model and prototype performance characteristics of a Savonius rotor windmill. *Wind Engineering,* 2, 75.
34. T. D. Ashwill. 1992. *Measured Data for the Sandia 34-meter Vertical Axis Wind Turbine*. SAND 91-2228. Sandia National Laboratory: Albuquerque, NM.
35. D.R. Miller and P.J. Sirocky. 1985. Summary of NASA/DOE Aileron Control Development Program for wind turbines. In *AWEA*, *Proceedings of Windpower Conference*, p. 537.
36. DOE-EPRI Wind Turbine Verification Program. www.p2pays.org/ref/11/10097.pdf.
37. P. Veers, G. Bir, and D. Lobitz. 1998. Aeroelastic tailoring in wind-turbine blade applications. In *AWEA, Proceedings of Windpower Conference,* p. 191. www.sandia.gov/wind/other/AWEA4-98.pdf.
38. Proven Wind Turbines (now Kingspan). www.kingspan.com/gb/en-gb/products/renewable-technologies.
39. LM Wind Power. www.lmwindpower.com.
40. Sandia National Laboratory. Wind concepts, analysis, and design tools. http://energy.sandia.gov/?page_id=352.
41. Siemens, Wind Turbine Blades. www.siemens.com/global/en/home/markets/wind/turbines-and-services/technology/blades.html.
42. Danish Wind Industry Association. Blade testing. http://drømstørre.dk/wp-content/wind/miller/windpower%20web/en/tour/manu/bladtest.htm.
43. J. Wei and J. McCarty. 1993. Acoustic emission evaluation of composite wind turbine blades during fatigue testing. *Wind Engineering*, 6, 266.
44. Massachusetts Clean Energy Center, Wind Technology Testing Center. www.masscec.com/wind-technology-testing-center.
45. J. Paquette, J. van Dam, and S. Hughes. 2007. *Structural Testing of 9-m Carbon Fiber Wind Turbine Research Blades*. Paper presented at Wind Energy Symposium. www.nrel.gov/wind/pdfs/40985.pdf.
46. D.J. Malcolm and A.C. Hansen. 2006. WindPACT turbine rotor design study, June 2000–June 2002. Subcontract Report NREL/SR-500-32495. www.nrel.gov/wind/pdfs/32495.pdf.
47. J. Jonkman. FAST: An aeroelastic design code for horizontal axis wind turbines. http://wind.nrel.gov/designcodes/simulators/fast.
48. P. Gipe 2016. Wind energy for the rest of us, a comprehensive guide to wind power and how to use it. www.wind-works.com.
49. J. Schmid and W. Palz. 1986. *European Wind Energy Technology: State of the Art of Wind Energy Converters in the European Community. Solar Energy R&D in the European Community, Series G, Wind Energy*, Vol. 3. Boston: D. Reidel: Boston, MA.
50. National Wind Technology Center. Lancaster Tokyo Furling Workshop presentations. http://wind.nrel.gov/furling/presentations.html.
51. J.M. Jonkman and A.C. Hansen. 2004. Development and validation of an aeroelastic model of a small furling wind turbine. NREL/CP-500–30589. www.nrel.gov/docs/fy05osti/39589.pdf.
52. M. Bikdash. 2000. Modeling and control of a Bergey-type furling wind turbine. http://wind.nrel.gov/furling/bikdash.pdf.
53. B. Vick et al. 2000. Development and testing of a 2-kilowatt wind turbine for water pumping. AIAA-2000–0071. In *Proceedings of 19th ASME Wind Energy Symposium*, p. 328.
54. B. Vick and R.N. Clark. 2000. Testing of a 2-kilowatt wind-electric system for water pumping. In *Proceedings of Windpower Conference,* CD.

7 Electrical Issues

7.1 FUNDAMENTALS

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

Current: The current is the flow of charge q (electrons in most cases) past some point. Charge is measured in coulombs. Direct current (DC) results from flow in one direction, and alternating current (AC) results 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 60 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 (V). 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 a 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 (metal) depends on the square of the current:

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

The implication is that electric power needs to be transmitted at high voltages. In the summer, 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 transmission lines. Wind turbines

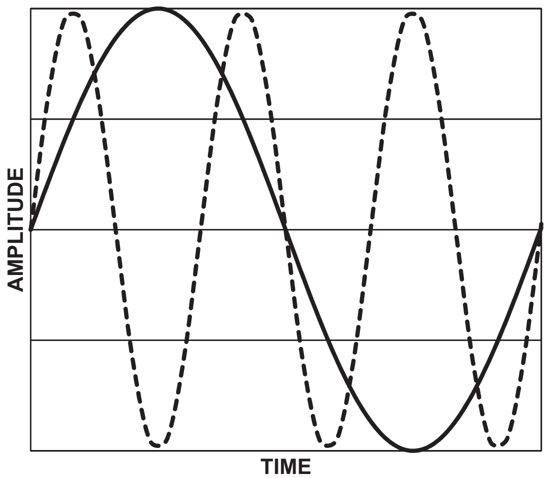


FIGURE 7.1 Two sine waves with different frequencies.

with generators at 240 or 480 V must be fairly close to the load or utility line. At higher voltages, smaller diameter wire can be used. Transformers change the voltage in AC systems, so every large turbine in a wind farm will have a transformer 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: An electric field *E* originates or terminates 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: A magnetic field ***B*** arises from moving charges or intrinsic spin (a property of particles just like charge is a property of particles). Some materials have magnet fields and are called permanent magnets. Permanent magnet alternators use rare earth atoms that cost more than iron, nickel, and cobalt. China is the source of a lot of the rare earths—a strategic asset that goes beyond wind turbines because rare earths are also needed for hybrid and electric vehicles.

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. The theory serves the entire electric power industry and led to communication via electromagnetic waves that we accept as common today.

If charged particles are placed in external electric fields and moving charged particles are placed in external magnetic fields, a force is exerted 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 (motor) and the conversion of mechanical energy to electric energy (generator).

Motor: A loop of wire contains moving charges (current) due to a connection to an electric plug. The loop is in an external magnetic field; therefore, a force on the charges and a torque on the wire constitute 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**. The motor contains a coil of wire with many loops. Check the links listed at the end of this chapter for information on how an electric motor works.

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

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, directly or through a gearbox. The charges (electrons in the wire) are moving in an external magnetic field, and there is force on the charges. A coil may contain many loops of wire. A single coil is known as a single-phase generator; three coils of wire constitute a three-phase generator.

An external magnetic field can be produced by permanent magnets or electromagnets. For an electromagnet, a current in a coil produces a magnetic field, and an iron core in the coil will strengthen the magnetic field. The number of coils is referred to as poles. The current from a utility

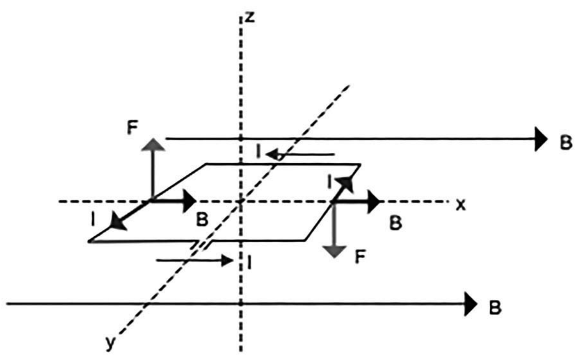


FIGURE 7.2 Forces on the sides of a current-carrying loop in an external magnetic field. The resultant of the set of forces gives a torque, T, which makes the loop rotate, a motor.

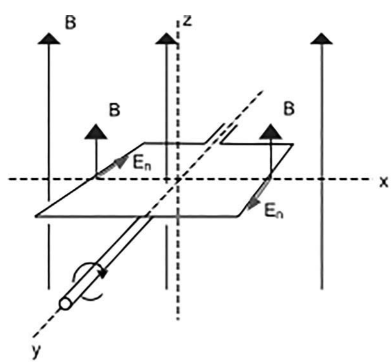


FIGURE 7.3 Rectangular loop rotated by outside force with angular velocity, ω, in a uniform external magnetic field (generator).

grid or a generator is used to produce the magnetic fields. Check the links at the end of the chapter to learn how an electric generator works.

7.1.1 Faraday's Law of Electromagnetic Induction

Another way of looking at electromotive forces is by 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:

$$\Phi_M = \mathbf{B} \cdot \mathbf{A} = \mathrm{BA}\cos(\theta) \tag{7.10}$$

where θ is the angle between **B** and **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 them may be changed by rotating a loop of wire. This yields an alternating voltage and current that vary like a sine wave.

Induction requires two coils. The changing magnetic flux in one coil causes a changing current in the adjacent coil. A transformer works by induction. If the load is pure resistance, the voltage is in phase (0 phase angle) with the current. With a capacitor, the voltage lags the current by 90°. With an inductor, the voltage leads the current by 90° (Figure 7.4). All voltages in the figure are set at an angle of zero, and the current is shown in relation to the voltage (starting at a different angle for the sine curve). Check the links at the end of the chapter for information about the relation of voltage and current.

7.1.2 Phase Angle and Power Factor

The instantaneous voltage and current are given by

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

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

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

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

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

All real circuits involve 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:

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

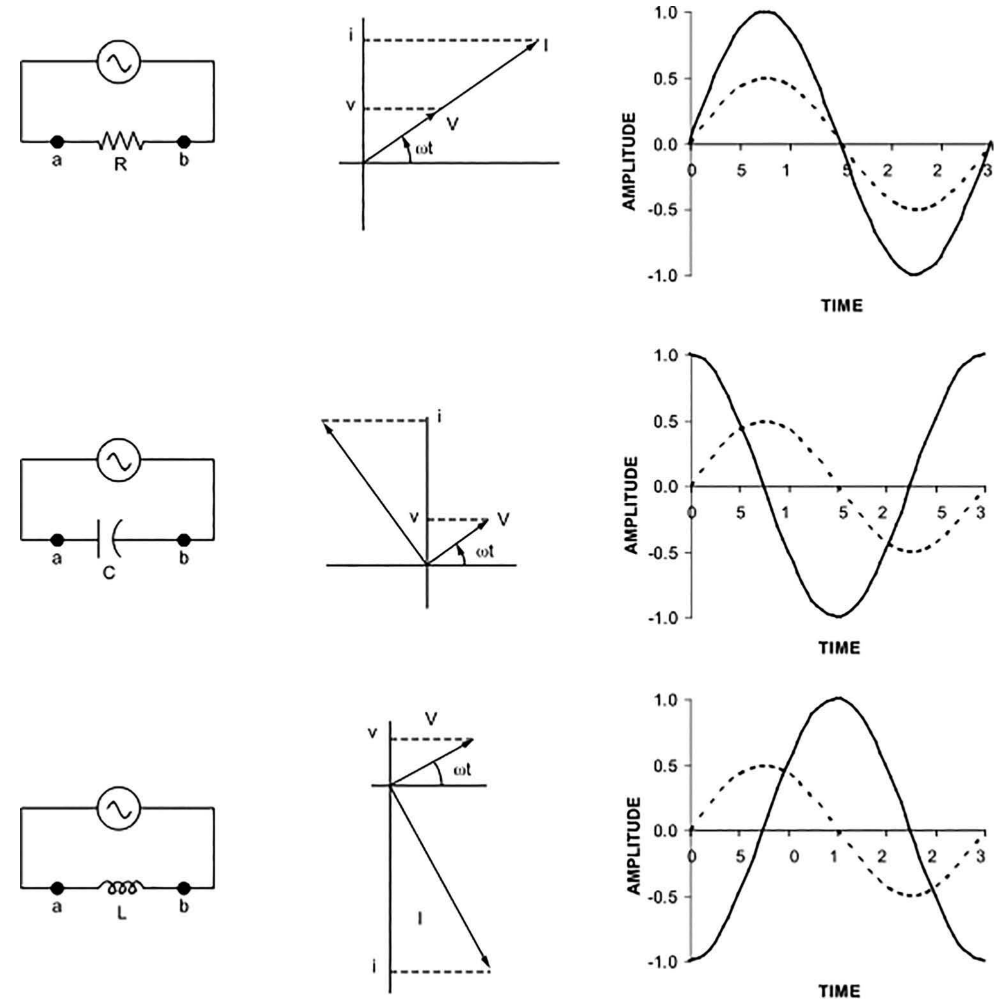


FIGURE 7.4 Current and voltage across a resistor, capacitor, and inductor, showing the phase relationship between the voltage (dashed line) and current (solid line).

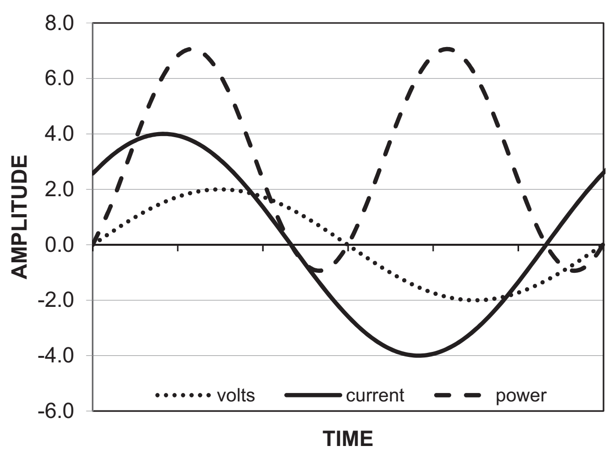


FIGURE 7.5 Instantaneous power in arbitrary AC circuit.

The average power is found by integrating over one cycle:

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

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

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

The equation applies to a single-phase system. For three phases, the measured current is reduced by $3^{0.5}$. For a three-phase transfer of power, each leg transfers 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

$$P_{\text{avg}} = V\ I \cos\phi \qquad (7.14)$$

where cos φ 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 utility companies because the utility grid supplies the reactive power for the induction generators. Therefore, some wind turbines and most wind plants have capacitors added to the turbines or to the electric substations. 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 (subdivided into induction generators and permanent magnetic alternators). The operation is constant or variable rpm, and as noted, constant rpm operation only reaches maximum power coefficient at one wind speed (Figure 6.14).

The variable rpm operation up to the rated wind speed is along the line of maximum power coefficient (Figure 5.13); 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 achieved 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. There is a trade-off between wind rotor efficiency and the cost and efficiency of conversion for variable frequency to constant frequency. An AC synchronous generator must be regulated to the correct rpm and synchronized with the grid. Induction generators essentially operate at constant rpm with a small variation known as slip. Induction generators are tied to the frequency of the grid because 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 a wind turbine is connected through an inverter, the inverter can handle the phase.

A generator is composed of an armature (coil of wire around metal core) and a field. Power is taken from the armature. The field controls the power and consists of permanent magnets or an electromagnet (energized coil of wire). In the latter case, the generator contains two coils: (1) a stationary coil or stator and (2) a rotating coil or rotor. In a DC generator, the armature rotates and power is taken from a commutator by brushes. Brushes need maintenance so alternators are used. In an alternator, the field rotates and the variable AC output is converted to DC by a rectifier circuit. The DC is then converted into constant voltage and constant frequency by an inverter.

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

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 that are always potential problems for control signals and even for power transfer. However, strict observation schedules on length of the power drop cord or trip relay for yaw must be followed.

A number of wind turbines also use direct drive with permanent magnet alternators. 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 a 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 a grid, primarily because of the complications of controlling 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, involve fewer operation and maintenance costs, and have simple controls. The induction motor or generator is brought up to synchronous speed and 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 these controls.

The rotor is in the center of a four-pole stator whose magnetic fields are supplied by a three-phase utility grid. The rotor cage consists of a number of copper or aluminum bars connected by aluminum end rings. The rotor has an iron core consisting of thin insulated steel laminations with holes

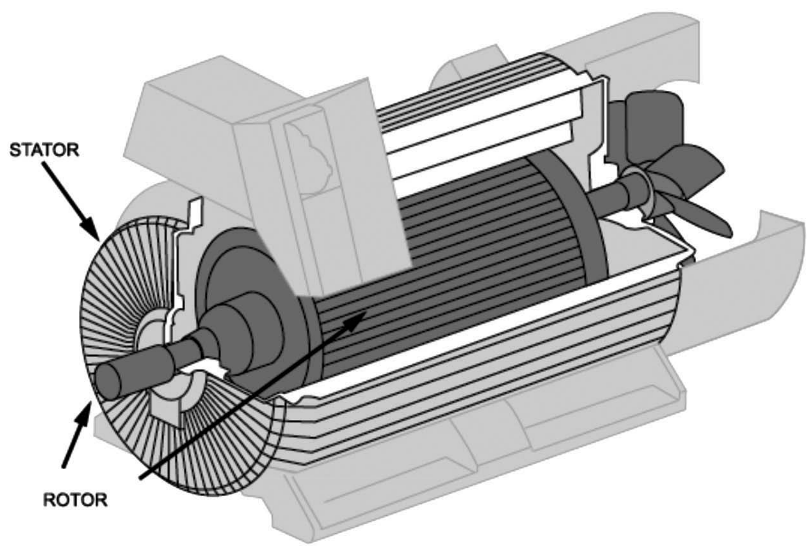


FIGURE 7.6 Cutaway drawing of an induction generator.

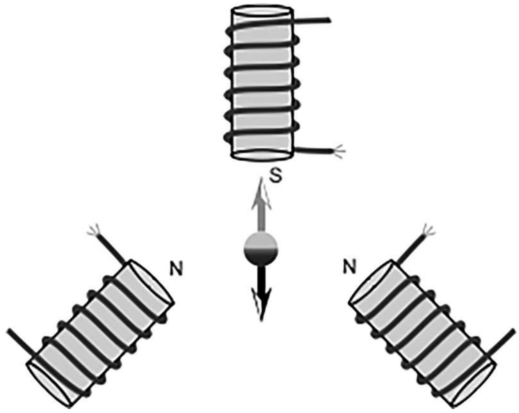


FIGURE 7.7 Three-phase AC generator. Rotating magnetic field produces AC voltages across each pair of terminals. Phase separation = 120°.

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 is 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 shown in Figure 7.8.

Some large wind turbines had two generators, one for low wind speeds and the other for high speeds. A common design for newer machines is pole changing that allows them to run as a small or large generators, 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 a generator to operate below synchronous speed or it would turn into a gigantic fan. The control mechanism must measure rpm, with some leeway for wind speeds at the cut-in value, to turn the generator on and off, and at high wind speed to cut out and restart the generator after the winds decline. Some wind turbines use the motor/generator for start-up because 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. As rpm increase due to wind power and when the motor/generator surpasses the synchronous speed, it now operates as a generator.

The time delay reduces on-off cycling when the wind is near the cut-in and cut-out speeds. In one case, a small (5-kW) downwind wind turbine would start in the upwind position because the winds shifted 180° from the position when the turbine shut down. The upwind position is an unstable condition for a downwind rotor with coning. The control system indicated start-up but 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 types for wind turbines from 25 kW to MW because the controls for synchronization to the line are simple, rugged, and mass produced. When a failure occurs on a utility grid, they automatically disconnect and present no safety problems. Induction generators decrease the power factor, and correcting capacitors are installed on individual wind turbines or at wind farms.

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

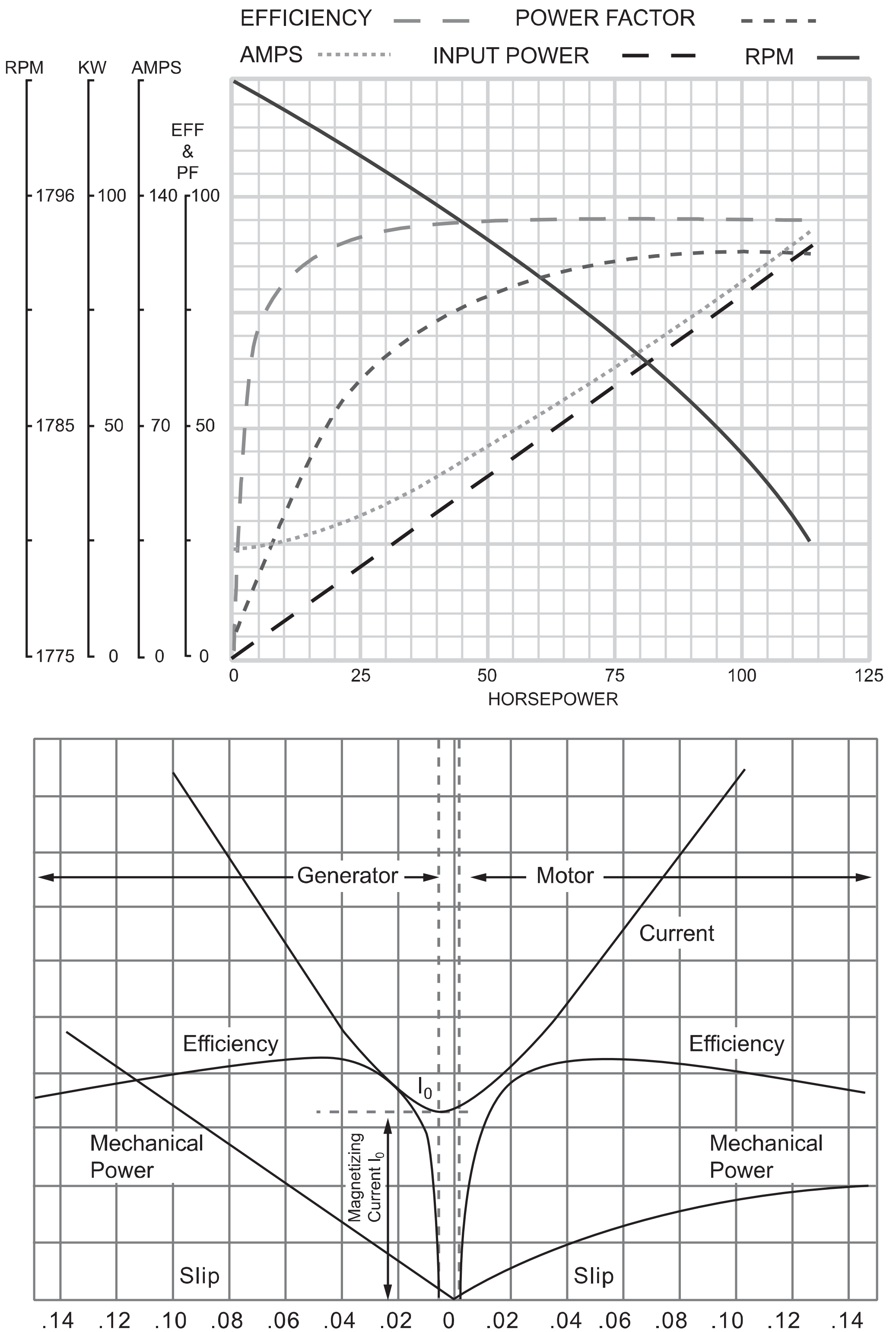


FIGURE 7.8 Operating characteristics of induction motor (420 V, 75 kW). The curves for the induction generator are essentially a mirror image as shown by the bottom graph.

FIGURE 7.9 Induction generator, 750 kW; stator; and slip rings for transferring power. (Photos courtesy of Wade Wiechmann.)

7.2.2 Doubly Fed Induction Generator, Variable rpm Operation

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

7.2.3 Direct-Drive Generator, Variable rpm Operation

This type of generator has no gearbox and operates at the same rpm as the wind rotor, 10–25 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. The trade-off is between no gearbox and large size with power electronics.

7.2.4 Permanent Magnet Alternator, Variable rpm Operation

This is also a direct-drive system with no gearbox and is common on small wind turbines. The usual control for high winds is by furling using a tail. However, Southwest Wind Power had a downwind unit that used electrodynamic braking for high winds and shutdowns.

Manufacturers offer a number of large 1.5–8 MW wind turbines; direct drive, permanent magnet generators. The direct drive eliminates two-thirds of the conventional drive train; gearbox,

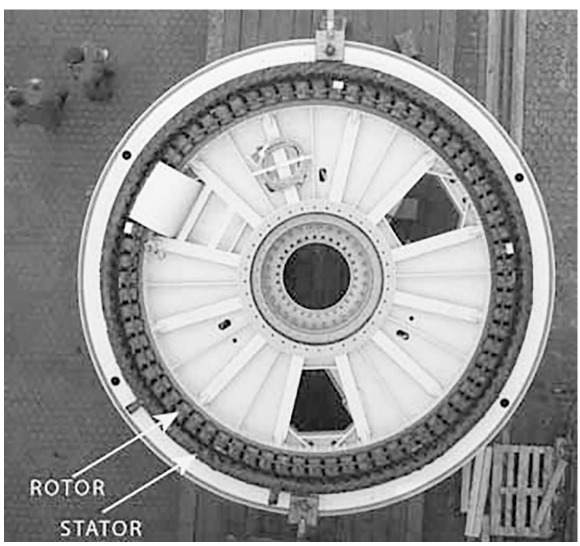


FIGURE 7.10 Ring generator for gearless Enercon, E66. Size can be estimated by comparison to two men in the upper left corner. (Photo courtesy of Thomas Schips.)

coupling, and high-speed generator. The larger units are for the offshore market as the direct drive turbines are simpler, lighter, and easier to maintain. A disadvantage is that the excitation cannot be controlled.

7.2.5 Generator Comparisons

All the above generators have been used in wind turbines. The trade-off factors are (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 utilized two generators, one of which was for lower wind speeds. The Vestas V47 had 200-kW and 660-kW generators. Another method is to change numbers of poles, for example, six poles for low wind speed and four poles for higher speeds. The Bonus generator was rated for 260 and 1,300 kW.

The generator for the MOD-5B was rated at 3.2 MW and was a variable speed (1,330–1,780 rpm) wound-rotor induction type. 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 and maximum C_P. This means low rpm generators with large numbers of poles. Project Eole located at Cap Chat, Canada, was a large VAWT rated at 4 MW. Because it 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 gearboxes on large wind turbines. The output is rectified and then converted to constant frequency. Over 27,000 units from 300 kW to MW size have been installed. In 2007, Enercon built a 6-MW unit, 126 m in diameter. This has evolved into a product line with 126- and 138-m diameters, generator size from 3.5 to 4.2 MW.

The Sandia VAWT test bed (34 m diameter, rated at 500 kW) located at the Agricultural Research Service facility in Bushland, Texas, was designed as a variable speed, constant frequency system. It included a load-commutated inverter, AC-adjustable speed drive, and 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. It had two induction generator options: six poles, 30 kW (wind rotor 60 rpm) rating for medium wind speed regimes, and four poles, 50 kW (wind rotor 90 rpm) rating 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 sizes of the wires connecting a generator to a grid depend on the current and distance to the connection. For small wind turbines, manufacturers recommend wire sizes for different wire runs, however, see Table 7.1.

FIGURE 7.11 Left: Generator, gearbox, and Jay Carter, Sr. Right: Stator and rotor of a 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	2	1
80	4	6	8	6	4	4	3	2	2	1	1	1	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	0	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

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 and meet the quality needs of customers on the grid. The four types (Figure 7.12) of connections depend on the electrical conversion, generator, and connection (direct or partial and full converter). Induction generators require reactive power from a grid, and capacitor compensation is often used at the wind turbines or at a substation.

The power output of variable rpm wind turbines is smoother (less flicker) than the output of constant rpm wind turbines because rapid changes in the power are smoothed out by rotor inertia. If a converter is large enough, variable rpm wind turbines can also be used for voltage and frequency control. Power electronic converters produce harmonics that may need to be filtered.

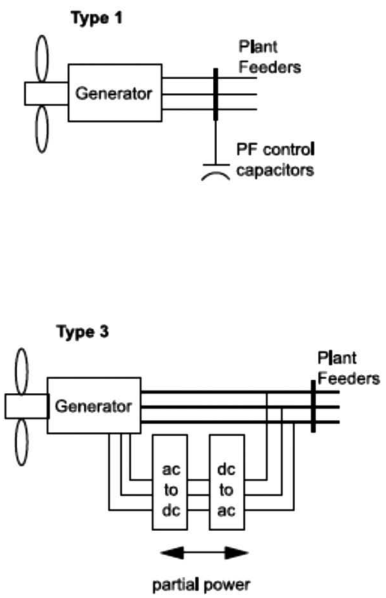


FIGURE 7.12 Four types of dynamic models, wind turbine connection to grid.

The voltage at each wind turbine on a wind farm varies independently, and turbines may be shut down to correct faults (see Section 5.6.2) or perform maintenance. Capacitor compensation may lead to harmonics and self-excitation, with constant rpm, induction generators [10]. However the wind speeds are so variable, it is improbable that self-excitation will last very long. Fluctuations in voltage and frequency must be kept within ranges acceptable to the utility at the point of connection to the grid (Figure 7.13).

Faults on a utility grid will also cause a reaction from the wind turbines. A wind farm was monitored for 1 year [11], and 215 faults were noted. At the monitoring node, the voltage drop and spike in current described the fault (Figure 7.14). Most fault events 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 a 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 voltage restoration.

The loss of generation from a wind farm during a fault varies from 0 to 100% of its capacity. In terms of loss of generation, the benefit of wind power generation is the amount of power disconnected from the wind farm, as the loss of a single generator in a wind power plant may be less than 1% of total generation. During the year of monitoring, only 1% of all the faults caused high generation losses ($P_{gen} > 0.8\ P_{rated}$). Note that many engineers use the term *wind plant* because a wind farm really functions as a wind-powered electric generation plant.

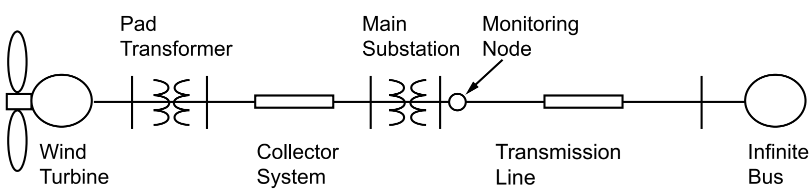


FIGURE 7.13 Typical network topology of large wind farm.

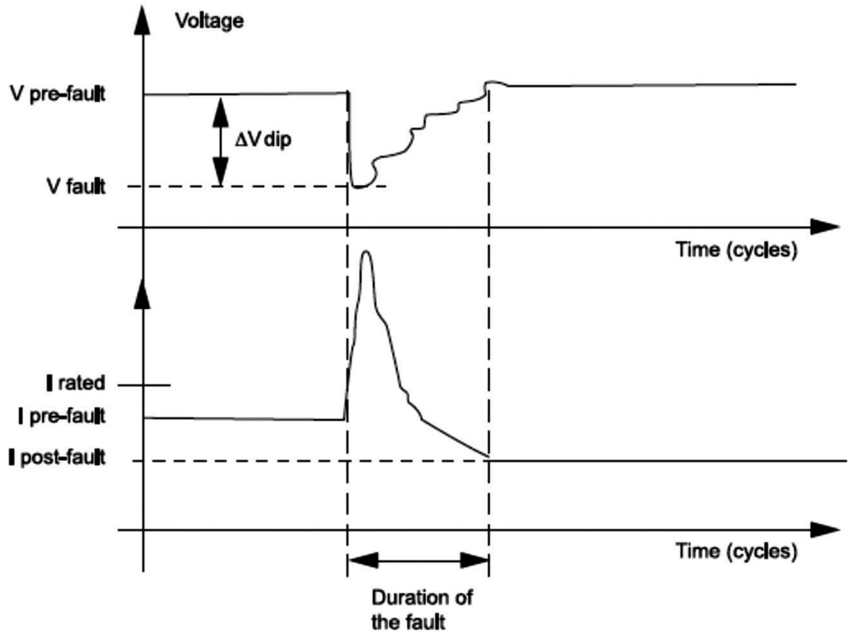


FIGURE 7.14 Voltage and current at connection to wind farm after fault on utility line.

7.4 ELECTRONICS

Electronics are used extensively in the control of wind systems. Controllers generally consist of one or more computer processing units (CPUs) and programmable logic controllers (PLCs) that may 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) units for individual wind turbines, village projects, wind–diesel systems, and entire wind farms.

Electronics for power conversion and control are major parts of any wind turbine system, and solid-state inverters allow variable frequency output to be connected to a utility grid. Induction generators on constant rpm units may require a soft start to reduce mechanical stress and reduce the interactions between the utility grid and the wind turbine during connection.

7.4.1 Controllers

A controller monitors the condition of a wind turbine, collects statistics on its operation, and controls switches for different operations and functions. A controller contains one or more CPUs.

The simplest controller senses the voltage levels of batteries during full charge and discharge and may display the information on light indicators. As the battery bank voltage approaches the regulation level, a wind turbine is furled manually or the controller may switch power to a regular load or a dump load. If no load is available, the wind turbine may be brought to a slow rpm. The controller may include an electrical braking mode used for parking the turbine before climbing or lowering the tower to work on the turbine. Equalization of the batteries (restoring them to a high rate of charge) must be performed monthly. Water levels should be checked and distilled water added as needed.

Control of turbines for furling is accomplished mechanically. If a unit is connected to a grid through an inverter, the power output of the wind turbine is converted to DC and a disconnect switch is mandatory. Southwest Wind Power had a unique wind turbine. The DC rectifier, controller, and inverter are all inside the nacelle (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.

One option is a wireless remote display to show performance in real time and collect kilowatt-hour data for days, months, and years. The remote may be connected to a personal computer (PC) for monitoring turbine performance, and software can generate a power curve for the wind turbines.

For wind turbines with induction generators connected to a 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 if needed, connection of the generator, and control for shutdown and overspeed. The controller will also have sensors for faults and any fault will shut down the wind

FIGURE 7.15 Disconnects and controller for 50-kW wind turbine.

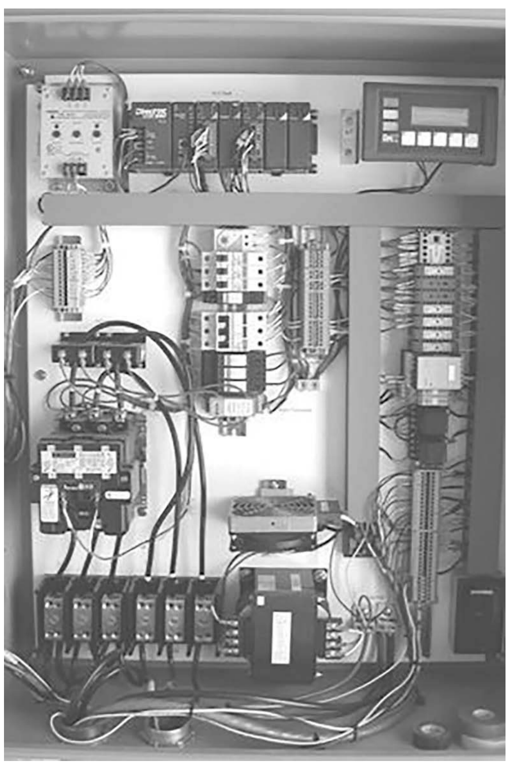


FIGURE 7.16 Controller for 50-kW wind turbine with induction generator (constant rpm operation).

turbine. The controller may provide communication to an external personal computer on-site or far away. Additionally, the computer may be able to change the parameters of the controller.

Large wind turbines require monitoring of 500 to over 1,000 parameters and may require two controllers—one in the nacelle and one at the bottom of the tower, which is connected with fiber optics. Some models include 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 operator, owner, or service contractor.

Statistics are collected at the computer to provide a baseline for each wind turbine. Finally, for wind farms, supervisory control and data acquisition (SCADA) are components of control systems [12, Sec. 1.4]. In addition to manufacturers, several other companies produce SCADA systems for wind farms. Because wind farms can utilize different wind turbines, operational information on each wind turbine is compared to a baseline database to alert operators of potential problems. At an on-site or remote-control room, operators can monitor each wind turbine on a farm and turn them on and off. In cases of high winds when transmission lines were full, wind farm output had to be curtailed. Control systems shut down the turbines within a short period. The latest control strategy to improve performance is high-wind ride-through. Instead of shutting down due to high winds, the unit is curtailed to values below rated power. Units also derate instead of shut down for high component temperatures, and high or low ambient temperatures (both in the control logic and sometimes manually in a remote operating center).

A management system can integrate wind farm SCADA, on-site meteorological wind forecasting, and market price data to enable operators to maximize energy production and the resulting income. Control strategies are proprietary because they are intended to maximize energy production within wind regimes and minimize turbine system 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]. Power electronics of large wind turbines allow them to operate more efficiently. A common system for doubly fed wound induction generators involves a converter connected to the rotor of the generator that directly controls currents in the rotor windings so the mechanical and electrical rotor frequencies are decoupled. Only a fraction (20 to 40%) of the rated generator power passes through the converter. The operational speed range of the generator depends only on the converter rating.

7.4.3 Inverters

A number of inverters are on the market, but only a few manufacturers produce inverters for wind turbines. Inverter designs need to accommodate the very different inputs of wind turbines. Inverters for photovoltaic devices 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 DC to the constant voltage and frequency of the grid.

Because wind turbines are controlled mechanically, the inverter controls the electrical aspects of synchronization of phase and power transfer. Some wind systems use battery storage

before the inverter and require a different inverter design. Early inverters used short-length, square wave pulses with proper timing on the cycle to input power to a grid. The square wave pulses added harmonics to the output. Later inverters improved and had efficiencies over 90% under 75% load with 2% harmonic distortion. At low winds and loads, inverter efficiencies will decrease.

The field test of a wind turbine (permanent magnet alternator, three-phase, 10 kW) connected to a 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. If the pause happens too many times within a certain period, the inverter quits functioning and must be reset manually.

The main safety function of the inverter is to disconnect the wind turbine from the utility line when a fault occurs on the utility line. This prevents hot wires because the generate will continue to operate. A disconnect (may be fused) is needed between the wind turbine and inverter along with a fused disconnect between the inverter and utility grid.

7.5 LIGHTNING

Lightning is always a problem for electronics, especially for wind turbines connected to grids. Lightning strikes on a grid will send spikes over long distances. A wind turbine is generally the tallest lightning rod around, so lightning protection via a path to ground is imperative. Manufacturers' instructions on grounding and number and connection of copper rods (size and depth) must be implemented along with other measures for protecting controllers and inverters, from varistors to blow-out cans. Even then lightning can still cause problems by damaging controllers, electrical systems, blades, and generators. Furthermore, the induced electromagnetic fields may damage the pitch control systems inside a hub. Damage due to lightning is a very costly repair because blade and generator replacement may require a crane.

A 1995 German study estimated that 80% of wind turbine insurance claims paid covered damages caused by lightning [15]. Mean annual thunderstorm days and lightning flash density data show regions of the United States where wind turbines are subject to the greatest risk from lightning. 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 study information also includes repair costs [17]. A later study has statistical data from 304 cases about lightning damage on wind turbine blades [18].

Lightning protection for wind turbines has improved but lightning is capricious and sometimes even the best protection is not sufficient. Blades should have internal lightning conductors running all the way to their tips. One example of lightning protection added after installation was implemented after surges on the utility line damaged the controller. The solution was an underground copper grid connecting all the guy wires plus the turbine tower.

Hub heights are so tall that they can generate "up lightning." It originates from the turbine's own electric field and leaps from the tip of a blade to meet a downward bolt.

7.6 RESISTANCE DUMP LOAD

If a wind turbine uses resistive loads for overspeed control, the resistors must be outside. During loss of load and high winds at the AEI Wind Test Center, the resistors inside the control shed, along with the controller and inverter, became so hot the control shed caught fire and burned to the ground. Luckily, the fire burned the insulation off the power wires from the wind turbine. They shorted together and shut the wind turbine down before it was destroyed.

PROBLEMS

1. What is the voltage drop across a 100-Ω 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-V AC?
5. If the phase angle of a 240-V AC, 20-amp circuit is 20°, how much is the power reduced from maximum?
6. What is a three-phase generator?
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 the 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 25-m tower. Peak power can be 30 kW. Calculate maximum current and reduce it by a factor of 1.7 because the system is three-phase. Each leg (wire) of the three-phase system carries 1/3 of the current. Use Table 7.1.
11. A 100 kW, three-phase, 480-V generator is connected to a transformer within 10 m of the base of a wind turbine. Peak power can be 120 kW. Remember to count the wire down the 30-m tall tower. What minimum size wire is needed for each phase? Calculate current and reduce it by a factor of 1.7, because the system is three-phase. 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 of induction generators, constant rpm, and stall control.
14. List two advantages and two disadvantages of doubly fed induction generators, variable rpm, and pitch control.
15. What happens at a wind farm when faults occur on the utility line?
16. Why are SCADAs used at wind farms?
17. What type of wind turbines use power electronics? Why?
18. List three functions of a wind turbine controller.
19. What is the function of an inverter? What types and sizes of wind turbines use inverters?
20. Lightning strikes a blade and essentially destroys it. If you have Internet access, use Ref. [17] and estimate the cost to replace the blade.

LINKS

Danish Wind Industry Association. http://windpower.org/en.
How Stuff Works. Electric motor. https://electronics.howstuffworks.com/motor.htm.
How Stuff Works. Generator. http://science.howstuffworks.com/electricity2.htm.
Lessons on electricity. www.sciencejoywagon.com/physicszone/07electricity/.
Walter Fendt. Direct current electrical motor and generator. www.walter-fendt.de/html5/phen/generator_en.htm.
Wikipedia. Grid tie inverter. http://en.wikipedia.org/wiki/Grid_tie_inverter. Google wind turbine lightning for images and videos of strikes and damage.

REFERENCES

1. T.S. Jayadev. 1976. Induction generators for wind energy conversion systems. AER-75-00653. Available from NTIS.
2. G.L. Johnson and H.S. Walker. 1977. Three-phase induction motor loads on a variable frequency wind electric generator. *Wind Engineering,* 1: 268.
3. D. Curtice et al. 1980. *Study of dispersed small wind systems interconnected with a utility distribution system*. RFP-3093/94445/3533/80/7. Available from NTIS.
4. M. Hackleman. 1975. *The Home-Built Wind-Generated Electricity Handbook*. Earthmind: Saugus, CA.
5. J. Barble and R. Ferguson. 1954. Induction generator theory and application. *AIEE*, February, p. 12.
6. L.L. Freris. 1990. *Wind Energy Conversion Systems*. Prentice Hall: Englewood Cliffs, NJ, Chapter 9.
7. D. Eggleston and F. Stoddard. 1987. *Wind Turbine Engineering Design*. Van Nostrand Reinhold: New York, Chapter 14.
8. G. Johnson. 1985. *Wind Energy Systems*. Prentice Hall: Englewood Cliffs, NJ.
9. H. Polinder et al. 2004. Basic operation principles and electrical conversion systems of wind turbines. www.tandfonline.com/doi/abs/10.1080/09398368.2005. 11463604.
10. E. Juljadi et al. 2006. Power quality aspects in a wind power plant. IEEE and Power Engineering Society. www.nrel.gov/docs/fy06osti/39183.pdf.
11. E. Juljadi et al. 2008. Fault analysis at a wind power plant for one year of observation. IEEE and Power Engineering Society.
12. European Wind Energy Association. 2009. *Wind Energy: The Facts*. Earth Scan: London.
13. R. Erickson, S. Angkititrakul, and K. Almazeedi. 2006. A new family of multilevel matrix converters for wind power applications. Final Report, July 2002–March 2006. NREL/SR-500–40051. www.nrel.gov/docs/fy07osti/40051.pdf.
14. NREL. 2003. Wind turbine generator system safety and function test report for Bergey Excel-S with Gridtek-10 inverter. NREL EL-500-33963. www.mapcruzin.com/wind-power-publications/research-development/33963.pdf.
15. R. Kithil. 2008. Lightning hazard reduction at wind farms. lightningsafety.com/nlsi_lhm/wind1.html.
16. T. McCoy, H. Rhoads, and T. Lisman. 2000. Lightning activities in the DOE-EPRI turbine verification program. In *AWEA, Proceedings of Windpower Conference*. www.nrel.gov/docs/fy00osti/28604.pdf.
17. B. McNiff. 2002. Wind turbine lightning protection project, 1999–2001. NREL/SR-500-31115. www.nrel.gov/docs/fy02osti/31115.pdf.
18. A. Garolera, et al. 2016. Lightning damage to wind turbine blades from wind farms in the U.S. *IEEE Transaction on Power Delivery*, 31(3): 1043–1049.

8 Performance

It is important to remember that the load is part of a wind energy conversion system (Figure 8.1). The most common application is the generation of electricity—a good match of 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, a 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 its wind regime. Compromises on efficiencies for system components should be combined to maximize annual energy production within the initial and life cycle costs. The last two factors may oppose each other, for example, reducing the initial costs may increase life cycle costs. The comparison will cover wind turbines that generate electricity.

Power curves and power coefficients have been measured experimentally, and peak efficiencies are around 0.40 for vertical axis wind turbines (VAWTs) to 0.50 for horizontal axis wind turbines (HAWTS; Figure 6.14). For constant rpm operation, for example by an induction generator, the rotor will operate at peak efficiency at only one wind speed (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. One operates at low wind speeds and the other at high wind speeds. The Vestas V27 utilized a 50/225 kW asynchronous generator with synchronous speeds of 750/1,000 rpm. Another possibility for increasing generator efficiency is to change the number of poles of the generator between low and high wind speeds. The Mitsubishi rated for 1 MW 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 (or load factor) is the average power divided by the rated power and is equivalent to an average efficiency factor.

$$\text{CF} = \text{average power}/\text{rated power} \tag{8.1}$$

In general, capacity factors are calculated from kilowatt-hours produced during a certain period: power = energy/time. The time periods vary; however, the most representative period would be 1 year, although capacity factors for a month and a quarter have been reported. Capacity factors of 0.3 are good, 0.4 and greater is excellent, and a 0.10 factor is too low.

For wind sites and wind farms with class 4 and above winds, annual capacity factors should be 0.35 or greater. During windy months, capacity factors can exceed 0.50. Capacity factors are somewhat arbitrary because of the different sized generators that have the same rotor diameters. For February 2002, Lake Benton I, Minnesota, reported a capacity factor of 0.49, and Lake Benton II reported 0.60. The difference was caused by the larger diameters of the wind turbines at Lake Benton II. Both systems had the same size generators but Lake Benton II's turbines swept a larger area.

Annual capacity factors of 40% and greater indicate a good to excellent wind regime and good operation and maintenance. Annual capacity factors below 20% generally indicate poor performance for the wind turbines. Also, capacity factors improve as older wind turbines from the 1980s and 1990s are decommissioned.

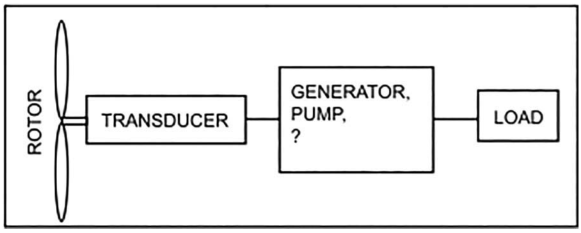


FIGURE 8.1 Wind energy conversion system.

If information given is installed capacity and capacity factor, then energy production can be estimated. For example: 16 GW * 0.35 * 8760 h = 49 TWh.

Availability: The availability is the percentage of time a unit is available to operate and it serves as a measure of reliability. For prototypes and early production models, the availabilities were 0.50 or even lower. Third-generation models have availabilities of 0.95–0.98. Manufacturers may define availability differently, so be careful when comparing availabilities of different wind turbines. Reliability and operation and maintenance affect system performance.

Connect time: The connect time (energized hours) is the amount of time or percent of time a unit actually generates power. In the Texas Panhandle, a typical unit should generate power around 60% of the time. This is a large number and can be put into perspective by comparing wind turbines to automobiles. Suppose your car went 160,000 km (100,000 miles) without 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 of operation for a wind turbine.

Lifetime: Wind turbines are designed for 20–30-year lifetimes. This can be achieved by considering the lifetimes of the components [1] and by performing preventive maintenance. Some components, such as bearings in gearboxes, may have to be replaced within a turbine lifetime. Twenty-five years of operation for a wind turbine would be equivalent to 8 million km for a car, so major repairs will be required.

Jamie Chapman, formerly of U.S. Windpower, noted that, “Estimated minimum standards for non-routine 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 many problems and were replaced within 5 years or dismantled. Others required major retrofits. Some of the early wind farms in California began replacing the 50–100 kW wind turbines with megawatt-size turbines (repowering), starting in 1998. The smaller wind turbines were then refurbished for the distributed market.

Design of generators and gear trains is well known. Loads produced by a rotor are the major factors, especially stochastic loads caused by the turbulent character of winds. As the industry matured, engineers designed blades, gearboxes, and generators specifically for wind turbines. Airfoils for horizontal axis wind turbines have been designed to provide improved performance and increased energy production.

Reliability: Most first-generation wind turbines [2] lacked reliability and quality control. Prototypes generally failed within months. Lack of reliability lead to larger maintenance and operation costs after installation. Manufacturers and dealers were caught in a bind because retrofit programs in the field were very expensive. The most successful wind farms utilized reliable wind turbines and followed good operation and maintenance programs.

If a dealer has to service a small wind system more than once during the first year of warranty, he probably lost money. Typical service charges are $60/h or more. A large service area means a dealer spends most of his time on the road.

Specific output: The most important factors for determining annual energy production are the wind regime and the rotor swept area. One way to compare wind turbines is by annual specific energy

(kilowatt-hours per square meter). Stoddard [3] tabulated data for wind turbines in California, where the best value was 1,000 kWh/m^2 without considering the wind regime. Comparing the averages of a large number of units in similar locations will give a good estimate of performance. Calculating the ratio of annual kilowatt-hours/weight of rotor or weight on top of tower gives an idea of a goal for cost comparisons. As for any mature industry, costs are based primarily on the ratio of cost/weight of material. Other specific outputs are kW/m^2 and kWh/kW, but these ratios are not as useful.

Wind turbines manufactured in Denmark were more massive and captured over 50% of the California wind farm market from 1982 to 1985 because they were rugged and reliable. However, after 5 years, a major problem developed with deterioration of the fiberglass-reinforced plastic (FRP) blades at the roots due to fatigue. The repair and replacement market for blades was estimated at $80 million.

8.2 HISTORICAL WIND STATISTICS

The wind industry essentially began with installations in Denmark and then the wind farms in California. Because there were subsidies, governments were interested in performance, so data were collected and made available to the public.

The WindStats Newsletter contained reports and wind production tables for thousands of wind turbines in Denmark and Germany (now only available in a few library archives). It reported location, manufacturer, kilowatt rating, swept area, tower height, monthly and quarterly energy production, quarterly capacity factor, specific output (kWh/m^2 and kWh/kW), and installation data.

The Sindal Report [4, free download] was a quarterly publication about wind power market trends along with individual production data for more than 6,000 wind turbines in Denmark and Sweden. The last report available is Spring, 2014. Data cover land and offshore locations. Graphs of monthly averages by quarter were presented for energy (kWh), capacity factors, and specific output (kWh/m^2 and kWh/kW) for a range of turbine sizes. For some megawatt wind turbines in 2012, capacity factors ranged from 33 to 47% with the offshore wind farms achieving the largest values. Specific outputs range from 1,100 to nearly 1,400 kWh/m^2 (Table 8.1). For these megawatt wind turbines, energy production for 2012 ranged from 6 to 13 GWh. Of course energy production depends primarily on wind regime (offshore production will differ somewhat) and rotor area, and secondarily on rated power.

8.3 WIND FARM PERFORMANCE

Capacity factors are somewhat arbitrary and depend on rated power of a wind turbine, which can be the same for different size rotors or different based on rated wind speed. Of course, the most important issue is annual energy production that depends primarily on rotor area and wind regime. Some

TABLE 8.1
2012 Performance Data for Megawatt Wind Turbines Cited in Sindal Reports

	Units(#)	Rated (MW)	Land or Offshore	Energy (GWh)	CF (%)	Specific Output (kWh/m^2)
Manufacturer						
Enercon	34	2.3	L	6.1	33	1386
Siemens	74	2.3	L	7.1	36	1146
Siemens	229	2.3	O	9.4	47	1398
Siemens	15	3.6	L	13.0	42	1296
Vestas	73	3.0	L	8.5	32	1311
Vestas	8	3.0	O	8.9	34	1324
Vestas	15	3.1	L	10.7	40	1084

energy production statistics published by the Federal Energy Regulatory Commission (FERC) are actual reported values for power plants in the United States. In many countries, electricity production figures are calculated from average capacity factors and installed capacity.

Because non-hydro renewables, especially wind power, have increased dramatically in installed capacity and energy production, national energy agencies such as the Energy Information Administration (EIA) in the United States now report those values. The EIA also reports international data. Of course, other sources of world production data are international energy, national energy, and national wind energy associations.

Capacity factors have improved with the newer and larger wind turbines, so it is expected that wind farms installed in good to excellent wind regimes since 2000 will demonstrate better capacity factors (35–50%) than the older installations. The early wind farms in California had average capacity factors below 20%. Availability and capacity factor are related. Both measurements will be low if wind turbines have operational problems. For example, during the first year of operation at Horns Rev, an offshore wind farm in Denmark, the capacity factor was only 26%; however, the next year it reached the expected value.

At the Scroby Sands offshore wind farm (30 wind turbines, 60 MW) in the U.K., energy production was limited in the first year of operation. Numerous mechanical problems led to the replacement of 27 intermediate-speed and 12 high-speed gearbox bearings along with four generators. The capacity factor for the first year was 29%, not the predicted 40%. Another example was a 38-turbine, 80-MW wind farm that encountered software and blade malfunctions. One year after installation, 13 turbines were still not operational, but all 38 turbines were operational in the second year.

8.3.1 California Wind Farms

The California Energy Commission (CEC) instituted a program in 1984 for regulating reporting performance of wind systems. All California wind projects producing more than 100 kW that sell electricity to power purchasers must report quarterly performance. The quarterly reports must indicate turbine manufacturers, model numbers, rotor diameters, kilowatt ratings, number of cumulative and new turbines installed, projected output per turbine, output for each turbine model, and output of entire project. The reports do not provide information on every wind energy project in California. Non-operating wind projects and turbines that do not produce electricity for sale, such as those installed by utilities, government organizations, and research facilities, are not required to file reports

Annual reports are compilations of data from the four quarters and contain summary tables that reflect resource areas. Report summaries are available for 1985–2003 and then WPRS was reinstated in 2014 [5].

Only small wind turbines (10–18 m diameter, 5–100 kW) were available in the early 1980s. At the end of 1985, the largest installed capacity was U.S. Windpower's 181 MW, followed by Fayette's 146 MW. The wind farms produced 0.65 TWh, which was 45% of that predicted by the plant operators. Average capacity factor was 13%, much lower than the 20 to 30% cited in technical reports. Foreign (and newer) wind turbines had a capacity factor of 17%. The ten largest manufacturers represented 80% of the installed capacity, and four of those accounted for 53%. The average installed cost of the 10,900 wind turbines was $2,000/kW (range of $700–$2,300).

By 1990, 1,500 MW had been installed in California and produced 2.68 TWh, enough to power the residential needs of San Francisco. Kenetech, formerly U.S. Windpower, still produced the largest number of units and had the largest installed capacity. The sizes of wind turbines increased from 100 to 750 kW. By 2010, California wind farms had a capacity of 3 GW and generated over 6 TWh/year, around 3% of total electric production and new wind turbines were capable of generating 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. For the third quarter, Kenetech had a value

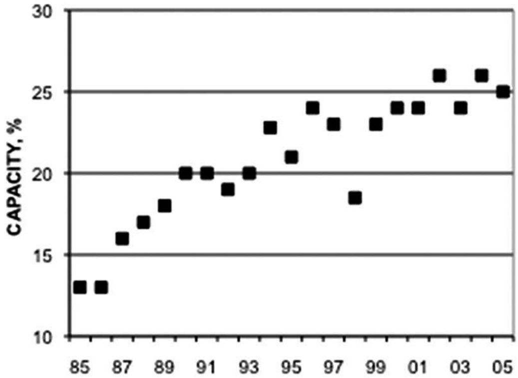


FIGURE 8.2 Average capacity factor for wind turbines in California wind farms. (California Energy Commission.)

of 40% and Bonus achieved 39%. Fayette had a capacity factor problem. At one time, it had the second largest installed capacity, but its capacity factor was a very low 5% because its 90 kW, 10-m turbines were overrated. The vertical axis wind turbines of Flowind also had low capacity factors (10%). Its annual capacity factor increased to 30% with the new, larger wind turbines (Figure 8.3). The specific kWh/m^2 output varied from low values to over 1,000 kWh/m^2 (Table 8.2).

In the 1990s, the older wind turbines, primarily in the range of 50–100 kW (55% of MW capacity installed), were cannibalized for parts and uneconomic wind turbines were dismantled. A number of trends were noted. Wind turbines became larger (megawatt ratings), capacity factors improved, and reliability increased.

Specific output (Figure 8.4) increased when poorly performing units were taken out of service and newer wind turbines installed in 1997–1998. The larger specific output shows the type of performance that can be expected with good wind turbines in an excellent wind regime. Turbines will show annual variations of both capacity factor and specific output because of differences in yearly wind regimes and differences between locations. Wind is site-specific and variations must be expected.

From 2012 to 2016, wind energy production increased from 3.2 TWh to 13.5 TWh from a respective capacity of 1,524 and 5,700 GW [6]. The capacity decrease from 6,001 MW in 2015 was due

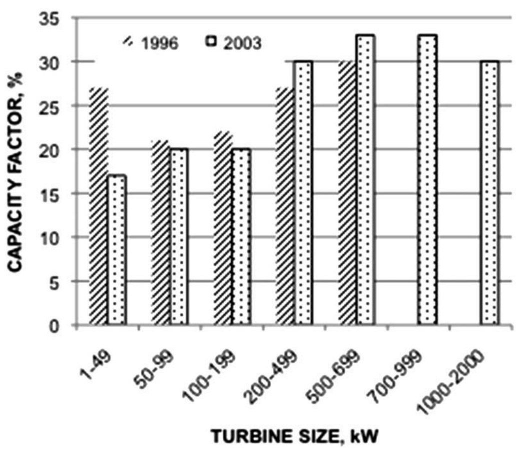


FIGURE 8.3 Capacity factor by range of wind turbine sizes in California.

TABLE 8.2
Specific Output, kWh/m², for Wind Turbines (Most, But Not All Manufacturers) in California, 1989

					Per Turbine	
Turbine	**Dia (m)**	**Rated (kW)**	**# Units**	**Capacity (MW)**	**kWh**	**kWh/m²**
Fayette	10	90	1363	123	41,000	522
Bonus 65	15	65	644	42	1,13,000	640
Vestas 15	15	65	1330	86	53,000	300
Micon 60	16	60	531	32	95,000	473
Nordtank 60	16	60	152	9	1,70,000	846
Micon 65	16	65	126	8	1,84,000	916
Nordtank 150	16	65	375	24	1,00,000	498
Vestas 17	17	100	1071	107	1,45,000	639
U.S. Windpower	18	100	3419	342	2,20,000	865
Micon 108	20	108	967	104	2,30,000	732
Bonus 120	20	120	316	38	2,76,000	879
Carter 250	21	250	24	6	2,50,000	722
Nordtank 150	21	150	164	25	2,40,000	693
Flowind 19	21	250	200	50	1,42,000	410
Danwin 23	23	160	151	24	3,90,000	939
Vestas 23	25	200	20	4	4,34,000	885
WEG MS2	25	250	20	5	5,60,000	1141
Mitsubishi	25	250	360	90	4,86,000	991
DWT 400a	35	400	35	14	10,00,000	1040
					average	756

[a] Estimated kWh.

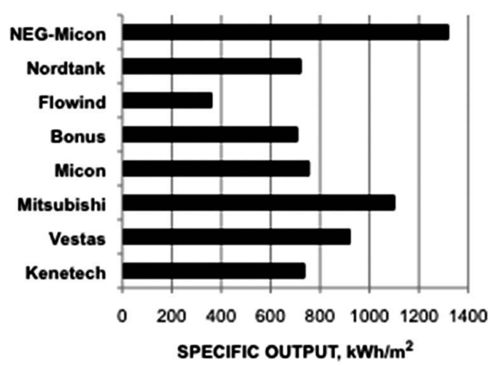


FIGURE 8.4 Specific output for manufacturers with largest installed capacity, California. NEG Micon does not include the older Micon units ranging around 100-kW capacity.

primarily to decommissioning of old wind farms. Wind energy represented 6.8% of the total electric production in California.

Data from 2014 [7] show that the average specific energy was 680 kWh/m² for all projects, which reflects the number of smaller turbines Specific power was 0.38 kW/m². Capacity factors for large projects ranged from 12% in January to 45% in June. The Ocotillo Express (265 MW) had CF = 23% and the Alta (860 MW) had a CF = 21% (2016 data).

8.3.2 Wind Farms in Other States

By 2017, wind farms have been installed in 41 states and they generated an estimated 254 TWh. Capacity factors are better for most of the wind turbines installed over the last 10 years as it is now a fairly mature industry. Texas has the largest capacity, 22.6 GW; followed by Oklahoma, 7.5 GW; Iowa, 7.3 GW; and California, 5.6 GW.

Performance data of net kWh generated and dollar value of those sales are reported quarterly to FERC. From that data capacity factors and specific energy can be calculated. However, similar data for wind farms are not available from the Electric Reliability Council of Texas (ERCOT). For FERC see Links at the end of the chapter; you must know the name of the reporting entity.

Annual capacity factors (Figure 8.5) and specific outputs (Figure 8.6) were analyzed for five wind farms (Table 8.3) in the Southern High Plains. The numbers are correlated, however the most important is specific energy, as energy is sold. Because all the turbines were from the same manufacturer, the difference in performance would primarily be due to local wind regime and operation

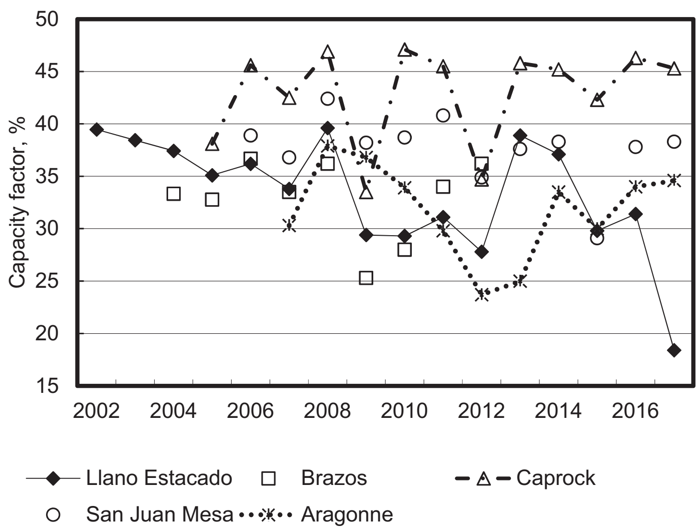


FIGURE 8.5 Annual capacity factors for wind farms in Texas and New Mexico.

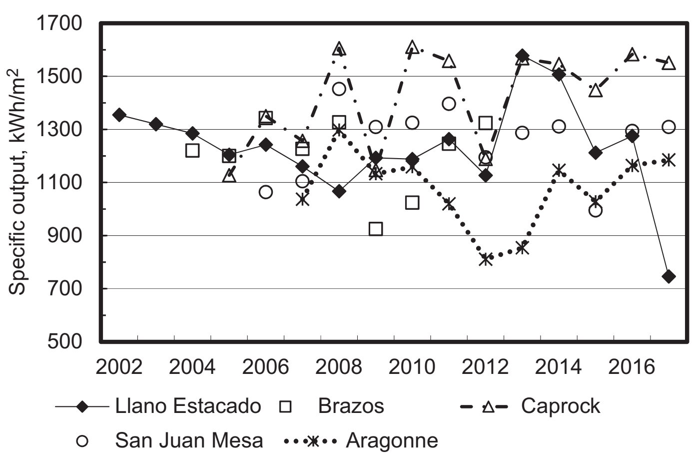


FIGURE 8.6 Annual specific outputs for wind farms in Texas and New Mexico.

TABLE 8.3
Installed Capacities of Mitsubishi 1-MW Systems at Various Wind Farms

Location	Wind Farm	Capacity (MW)	Rotor Diameter (m)	Hub Height (m)
White Deer, TX	Llano Estacado	80	56	60
Fluvana, TX	Green Mountain, 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
Pastura, NM	Aragonne Mesa	90	61.4	69

and maintenance. There was a slight difference as all the turbines at Llano Estacado and 60 at Brazos had a smaller rotor diameter and a shorter hub height. Data for Brazos were unavailable after the second quarter of 2013. Average capacity factors were from 32 to 42% with a maximum of 47.1% for Caprock. The very low performance at Llano Estacado in 2017 was due to the operator not doing any maintenance that involved purchasing parts. From the data it appears around 40% were not running. It appears that Aragonne was a class lower wind site with specific outputs around 1,200 kWh/m^2 (discarded 2012–2013) versus Caprock with an annual average of 1,426 ± 186 kWh/m^2. The largest annual specific output for Caprock was 1,606 kWh/m^2. During the breakdown period and the first year (maybe less than full year) the capacity factors may be lower; notice values for Caprock and Aragonne. In general, the yearly variation is consistent across the region (2009 and 2012 were low wind years). However, the downtrend in capacity factor at Llano Estacado, Brazos, and Aragonne were probably caused by a decline in reliability or operational problems, especially for Llano Estacado which had the most years of operation.

Manufacturers now offer wind turbines with various size rotors and rated powers for different wind regimes or wind classes. Note whether they refer to wind classes defined for the United States or for Europe (see Tables 4.1 and 4.2).

Specific energy output (Figure 8.7) and capacity factors were compared for different manufacturers (Table 8.4) for wind farms near Amarillo, TX and for one location in South Central Oklahoma. Specific energy output and capacity factors and are fairly consistent for the different manufacturers in the High Plains except for Llano Estacado, which shows major problems from 2010–2012 and then declining output starting in 2013. Llano Estacado and Blue Canyon

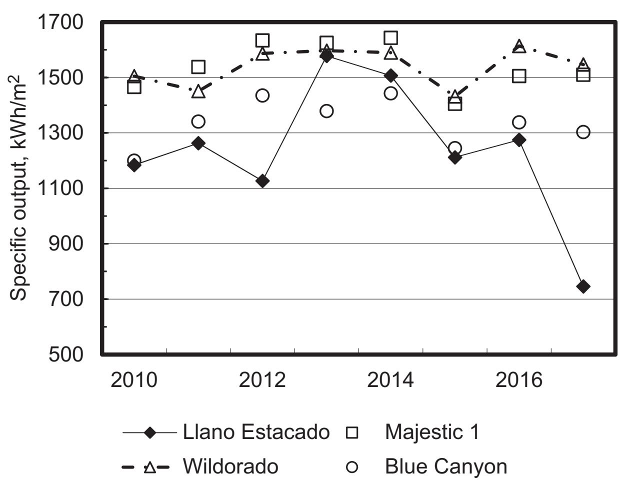


FIGURE 8.7 Annual specific outputs for wind farms with different wind turbines.

TABLE 8.4
Wind Farm Location and Installed Capacity: At Each Wind Farm All Turbines Have the Same Specifications

					Turbine Specifications		
Location	**Wind Farm**	**Year**	**Capacity (MW)**	**Manufacturer**	**Rated (MW)**	**Diameter (m)**	**Height (m)**
White Deer, TX	Llano Estacado	2002	80	Mitsubishi	1.0	56	60
Panhandle, TX	Majestic 1	2008	79.5	GE	1.5	77	80
Wildorado, TX	Wildorado	2007	161	Siemens	2.3	96	82
Lawton, OK	Blue Canyon	2003	74.3	NEG-Micon	1.65	72	70

had earlier model wind turbines. During 2010–2017, the Wildorado Wind Ranch had an average capacity factor of 45.9 ± 1.8% and average specific energy of 1540 ± 70 kWh/m^2, which is a reflection of a good match of rotor area and rated power plus a good wind regime (class 4). There is essentially no difference due to manufacturer or turbine size (1–2.3 MW), however, the wind regime at Blue Canyon is lower. The Wildorado and Llano Estacado wind farms are within 100 km (63 miles) of each other and Majestic is 25 km (16 miles) west of Llano Estacado. The elevation increases from east to west with Wildorado being 170 m (555 ft) higher than Llano Estacado. There is a slight difference in topography as Wildorado is on the south edge of the the breaks of the Canadian River, which could give some speed up for north winds and wake expansion for south winds. The wind regime for Blue Canyon is slightly lower as shown by specific energy output.

For location and topography of wind farms, browse Google Maps and for more analysis use Google Earth. See Links for other interactive maps.

Wind farms in the Turbine Verification Program had to provide public data on performance through the Electric Power Research Institute (EPRI). 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. The difference was partly due to the control method, and partly due to differences in wind regimes.

The Sandia National Laboratory maintains the Continuous Reliability Enhancement for Wind (CREW) database for the analysis of wind plant operations. Wind turbine reliability benchmark reports [8,9] include operating performance at a system-to-component level and identify opportunities for technology improvement. The database (2013 data) represents a small portion of United States wind farms (10 plants, 800–900 turbines, and 180,000 turbine days of operation). However, the database is very useful as it provides the first benchmarks on performance. Key metrics improved from 2011–2012 (Table 8.5) and components affected are shown in Table 8.6. The availability time accounting (Figure 8.8) showed that the units were generating 59% of the time and unscheduled maintenance took 1% of the time.

Good operation and maintenance (O&M) is essential for wind farms. The AWEA recommended practices [10] are based on the input of expert wind project operators, engineers, technicians, and designers.

8.3.3 Other Countries

By the end of 2017, the installed wind capacity in Europe was 169 GW (153 GW onshore) and production was 336 TWh—about 12% of the gross final consumption [11]. Sixteen countries had capacities over 1 GW and 9 had more than 5 GW. Germany had the largest installed capacity

TABLE 8.5
Key Metrics (%) for 2011 and 2012

Metric	2012	2011
Operational availability	97.0	94.8
Utilization	82.7	78.5
Capacity factor	36.0	33.4
Mean time between events (h)	36	28
Mean downtime (h)	1.6	2.5

Source: Continuous Reliability Enhancement for Wind (CREW) Database, Sandia National Laboratory, Albuquerque, NM.
Operational availability = generating + reserve shutdown, wind + reserve shutdown, other.

TABLE 8.6
Average Events per Turbine per Year by Component[a]

Component	Number per Turbine per Year
Wind turbine (other)[b]	90
Electric generator	40
Controls	12
Power distribution	10
Gearbox	8
Braking system	5
Structure and enclosures	4
Yaw	3
Hydraulic control	2
Drivetrain	1

[a] Some events automatically reset; others need intervention.
[b] Wind turbine (other) condition occurs mainly when technician has turbine in maintenance/repair mode.

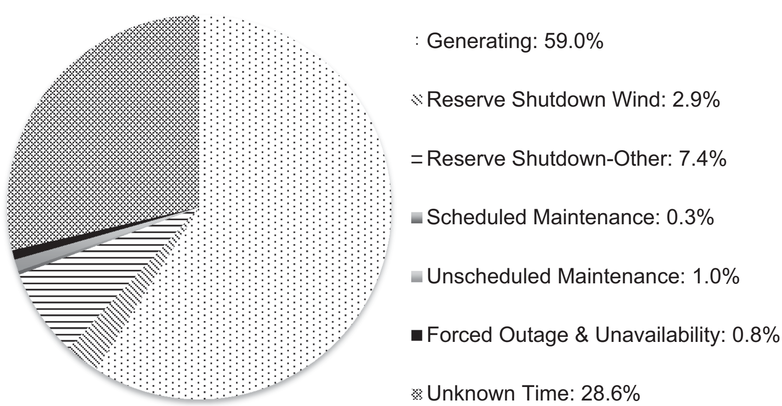


FIGURE 8.8 Availability time accounting. Substantial portion of unknown time attributable to pilot program and beta testing. (From the Continuous Reliability for Wind (CREW) Database, Sandia National Laboratory, Albuquerque, NM.)

(56.1 GW), followed by Spain (23.2 GW), the U.K. (18.9 GW), and France (13.8 GW). In terms of wind percent of total electric production the largest is Denmark 44%, then Portugal and Ireland, 24%; Germany, 20%; and Spain, 19%.

The annual capacity factor (also referred to as load factor) for onshore wind was 23.5% and for offshore it ranged from 29 to 48% (average 37%). The average size of new offshore wind turbines was 5.9 MW. The largest capacity factor was 67.9% in Germany in February of 2017.

It is interesting to compare the above information about Europe with that from previous editions. At the end of 2012, the installed wind capacity in Europe reached 106 GW and produced 230 TWh—about 6% of the gross final consumption. France advanced to around 14 GW from around 1 GW.

The installed capacity and average capacity factors for the U.K. for 2017 were 12.1 GW, 26.6% for land and 6.4 GW, 37.2% for offshore, the latter an increase from 30% in 2010. Capacity factors were calculated as 5 year rolling averages. The estimated annual energy production was 60 TWh, compared to 18.7 TWh in 2012. The U.K. still leads in offshore wind farms in the world.

Many countries supply national energy data and statistics and also have national and regional wind energy associations. For example, wind power produced 15.5 TWh (2016) from installed capacity of 6.4 GW in Sweden, a capacity factor of 29%. Spain has an installed capacity of 23.1 GW and produced 47.9 TWh (18.4% of electrical demand) for a capacity factor of 28%. The average capacity factor for New Zealand wind farms (690 MW) in 2017 was around 40% and they provided around 6% of the electricity consumption.

China is the leading country in installed wind capacity (188.2 GW in 2017), and wind produced around 360 TWh (4%) of the country's electricity. Lack of adequate transmission resulted in curtailment of 15% and the largest curtailment was in East Inner Mongolia. Of course, curtailment reduced capacity factors for those wind farms.

India wind capacity was 32.8 GW, (which ranks fourth in world), wind produced around 57 TWh, and accounts for around 1.6% of electric generation. Capacity factor was around 20% for 2017, an increase from 14% in 2015.

Denmark was an early proponent of wind power and has reached the stage at which its onshore cumulative capacity has essentially leveled off. Its total installed capacity and number of turbines increased through 2002. From 2001 to 2003, 1,300 small wind turbines and those with poor siting were replaced with larger turbines, so the installed capacity still increased until 2003, then leveled off at 3,130 MW although the number of turbines decreased from 6,400 to 5,267 (January 2007). As of 2017, the installed capacity was 5,475 MW, 4,211 MW onshore. For example in 2017, 101 onshore wind turbines were commissioned and 158 were decommissioned. On some days Denmark has an excess of wind power and exports electricity to other countries.

This means that the average power per wind turbine increased from 1 MW to around 2 MW, which included the large wind turbines installed offshore. The average capacity factor was 25% for the smaller wind turbines; the offshore wind farms have capacity factors of 45 to 50%

The first-year performance of the Nysted offshore wind farm had wind farm availability of 96% [12]. 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 revealed increased vibration levels in the gearboxes. The gearboxes were designed for easy gear changes and two gearbox bearings were replaced in every wind turbine. A nacelle crane was used and average downtime was 48 h/turbine. The problem was solved and the 2011 capacity factor was 50%.

8.4 WAKE EFFECTS

Vortices are generated by the tips of blades, the trailing edges of blades, and the tower; and they increase the turbulence of a wake. The tips of airfoils and trailing edges are designed to reduce

the vortices and also 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 [13].

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? The wakes from wind turbines create turbulence and along with wind speed deficits result in array losses reflected by 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.

Downwind units will produce reduced energy, so the question is: How much increase of spacing within a row and between rows will increase production? In fairly flat areas, the rows will be placed perpendicular to the predominant wind direction, within-row spacing would be two to four rotor diameters, and between-row spacing would be five to ten or more rotor diameters.

Offshore wind farms generally utilize larger spacing; for example, Horns Rev in the North Sea off the coast of Denmark has a seven-rotor diameter spacing (within 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 in fairly well-defined regions at different downwind distances, and wake geometry models show this information [14]. Field tests on single and multiple wind turbines measured the velocities and power deficits downwind. The wake effects were still noticeable 10 rotor diameters downwind from a rotor.

Wind turbines have close spacing between rows at wind farms in San Gorgonio Pass, California, due to the high cost of land. Energy production was reduced for the second row and even more for the third row, which experienced wake effects from both the first and second rows. Field measurements of wake effects inside 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 5-km downwind from a 50-MW array [15]. In California, early wind turbines were small (25–100 kW). Larger wind turbines on taller towers were interspaced within rows later.

It is more difficult to predict output and array losses without an extensive wind measurement program for a wind farm. Exceptions are offshore wind farms where 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 resources of the Danish Seas. Comparisons have been made 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 [16].

The Nysted wind farm has 82 turbines (82.4-m diameter, 2.3 MW) with a 9×8 array. The distance between turbines within a row is 480 m and between rows is 850 m (5.8 D $\times$ 10.3 D). The velocity deficit is around 10% at 0–3 km downwind, and the wind recovers to 2% of the upstream values at around 5–20 km downstream, which depends on ambient wind speed, atmospheric stability, and the number of operating turbines [17]. Recovery is faster for unstable than for near-neutral conditions. In calm winds, the turbines are clearly visible on ocean wind speed maps.

The influence of wake effects on energy production [18] was estimated using data from met towers northwest and east of the Horns Rev wind farm and from the SCADA database that contains all observed data for each wind turbine. The Horns Rev wind farm has 80 turbines (80-m diameter, 2 MW) with an 8 by 10 array and a distance of 560 m between the turbines (7D spacing). For most selected cases, the wind turbines were operating at high wind speeds. An analytical model links the small- and large-scale features of the flow in the wind farm with equidistant space between units within a row and between rows.

For wind perpendicular to the row, a large power drop occurs between rows 1 and 2 (around 30%), and a smaller, almost linear power drop occurs between subsequent rows. From row 2 to

FIGURE 8.9 Wind turbine wakes at Horns Rev, Denmark. (Horns Rev 1 owned by Vattenfall. Photographer: Christian Steiness.)

row 9, the power drop is around 10–15%. For winds along the diagonal, the spacing is 9.3 D; however, this covers only three lines with eight turbines. At wind speeds of 9 to 10 m/s, a large power drop (25–35%) is noted from line 1 to line 2, a slight drop from line 2 to line 5, and then essentially a constant drop from line 5 to line 8.

The atmospheric conditions were just right to show the wakes of wind turbines at Horns Rev (Figure 8.9). Notice that the downwind wind turbines are in the wakes of the wind turbines from each of the previous rows. Compare this photo with the photo of the Nysted wind farm (Figure 9.15), also offshore of Denmark.

In the final analysis of performance, the main issues are energy production, return on investment, and value of the energy, which should include externalities. Capacity factors give indications about the wind regime and the relationship between rotor area and generator size. However, the main measures of performance should be annual energy production and average specific output (kilowatt-hours per square meter) per turbine type and model. Wind class should also be included as a check on comparisons of performances of wind turbines. Wake steering of turbines is now being considered to increase performance for wind farms.

8.5 ENERTECH 44

A long-term performance test of an Enertech 44 [19] provided monthly values of energy production, connect time, availability, and wind speed. The variations of power by month and year are shown in Figure 8.10. Connect time (time during which a unit is connected to a grid) is about 60% (Table 8.7) or over 5,000 h/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 Agricultural Research Service site in Bushland, Texas in May, 1982. All three models had 13.4-m diameter rotors. The original turbine was a 240-V single-phase induction generator with a rated capacity of 25 kW. The gearbox and generator were changed to a three-phase, 480 V, 40-kW induction generator (Table 8.8) in 1984. Later that year, a gearbox and 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.

The availability was good, even though the unit was a prototype, and several component failures occurred. 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. Additional downtime was for replacing gears in the gearbox and installing different generators. The year 1992 was a low year for wind power. The unit was down over 2 months while 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.

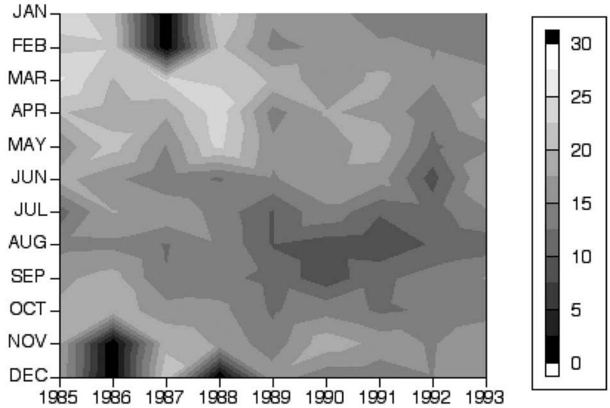


FIGURE 8.10 Average power in kilowatts (legend on right) by month for Enertech 44.

TABLE 8.7
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	3218	63	48092	40	99.9	5.7	25
83	5567	63.6	63710	29	92.6	6	
84	4611	52.6	72295		86.3	5.9	40
85	4662	55.5	91732	17	94.9	5.6	60
86	4121	47.1	77522	15	82.1	5.7	
87	3850	44	65638	12	81	5.6	
88	3971	45.3	71643		77	5.6	50[a]
89	5893	67.3	83452	19	99.4	5.3	
90	5831	66.6	86592	20	97.5	5.6	
91	5705	65.1	82390	19	96.6	5.9	
92	5641	64.6	73510	17	98	5.4	
93	5754	65.9	88363	17	96.4	5.7	
94	5769	66.4	79392	18	95.7	5.6	
95	4099	46.8	51931	12	72.8	5.7	
96	4991	56.8	76470	17	86.8	5.8	
97	4608	52.6	56958	13	75.4	5.5	Hybrid
98	4944	56.4	68885	16	93.2	5.5	
99	4487	51.2	65147	15	93.3	5.7	
2000	4241	48.3	66589	15	85.3	5.7	
Summary					Average	5.7	

[a] 60-kW generator, 40-kW gearbox.

After that, the unit was connected part of the time to a wind–diesel test bed (village grid), so it would not have the same connect time and energy production. The unit was down for half a month in 1999 due to control failure caused by lightning. A report on the reliability is available from the Agricultural Research Service. It shows causes for all downtimes for 20 years of operation. The unit was operational until 2012.

Capacity factors were higher for the small generators, but annual energy production is better with larger generators. However, the energy differences between the 40- and 60-kW generators were not significant. The power curves (Figure 8.11) include all efficiencies, from wind to electric output.

TABLE 8.8
Performance, Enertech 44/40 kW, 44/60 kW, Bushland, Texas, April to September 1986 (Anemometer at 10 am)

Date	# Days	Operating Time (h)	Connect Time (%)	Energy (kWh)	Availability (%)	Average Speed (m/s)
			44/40			
3/20–4/01					shakedown	
4/02–30	29	571	82	11,148	100	7.4
May	31	568	76	9078	99.7	6.4
Jun	30	511	71	8281	100	6.3
Jul	31	430	58	5017	100	5.0
Aug	31	302	41	2443	99.7	4.1
Sep	30	461	64	7240	100	5.8
Oct	31	412	55	6260	100	5.3
Summary	213	3254	64	49,467	100	5.8
			44/60			
11/17–30/84	17				shakedown	
Dec	31	366	49	7877	87.3	5.6
1985	365	4897	56	91,732	94.9	5.7
Jan–Sep 1986	273	3824	58	72,905	100	5.8
Summary	686	9087	57	1,72,514	97	5.7
			9-Month Breakdown–1986			
J	31	450.8	61	9790	100	5.7
F	28	342	51	7578	100	5.5
M	31	441.7	59	8803	99.9	5.9
A	30	466	65	8635	99.8	6.5
M	31	430	58	9103	100	6.2
J	30	360.9	50	5638	100	5.1
J	31	518.1	70	9839	100	6.4
A	31	369.5	50	5293	100	5.3
S	30	445	62	8226	100	6
Summary	273	3824	58	72,905	100.0	5.8

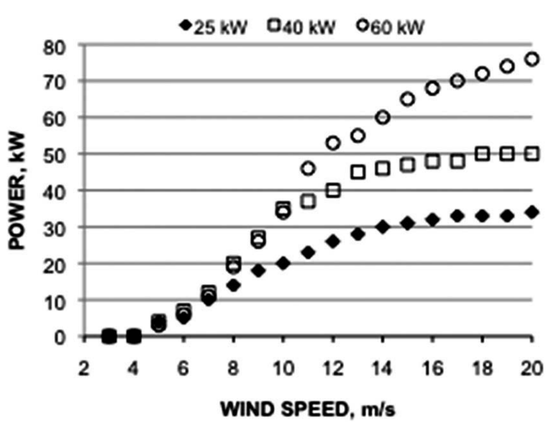


FIGURE 8.11 Power curves for Enertech 44 with different size generators.

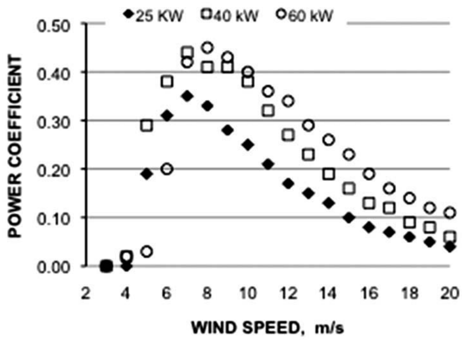


FIGURE 8.12 Power coefficient curves for Enertech 44 with different size generators.

The same information is presented by power coefficient curves (Figure 8.12). In other words, winds above 12 m/s are insufficient for the larger generator to offset the differences in generator efficiency at lower wind speeds. Furthermore, a larger generator and gearbox would increase the cost.

8.6 BERGEY EXCEL

A Bergey Excel wind turbine installed at the AEI Wind Test Center in August, 1991 operated until 2010, when the test center was moved from its location adjacent to the campus. The specifications were three phase, 240 V, permanent magnet alternator, rated at 10 kW. The variable voltage, variable frequency was converted to DC, then inverted to 60 Hz for connection to a utility line. Power and wind speed were sampled at 1 Hz and averaged over 15 min. The time sequence data were then averaged over 1 month for each 15-min period to calculate an average day for the month. As expected, the power (Figure 8.13) varied widely by season and time of day. Spring of 1992 was a below-average wind period.

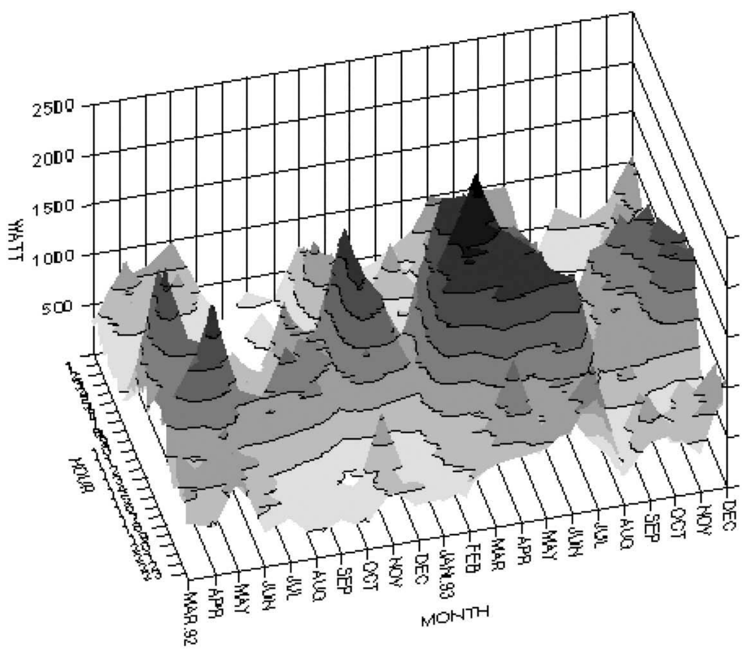


FIGURE 8.13 Power for Bergey 10-kW wind turbine for average day, by month from March 1992 to December 1993.

Power curves indicate performance, and when compared to the manufacturer's curve, the measured power curve (Figure 8.14) at the site was lower, even when corrected to standard density [20]. This means that the energy production would be lower than that predicted from the manufacturer's power curve. Part of the reduction is due to the efficiency of the inverter, especially at high wind speeds (see information on inverters in Chapter 7).

Power curves for shorter periods will indicate performance of a wind turbine when compared to baseline experimental power curves at a site. Of course, there is some data scatter, especially at high wind speeds with few data points. However, low power curves indicate a problem. Power curves for each month were plotted and then averaged to obtain a baseline curve (Figure 8.15). Notice that the system definitely had a problem in November.

8.7 WATER PUMPING

Water pumping by windmills is an old technology. Most changes of farm windmill technology have not been commercial. The electric-to-electric system for pumping larger volumes of water for villages and small irrigation plots [21] was designed and prototypes have been tested. Now such systems are available commercially. Windmill 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.

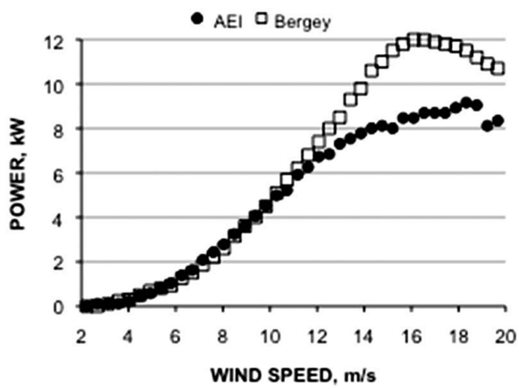


FIGURE 8.14 Power curve for Bergey Xcel compared to measured power curve at AEI Wind Test Center (1997–1999).

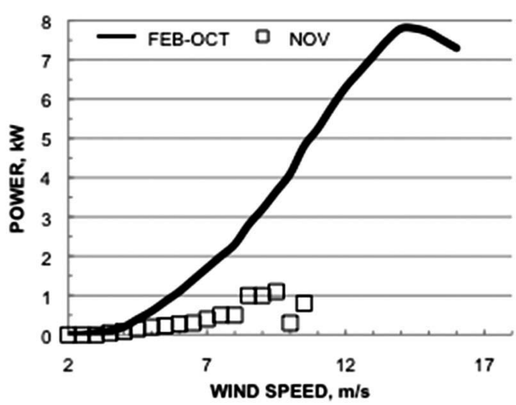


FIGURE 8.15 Power curves for Bergey, 10 kW, at Leroy, Texas.

8.7.1 Farm Windmills

Farm windmill designs have not changed since the 1930s. These windmills are well designed to pump small volumes of water for livestock and residential use. They are comparable to drag devices because of the large solidity (close to 1). The wind rotor has a peak efficiency of 15 to 18% at a tip speed ratio around 1. The wind rotor efficiency is higher than the overall efficiency because pump efficiency limits system performance.

Since a windmill is connected to a positive displacement pump, the rotor needs a lot of blades to achieve high starting torque. For a mechanical farm windmill with a positive displacement pump, the water flow rate is directly related to the number of strokes per minute. Overall average annual efficiency (wind to water pumped) is around 5–6% [22]. The curve for water flow is similar to the efficiency curve. Tables are available to estimate performance of farm windmills for different wind regimes, for example, Table 8.9. The same information is shown in Figure 8.16; however, the strong wind data from Table 8.9 were not plotted since they were close to fair wind data.

Performance tests of eight farm windmills [23] showed little difference between the four units that had reciprocating pumps, two of which had conventional reduction gears and two did not. The windmill equipped with a Moyno pump performed well, but the three airlift units performed poorly. The advantage of no moving parts in the well was offset by the lower efficiency of the pump and air compressor.

TABLE 8.9
Estimated Water Pumped by Farm Windmill

		Light Wind (3 –4.5 m/s)	Fair Wind (5–7.5 m/s)	Strong Wind (>8 m/s)
Depth (m)	**Pump Diameter (cm)**	**Cubic (m/h)**	**Cubic (m/h)**	**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
Depth (ft)	**Pump Diameter (in.)**	**Gal/h**	**Gal/h**	**Gal/h**
30	8.0	2145	3300	3630
55	6.0	1220	1875	2060
80	5.0	845	1300	1430
125	4.0	540	830	910
160	3.5	420	640	700
220	3.0	300	470	520
260	2.75	250	385	425
300	2.5	210	325	360
360	2.25	170	260	285
460	2.0	125	190	210
560	1.875	120	180	200
600	1.75	100	150	165

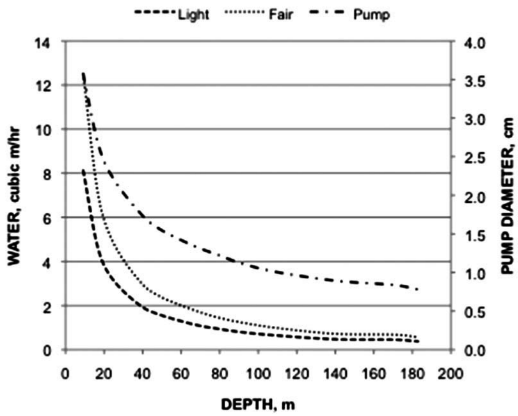


FIGURE 8.16 Pump diameter to use for depth to water and amount of water that farm windmills would pump in light and fair winds.

8.7.2 Electric-to-Electric Systems

A very promising development is a combination wind and electric-to-electric water pumping systems [24]. A 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 of the characteristics of the wind turbine rotor and the load. The overall annual efficiency is 12 to 15%—double the performance of a farm windmill. The water flow is higher at higher wind speeds for the wind–electric system shown in Figure 8.17 because of more wind power in this region. This is also a region where a farm windmill is furled, limiting the power output.

A farm windmill and a 1.5-kW wind–electric system [25] using a submersible pump are essentially the same size and the costs are almost the same. The wind–electric system pumped twice the amount of water from the same depth (Figure 8.18). However, during the low wind month of August, the farm windmill pumped more water. Another issue is that larger wind–electric systems can pump enough water for villages [26] or low-volume irrigation [27].

8.8 WIND–DIESEL AND HYBRID SYSTEMS

Around 1.1 billion people (about 70% of the populations of developing countries) do not have access to electric power because they are too distant from transmission lines of conventional electric power

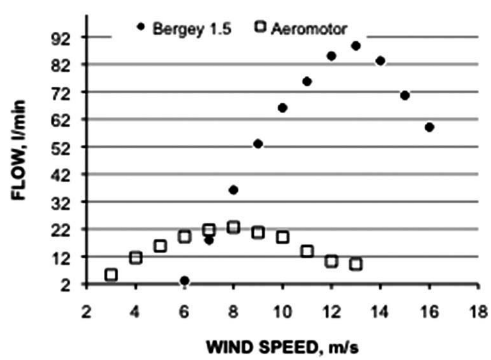


FIGURE 8.17 Water flow rates for mechanical, multibladed windmill (Aerometer) and a Bergey 1.5-kW electric-to-electric water pumping system.

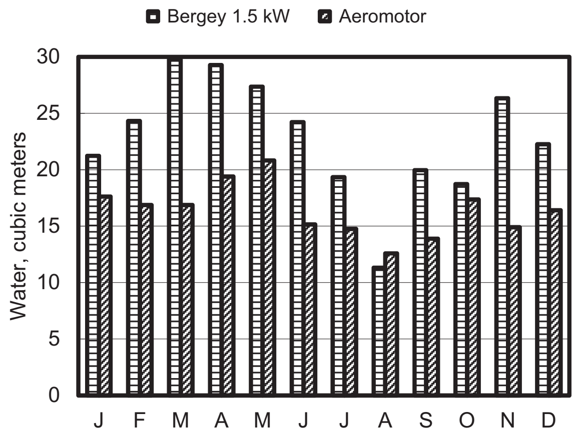


FIGURE 8.18 Predicted annual water pumped by a 1.5-kW wind-electric water pumping system and farm windmill.

plants. Extension of the grid is too expensive for most rural areas, and if extended, must be heavily subsidized. These people depend on wood, charcoal, biomass, or dung for cooking and heating, mainly collected by women and girls.

For remote villages and rural industries, diesel generators represent the power standard. Remote electric power was estimated at 10.6 GW in 1990. Much of that was produced by 133,816 diesel generators ranging in size from 5 to 1,000 kW, with power rating estimated at 9.1 GW. These estimates are low. In 2012, Brazil produced 3 GW and India produced 22 GW of village power from diesel systems. In the United States, remote power and backup generators have a capacity of 5.6 GW.

Many islands, especially those with low populations, rely on diesel generation sets to produce electricity. For example, the Maldives population of 316,000 relies totally on diesel sets (62-MW capacity). Canada utilizes more than 800 diesel generating sets with a combined installed rating of over 500 MW. Diesel generators are inexpensive to install but they are expensive to operate and maintain. Major maintenance is needed every 2,000–20,000 h, depending on the size of the system. Most small village systems generate power only in the evenings. Electric energy from diesel generators range from \$0.40 to over \$1.00/kWh for remote and isolated systems. Wind–diesel [28] is an alternative because of the high costs for generating pure diesel power in isolated locations. By 1986, more than a megawatt of wind turbine capacity was combined with existing diesel systems.

The grid of the Kotzebue Electric Association (KEA) in Alaska uses five diesel generators with a combined capacity of 11.04 MW. The annual average load is about 2.5 MW, with a peak 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 winters. Critical electrical and heating loads include the regional hospital, airport, and water system.

Typically, KEA runs one generator continuously during the winter and maintains the others as backups. In 2012, the association used around 5.3 million L (1.4 million gal) of diesel fuel, with an average efficiency of 3.8 kWh/L (14.6 kWh/gal). The fuel cost for the diesel generators was estimated at \$0.23/kWh since the delivered diesel cost was \$0.80/L (\$3.39/gal). Fuel costs represent about 60% of the operational cost. KEA receives its annual fuel supply during the short summer season when its river is navigable by barge. The fuel is stored in two, 3.78 million liter (1 million gallon) steel tanks.

The KEA wind farm project added wind turbines to an existing diesel plant [29]. As of 2012, the farm consisted of 19 turbines after 2 new EWT (900-kW) wind turbines increased the capacity to 2.94 MW. The farm is a high penetration system and storage and/or dump loads are needed to allow

excess power to be absorbed and then released during peak loads or used for thermal applications. KEA plans to install a 500-kW/3.7-MWh flow battery and electrical dump loads.

The first 3 turbines were installed in July, 1997, and 7 more were added in May 1999. The 10 wind turbines (Atlantic Orient, 66 kW, 15 m diameter) are located on a relatively flat plain 7 km south of Kotzebue and 0.8 km from the coast (Figure 8.19). 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 10 wind turbines should reduce the annual fuel consumption by about 340,000 L, which is about 6% of normal requirements. At the 1998 fuel cost of $0.25/L, the fuel reduction saves KEA and its member-owners around $84,600 each year. In addition to direct fuel cost savings, KEA's costs for storage and meeting pollution control requirements associated with diesel fuel will decrease.

In 2000, the 10 wind turbines produced 1.1 MWh of electricity, saving 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 and high-density air, KEA had to change the control system to reduce peak power output.

A Northern Power wind turbine (100 kW), three more 50-kW units, and one remanufactured 65-kW Vestas V15 were installed, and the association had 17 wind turbines at the site. In 2007, they generated 667,580 kWh of energy, resulting in a savings of 172,240 L of diesel fuel. Installing foundations in permafrost and operating in cold climates presented problems not found at lower latitudes. After the price for diesel fuel escalated to $1.25/L in 2008, wind–diesel generation became more economical.

With the addition of the two EWT wind turbines (900 kW) in 2012, the wind farm will generate around 4 million kWh/year so the annual displacement of diesel is around 1.05 million liters. With diesel cost at $0.80/L, the savings to KEA will be $800,000/year and will increase when diesel cost increases.

A number of prototype and demonstration hybrid systems that combine wind and photovoltaic generation have been installed, but performance for most projects has been poor. In the past, hybrid systems [30] experienced high failure rates from faulty components, poor maintenance,

FIGURE 8.19 Wind turbines at Kotzebue Wind Farm. Starting at left foreground: Northern Power, 100 kW; Vestas, 65 kW; some of the Atlantic Orient wind turbines (downwind), 50 kW; and EWT, 900 kW. (Photo courtesy of Rich Stromberg, Alaska Energy Authority.)

and inadequate support by system suppliers after installation. One problem with Atlantic Orient (Entegrity) wind turbines in Nome, Alaska, is that ice chunks sliding off the blades bent the tip brakes and caused loss of overspeed control and damage to the turbines. Hybrid systems will be covered in more detail in Chapter 10.

8.9 BLADE PERFORMANCE

A smart rotor blade [31] would include active aerodynamic control with spanwise distributed devices: trailing edge devices and camber control, micro tabs, boundary layer control (suction, blowing, synthetic jets, vortex generators), and structural integration. Blade performance has been evaluated through research and field experiments analyzing lift and drag data for airfoils and changing attack angles. The experiments studied the 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 [32]. The blade was a new NREL S809 thin airfoil, constant chord, no twist, on a three-blade downwind rotor (10 m diameter) with constant rpm and variable pitch. Dynamic stall occurred at a 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 8.20), to the point where a rotor will not turn. Also, falling chunks of ice from large blades present safety hazards. If icing is a major problem, heated blades may be an economic solution. Black blades have been used on some wind turbines to assist thawing when the sun comes out.

Accumulation of surface debris on the leading edges of blades from insects, grease, dust, sand, and air pollution causes energy losses, as noted by wind farm operators. A 60-kW wind turbine at an Agricultural Research Service installation showed a monthly energy loss of over 20%. Energy losses of 40% were observed when the wind speeds were above 13 m/s [33]. Insects on the blades (Figure 8.21), like on the windshield of a car, can reduce performance by 30% or more.

The impacts of insects on leading edges can be severe; but data showing amounts and heights of contamination are difficult to obtain [34]. Adhesive tape was wrapped around the leading edges 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 based on testing of wind turbines in California. This corresponded to using #80 rock tumbler grit at approximately 100–150, 250–300, and 500–600 particles per 5 cm^2.

Power was measured for two 24-h periods, and the data was averaged over 5 min for the Enertech 44. Measurements were made on dirty blades and made again after a rain cleaned the blades

FIGURE 8.20 Ice on Carter 25 blade. Blades with this much ice do not rotate.

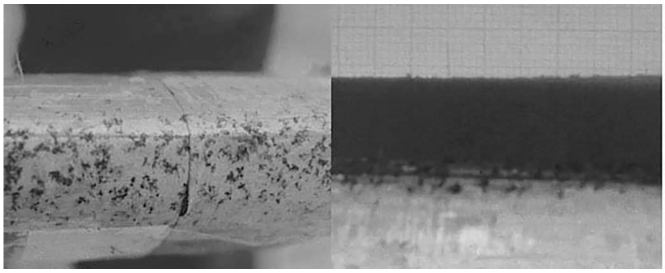


FIGURE 8.21 Left: Bugs on leading edge of PM blade. Right: Graph paper on the ground shows shadow of leading edge bugs that protrude 1–3 mm.

(Figure 8.22). Insects on the blades reduced the peak power about 20 kW (Figure 8.23) or 40%. The power curves for the data show the same information (Figure 8.24). This is another reason for wind farms to have baseline power curves for all turbines. They can then compare weekly power curves to baselines for performance checks.

California wind farms wash the blades after an insect hatch (Figure 8.25) to improve energy production. Active stall wind turbines attempt to compensate automatically for reductions in power output at wind speeds above the rated speed. Because insects on blades reduce 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 turbine (72-m diameter, 1,500 kW) [35]. No reduction in the power curve was noted because the active stall provided complete compensation for moderately contaminated blades. Slight reductions occurred around the knees of the power curves for severely contaminated blades. There was a slight reduction in power curves in the lower wind region for extremely contaminated blades. However, the power still reached nominal rates at a wind speed above the rated one and a significant reduction in high winds occurred beyond that point. The compensation for blade roughness is another reason for using active

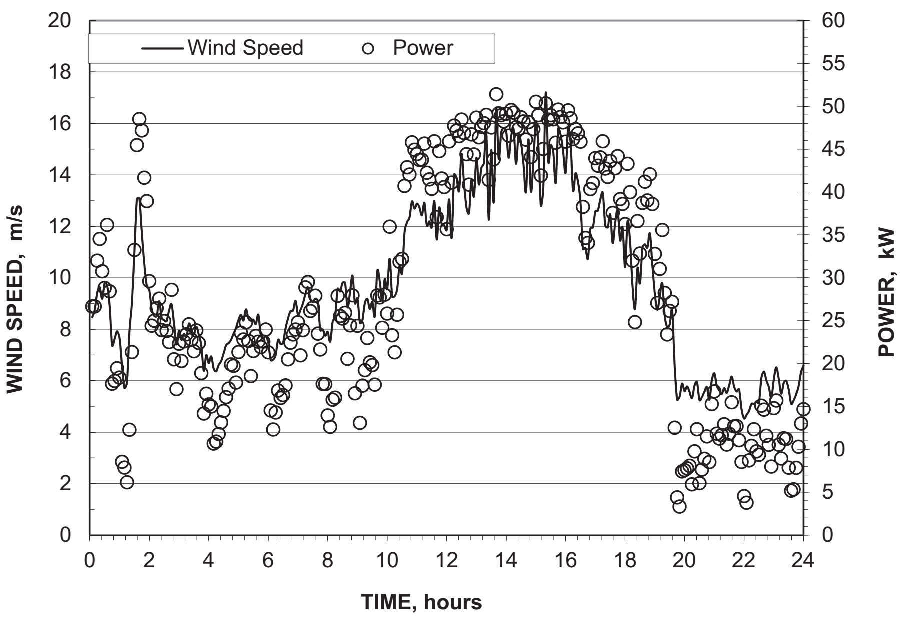


FIGURE 8.22 Enertech 44 performance with clean blades after rain, April 17, 1986. Maximum power is close to the 50-kW rated power.

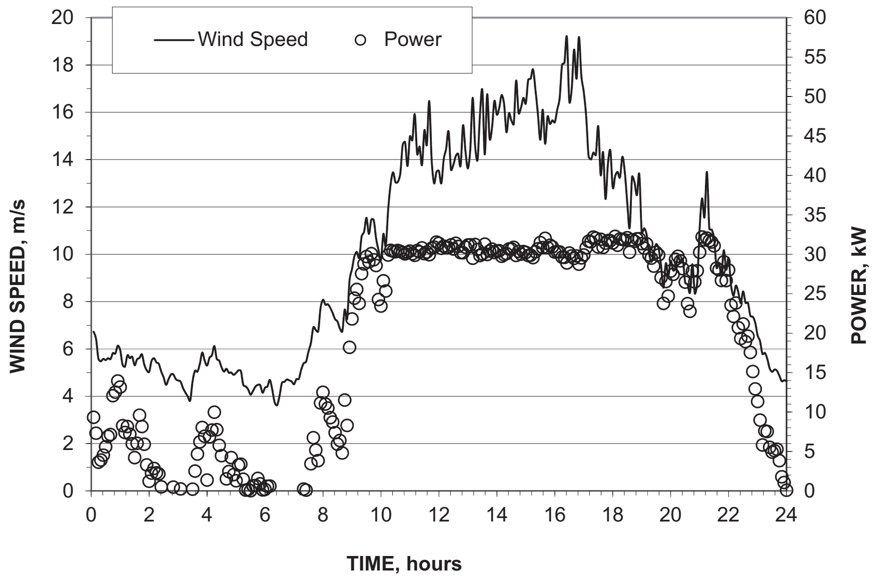


FIGURE 8.23 Enertech 44 performance with dirty blades on April 13, 1986. Maximum power leveled off around 32 kW.

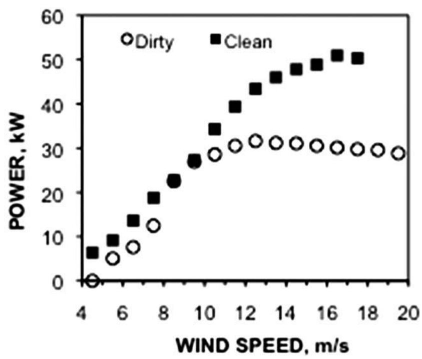


FIGURE 8.24 Enertech 44 power curves from data in Figures 8.22 and 8.23.

FIGURE 8.25 Spraying from tower to clean blades at San Gorgonio Pass in California. Spray is powered by the truck on the ground. Notice the man on the the boom washing the blade on the turbine.

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.

8.9.2 Boundary Layer Control

Boundary layer control describes all the methods that can be used to reduce skin friction drag by controlling the transition to turbulent flow, reducing the development of turbulent flow, and preventing separation of laminar and turbulent flows. Boundary layer control is intended to keep the flow attached further along the chord, thereby increasing lift and reducing drag and preventing dynamic stall—a hysteresis loop of lift caused by changing high angles of attack on blades that creates high loads.

One method of boundary layer control is using suction or blowing air through holes in a blade. Suction can prevent laminar and turbulent separation by removing flows of low momentum. The pressure difference needed for suction or blowing can be obtained from the centrifugal force acting on the air inside a blade or a pump can supply the difference.

8.9.3 Vortex Generators

A vortex generator mixes faster moving laminar flow with the boundary layer and delays flow separation from the blade and stall. Typically, counter-rotating pairs of vortex generators with ±20° angles of incidence at 10% chord are installed on the inner portions of a blade (Figure 8.26) that are thicker and more prone to dynamic stall. Vortex generators were installed on the MOD-2 and the MOD-5 wind turbines, and the performance improved [36].

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 increased, but 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 the air-jet vortex generator that showed improved performance over vane vortex generators in wind tunnel tests. The air-jet device was installed on a 150-kW wind turbine and increased the maximum power. The potential benefits were not conclusive, probably due to the placement of the jets on the outer part of the blade rather than on the inboard section. Production blades now have vortex generators (Figure 8.27).

8.9.4 Flow Visualization

The performances of blades, rotors, and towers can be checked by flow visualization: smoke, tufts, stall flags, pressure-sensitive liquid crystals, and oil streaks. Tufts (small pieces of string, frayed

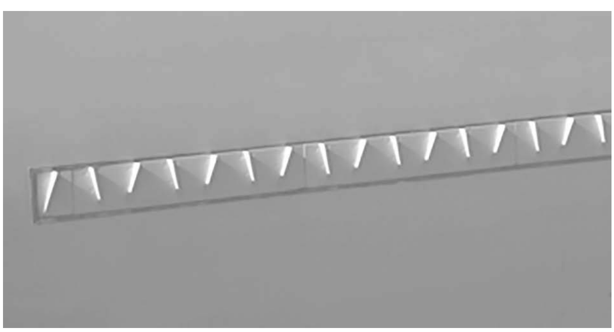


FIGURE 8.26 Shape and orientation of vortex generators on a blade of a GE wind turbine (77-m diameter, 1.5 MW).

FIGURE 8.27 Vortex generators on an inner portion of a blade of a GE wind turbine (77 m diameter, 1.5 MW).

on the end) are driven by frictional drag and stall flags are pressure driven. A stall flag responds to separated flow with an optical signal that exceeds a tuft signal by a factor of 1,000 [37]. Smoke shows the stream flow for airfoils in wind tunnels, the generation of tip vortices from the ends of blades, and their propagation downstream [38]. Smoke released from tethered smoke generators was used to observe the evolution of tip vortices from the MOD-2 [39]. The vortex became unstable when it passed through the wake of the turbine tower.

Blades on downwind turbines pass through the wake of a tower and the change in attack angle and flow across the blade also generate noise. Flow visualization was used to study the flows [40] 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 were downwind, constant rpm wind turbines. A video camera and a 35-mm camera were mounted on a boom attached to the root of a blade. Tufts 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 most of the blade.

Full or partial reattachment due to tower shadow was observed on each unit (Figure 8.28). Spanwise, flow was observed near the leading edge of the Enertech 21, and most of the 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 min in winds from 7 to 15 m/s on the Enertech 44 blade showed that flow was separated completely below 0.5 blade length. However, the flows on the highly twisted and tapered Carter 25 blade were attached in medium winds. The flow data showed a turbulent-type edge separation beginning at about half the radius and progressing forward. Pressure-sensitive liquid crystals were tried, but field results were not good because precise lighting is required to observe color changes.

It should be noted that vortices alternating on each side will be shed by cylinders in wind flow that can induce vibration in the cylinder. On the VAWT 34-m test bed, a spiral staircase on the torque tube eliminated these vortices.

8.10 COMMENTS

Wind turbine and wind farm performance data (annual, quarterly, monthly, or by period of peak demand) determine economic viability and aid comparisons of turbines. The main performance factors are the amount of energy produced and the cost of the energy compared to other energy

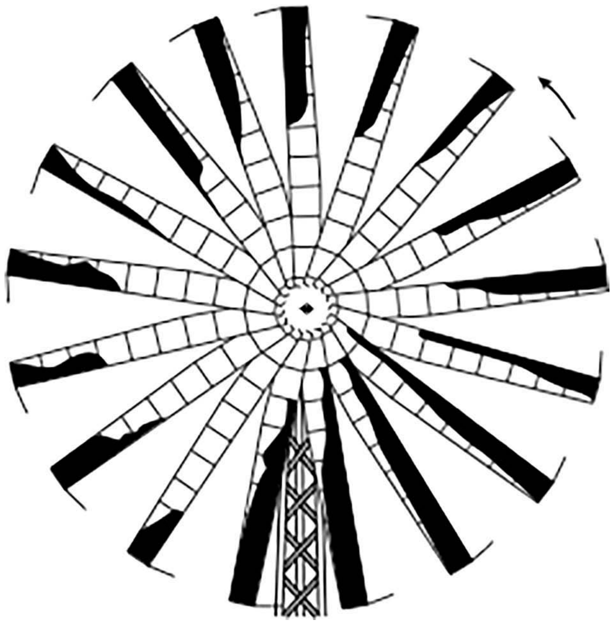


FIGURE 8.28 One blade of the Enertech 21 over one revolution. Shaded areas show representative pattern of the attached flow. Note the strong reattachment due to the tower shadow.

sources. Of course, electricity is the major application; water pumping is secondary. Capacity factors in good to excellent wind regimes should range from 30 to 50%, 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 if good preventative maintenance programs are followed.

PROBLEMS

1. From Table 8.2, calculate annual specific output (kWh/kW) for two different wind turbines.
2. From Table 8.2, calculate capacity factor for Fayette, Vestas 23, and Bonus 120.
3. From Table 8.4, what is the average capacity factor for 1989–1996?
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 8.5 calculate: (a) specific output (kWh/m^2) and (b) capacity factor for 7 months for Enertech 44/25.
6. From Table 8.5 calculate (a) specific output (kWh/m^2) and (b) capacity factor for 1985.
7. From Table 8.5 calculate specific output (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
# blades	2	3

(*Continued*)

Specifications	**Carter 300**	**Vestas V27**
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	1340	2900
Tower head (nacelle)	2091	7900
Tower	(includes gin pole) 8023	12,000
Guy cables, winch	1336	
Control box and panel	155	
TOTAL	14,250	22,800

8. For the Carter 300, calculate (a) specific output (kWh/m^2), (b) $IC/kW, (c) specific output (kWh/kg), and (d) kWh/$IC.
9. For the Vestas V27, calculate (a) specific output (kWh/m^2), (b) $IC/kW, (c) specific output (kWh/kg), and (d) kWh/$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 V90 (2 MW), estimate the annual specific output (kWh/m^2) for a medium wind regime (IEC IIA/IEC S). (b) For the Vestas V110 (2 MW), estimate the annual specific output (kWh/m^2) for a low wind regime (IEC IIIA).
12. For a 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 a 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 a 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 a 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. For a 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).
17. For an annual average wind speed of 6 m/s, compare the predicted annual energy production of the Enertech 44 for 25- and 60-kW wind generators. Use Figure 8.8 for power curves and use Rayleigh distribution (1 m/s bin width).
18. By approximately what percent will bugs on blades reduce the power?
19. Select a wind farm near 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. Or, if you cannot find a wind farm, use one from Figure 8.5.
20. Are there any village power systems in your country? If the answer is yes, determine whether performance data are available for one system. What is the size of the system and how much energy is produced annually?
21. Are there any wind–diesel systems in your country? If the answer is yes, determine whether performance data are available for one system. What is the size of the system and how much energy is produced annually?
22. List two types of boundary layer controls for wind turbines. Briefly explain each type.
23. Which type of wind turbines would perform best with heavy insect contamination on the blades? Why?

REFERENCES

1. R.N. Clark. 1983. *Reliability of Wind Electric Generation*. ASAE Paper 83–3505.
2. W. Pinkerton. 1983. Long term test: Carter 25. In *AWEA, Proceedings of Wind Energy Expo and National Conference*, p. 307.
3. F. S. Stoddard. 1990. Wind turbine blade technology: A decade of lessons learned, 1980–1990. California Wind Farms Report. Alternative Energy Institute, West Texas A&M University: Canyon, TX. Contact kstarcher@wtamu.edu.
4. Sindal. www.sindal-lundsberg.com/cms/.
5. California Energy Commission. California wind performance report summaries. www.energy.ca.gov/wind/documents/California Energy Commission.
6. California Energy Commission. Electricity from wind energy statistics & data. www.energy.ca.gov/almanac/renewables_data/wind/.
7. California Energy Commission. Wind energy in California, 2014 description, analysis, and content. www.energy.ca.gov/2017publications/CEC-200-2017-001/CEC-200-2017-001.pdf.
8. V. Peters, A. Ogilvie, and C. Bond. 2012. Wind plant reliability benchmarks. Sandia National Laboratory. Report 2012-7329P. http://energy.sandia.gov/wp/wp-content/gallery/uploads/Sandia-CREW-2012-Wind-Plant-Reliability-Benchmark-Presentation.pdf.
9. C. Carter, et al. 2016. Continuous reliability enhancement for wind (CRES) program update. Sandia Report. SAND2016-3844.
10. AWEA operations & maintenance recommended practices. https://awea.ebiz.uapps.net/PersonifyEbusiness/AllProducts/ProductDetails.aspx?productId=655145.
11. Wind Europe. 2017. Wind in power 2017, annual combined onshore and offshore wind energy statistics. windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2017.pdf.
12. P. Volund, P.H. Pedersen, and P.E. Ter-Borch. 2004. The 165-MW Nysted offshore wind farm first year of operation: Performance as planned. www.offshorecenter.dk/log/bibliotek/165%20MW%20Nysted%20Offshore%20Wind%20Farm.pdf.
13. W. Cleijne. 1990. Literature database on wind turbine wakes and wake effects. Report 90-130. TNO: Apeldoorn, The Netherlands.
14. P.B.S. Lissaman. 1994. Wind turbine airfoils and rotor wakes. In D.A. Spera, Ed., *Wind Turbine Technology*, p. 283. ASME Press: New York.
15. D.L. Elliott. 1991. Status of wake and array loss research. In *AWEA, Proceedings of Windpower Conference*, p. 224.
16. C.B. Hasager et al. 2007. Wind resources and wind farm wake effects offshore observed from satellite. Risoe National Laboratory, Wind Energy Department. www.offshorecenter.dk/log/bibliotek/Wind%20resources%20and%20wind%20farm.PDF.
17. M.B. Christiansen and C.B. Hasager. 2005. Wake effects of large offshore wind farms identified from satellite SAR. *Remote Sensing of Environment,* 98, 251.
18. M. Méchali et al. Wake effects at Horns Rev and their influence on energy production. www.researchgate.net/publication/241698693_Wake_effects_at_Horns_Rev_and_their_influence_on_energy_production.
19. R.N. Clark and R.G. Davis. 1993. Performance of an Enertech 44 during 11 years of operation. In *AWEA, Proceedings of Windpower Conference*, p. 204.
20. K. Pokhrel. 2001. Performance of renewable energy systems at a demonstration project. *Master's Thesis*, West Texas A&M University: Canyon, TX.
21. V. Nelson, N. Clark, and R. Foster. 2004. *Wind Water Pumping*, CD. Alternative Energy Institute, West Texas A&M University (also available in Spanish): Canyon, TX. Contact kstarcher@wtamu.edu.
22. R.N. Clark. 1992. Performance comparisons of two multibladed windmills. In *Proceedings of 11th ASME Wind Energy Symposium*, Vol. 12, p. 147.
23. J.A.C. Kentfield. 1996. The measured field performances of eight different mechanical and air-lift water-pumping wind-turbines. In *AWEA*, *Proceedings of Windpower Conference*, p. 467.
24. J.W. McCarty and R.N. Clark. 1990. Utility-independent wind electric water pumping systems. In *Proceedings of Solar Conference*, p. 573.
25. B.D. Vick, R.N. Clark, and S. Ling. 1999. *One and a Half Years of Field Testing a Wind–Electric System for Watering Cattle in the Texas Panhandle*. Paper presented at AWEA, Windpower Conference, CD.

26. M.L.S. Bergey. 1990. Sustainable community water supply: A case study from Morocco. In *AWEA, Proceedings of Windpower Conference*, p. 194.
27. B.D. Vick and R.N. Clark. 1998. *Ten Years of Testing a 10 kilowatt Wind-Electric System for Small Scale Irrigation*. ASAE Paper 98-4083.
28. R. Hunter and G. Elliot. 1994. *Wind Diesel Systems: A Guide to the Technology and Its Implementation*. Cambridge University Press: Cambridge, U.K.
29. Kotzebue Electric Association. www.kea.coop/renewable-energy/.
30. V.C. Nelson et al. 2001. Wind hybrid systems technology characterization: report for NREL. West Texas A&M University and New Mexico State University Canyon, TX and Las Cruces, NM. https://faculty.mu.edu.sa/public/uploads/1338115770.8294wind_hybrid_nrel.pdf.
31. T. Barlas and G. Kuik, 2010. Review of state of the art in smart rotor control research for wind turbines. *Progress in Aerospace Sciences*. 46. 1–27. DOI:10.1016/j.paerosci.2009.08.002.
32. C.P. Butterfield et al. 1991. Dynamic stall on wind turbine blades. In *AWEA, Proceedings of Windpower Conference*, p. 132.
33. R.N. Clark and R.G. Davis. 1991. Performance changes caused by rotor blade surface debris. In *AWEA, Proceedings of Windpower Conference*, p. 470.
34. E.M. Moroz and D.M. Eggleston. 1992. A comparison between actual insect contamination and its simulation. In *AWEA, Proceedings of Windpower Conference*, p. 418.
35. C.J. Spruce. 2006. *Power Performance of Active Stall Wind Turbines with Blade Contamination*. Paper presented at European Wind Energy Conference. www.researchgate.net/publication/293094790_Power_performance_of_active_stall_wind_turbines_with_blade_contamination.
36. R.E. Wilson. 1994. Aerodynamic behavior of wind turbines. In D.A. Spera, Ed., *Wind Turbine Technology*. ASME Press: New York, p. 215.
37. G.P. Corten. 2001. Flow separation on wind turbine blades. https://dspace.library.uu.nl/bitstream/handle/1874/653/full.pdf.
38. L.J. Vermeer. 2001. A review of wind turbine wake research at TUDELFT. AIAA-2001-0030. www.windenergy.citg.tudelft.nl/content/research/pdfs/as01njv.pdf.
39. H.T. Liu. 1983. Flow visualization in the wake of a full-scale 2.5 MW Boeing MOD-2. wind turbine. www.osti.gov/servlets/purl/6121505.
40. D.M. Eggleston and K. Starcher. 1989. A comparative study of the aerodynamics of several wind turbines using flow visualization. In *Proceedings of Eighth ASME Wind Energy Symposium*, Vol. 7, p. 233.

9 Siting

The crucial factor in siting a wind turbine or wind farm (also called wind park or wind plant) is the annual energy production and how the value of the energy produced compares to other sources of energy. Data from meteorological stations worldwide are are of little use when 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 turbine; therefore, other types of information are needed. Many countries are developing wind maps to aid development of wind farms. These maps can be used as guides to determine regions that have enough wind for small wind turbines. Also, wind maps for countries and large regions obtained from numerical models have sufficient resolution for determining general areas for siting small wind turbines. In the United States, WINDEXchange provides residential scale wind speed maps at 30 m for every state [1].

An annual average wind speed of around 4 m/s and greater is considered suitable for small wind projects. Tower heights for small wind turbines range from 10 to 35 m. Because small wind turbines are located close to loads, local topography will influence the estimations of wind speeds and siting decisions. If a location is on exposed terrain, hills, or ridges, wind speeds will be higher than speeds in a valley. In complex terrain, some sites will be adequate for small wind turbines and some will be too sheltered.

One of the important factors in the settlement of the Great Plains of the United States was that farm windmills could provide water for people and livestock. Therefore, if farm windmills are used or were used in the past in a region, the wind is sufficient for the use of small wind turbines in the region. Another possibility is to install met towers to compile reference data for a region. Generally, this is done by regional or state organizations or governments, not by individuals interested in siting small wind turbines.

Small wind turbines can be cost effective as stand-alone systems using the general rule that the average wind speed for the lowest wind month should be 3–4 m/s. General maps of wind power or wind energy potential for small wind turbines have been developed for large regions (Figure 9.1) [2]. These gross wind maps will be replaced by national wind maps developed for determining wind energy potential for wind farms. Finally, if wind farms already exist in an area, the wind is sufficient 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 [3]. Towers for small wind turbines should be a minimum of 10 m and preferably 20 m high; higher towers generally capture more energy (Figure 9.2). Again, the trade-off is the extra energy versus the cost of a taller tower. Towers of 35-m height are sometimes used.

As a general rule for avoiding most of the adverse effects of building wakes, a turbine should be located: (1) upwind of the prominent wind direction, or maybe the prominent wind direction of low wind months at a distance 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 above ground if the turbine is immediately downwind of the building. The above rule is not foolproof because the size of the wake also depends on the building's shape and orientation to the wind (Figure 9.3).

Downwind from a building, power losses become small at a distance equal to 15 times the building height. However, a small wind turbine cannot be located too far away from the load because the cost of wiring over a long distance is prohibitive. Also, more losses in wires will occur

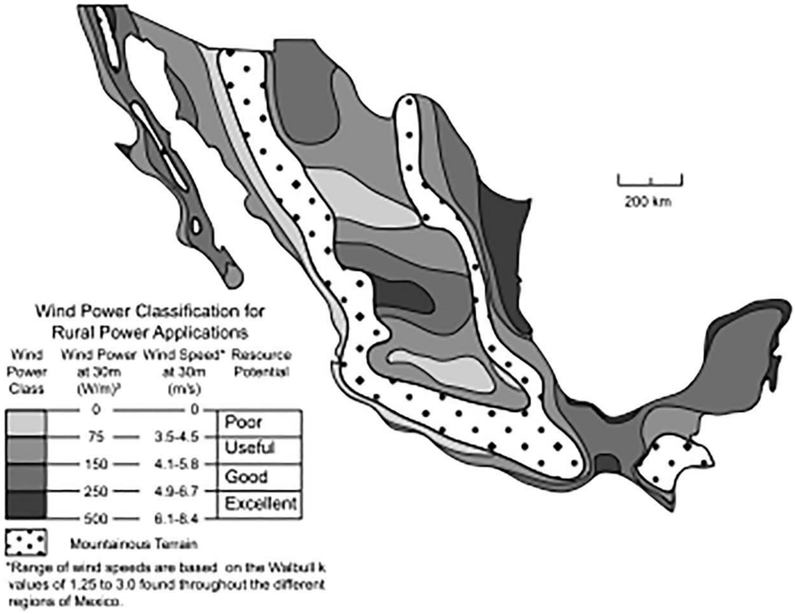


FIGURE 9.1 Wind power map for rural applications in Mexico. Notice the difference in the definition of wind power class and height, which is at 30 m.

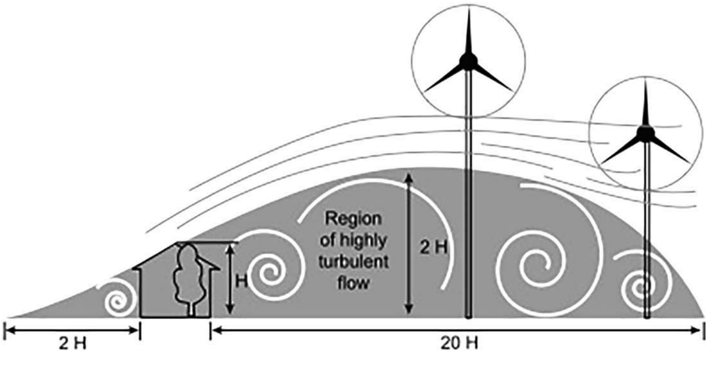


FIGURE 9.2 Height of a small wind turbine close to obstacles of height H.

if DC rather than AC transmits power from the wind turbine to the load. In general, small wind turbines should not be mounted on occupied buildings because of possible noise, vibration, and even turbulence. Tower heights for very small wind turbines vary from stub poles on sailboats to short (3–5 m) towers, and some are even mounted on buildings. Paul Gipe wrote numerous articles on all aspects of wind energy [4], and two of his books are about small wind systems [5,6].

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 from a photovoltaic (PV) panel on the roof of every home.

The Distributed Wind Energy Association [7] has online information about small wind turbines including information on siting. A *Small Wind Guidebook* has a section on siting and can be downloaded from the U.S. DOE, EERE (https://windexchange.energy.gov/small-wind-guidebook) An older guide for small wind turbines available from the National Renewable Energy Laboratory (NREL) [8] also contains similar information about siting.

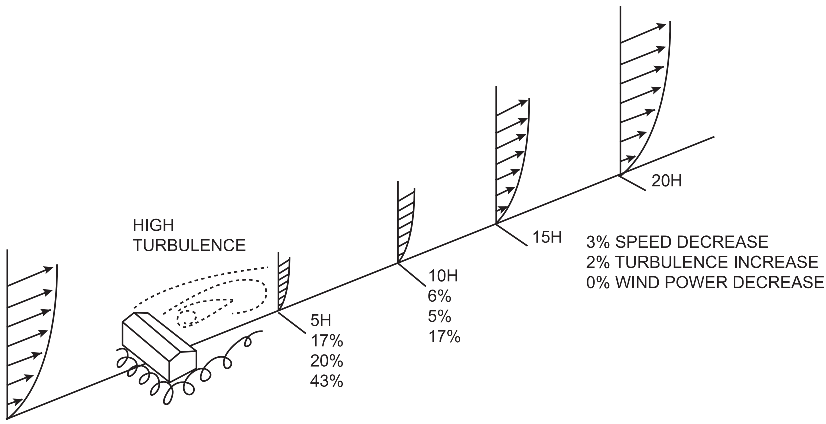


FIGURE 9.3 Estimate of speed, power decrease, and turbulence increase for flow over building. Estimates shown are for building height H. (M.M. Schwartz and D.L. Eliott. 1995. In *Proceedings of Windpower Conference*. With permission.)

RenewableUK, formerly the British Wind Energy Association, maintains a section on small and medium wind turbines [9] that includes information on the national wind speed database, small wind turbine technologies, planning, and case studies. An interactive map for wind speeds at 10, 25, and 45 m is available online [10], and the RenSmart Site Planner estimates energy production, yearly value, and pay-back time for wind and solar systems. National wind energy associations in other countries probably have sections on small wind turbines.

A number of designs were developed by architects, inventors, and even people selling wind systems (most not built or tested) to integrate wind turbines into building structures in urban areas. The designs usually touted the increase of wind speed caused by the building. However, in the real world, incorporating wind turbines into buildings is a difficult choice because of noise, vibration, and safety concerns. In some concepts of installations on buildings, the wind turbines must be mounted perpendicular to the predominant wind direction because the wind turbines are fixed in yaw.

According to Dutton et al., 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, and turbines integrated into buildings) in the U.K. [11]. The technical feasibility and various configurations are also discussed. There is an Internet site for urban wind turbines [12]. Available downloads include the *European Urban Wind Turbine Catalogue; Urban Wind Turbines: Technology Review (*companion text to the European Union's *UWT Catalogue); Urban Wind Turbine Guidelines for Small Wind Turbines in the Built Environment*; and *Windy Cities: Wind Energy for the Urban Environment*. The wind turbine guidelines include images of wind flow over buildings and example projects.

A newspaper in Clearwater, Florida, installed a stacked Darrieus unit next to its building. The unit consisted of three Darrieus turbines, 4.5 m in diameter, 6 m tall, 4 kW each (Figure 9.4). Fortis mounted three wind turbines (5-m diameter, 2 kW rather than the nominal 5 kW) on a factory and office building and experienced 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 × 3 m frame rated at 1 kW [13].

A building in Chicago mounted eight units horizontally on the roof (Figure 9.5), although other buildings mounted units vertically. Two 6-kW wind turbines mounted on the roof of a civic center in the U.K. were described in a case study [14]. A different concept is mounting a number of small wind turbines on the parapets of urban and suburban buildings. The horizontal axis wind turbine had a rated power of 1 kW and was mounted in a modular housing measuring approximately 1.2 × 1.2 m. Fourteen wind turbines installed on a corner of the Energy Adventure Aquarium building (Figure 9.6) in California constitute a kinetic sculpture.

FIGURE 9.4 Three-stacked wind turbines (Darrieus), 4 kW each, next to building. Notice the vman on top. (Photo courtesy of Coy Harris, American Windmill Museum.)

FIGURE 9.5 Eight helical wind turbines, 1 kW each, horizontal axis, on top of building. (Photos courtesy of Kurt Holtz, Lucid Dream Productions.)

The most spectacular structure featuring integrated large wind turbines is the Bahrain World Trade Center. The two 240-m towers with sail silhouettes have three cross bridges that carry wind turbines. The turbines are 29 m in diameter, rated at 225 kW, and are 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 Persian Gulf breezes into the paths of the wind turbines.

FIGURE 9.6 Twelve 1-kW wind turbines mounted on parapet of building. (Photo courtesy of AeroVironment.)

9.1.1 Noise

Although zoning is an institutional issue, the regulations will affect the potential for erecting small wind turbines and may specify turbine size, tower height, required space surrounding the tower, noise restrictions, and even visual concerns of 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 because the level drops by a factor of 4 at a distance of 15 m, and is generally masked by background noise.

A sound study with a 10-kW wind turbine (wind speeds at 9–11 m/s) showed levels of 49–46 dBA for the running turbine and at a distance of 15 m from the turbine, respectively. Essentially no difference was found at distances of 30 m and more. However, if a wind turbine rotor is downwind, some sound is made every time the blade passes the tower. Even if the sound is at the same level as background noise, 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 impacts of small wind turbines [15] from the vantage points of private property (neighbors' views) and public views (roads, recreation facilities, and natural areas). The considerations for neighbors' views 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, two additional factors must be considered:

5. Is the turbine seen from an important scenic or natural area?
6. What is the duration of the view?

Each factor is rated by a point system (Table 9.1), with a total of 12 points for the residential view and 18 for the public view. If the score (Table 9.2) is below the significant range, the wind turbine is unlikely to have a visual impact unless it is near or within a scenic view. The score is only a general indicator for visual impacts of small wind turbines. Wind turbines will be visible, at least from some viewpoints because they will tower above surrounding trees.

TABLE 9.1
Vermont System for Scoring Visual Impacts of Small Wind Turbines

	Neighbor View				Public View	
	1	2	3	4	5	6
Points	View Angle (°)	Distance (m)	Prominent	Screened	Vista	Duration (s)
0	>90	>900	Below Tree Tops	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 Mt	No Screening	Highly Scenic	>60

TABLE 9.2
Score Sheet for Determining Visual Impacts 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

In the Midwestern Plains of the United States that have few trees, small wind turbines are noticeable from 1–3 km—the same as trees around a farmhouse. Comparable structures such as cell phone towers, light towers at highway interchanges, radio towers, and towers for utility transmission lines have comparable heights. The difference is that those towers do not have moving rotors.

9.2 WIND FARMS

Long-term wind data are critical for siting wind farms. Data should be collected at a potential site for 2–3 years, after which other questions arise. What is the long-term annual variability? How well can we 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. The turbines should be located within a wind farm to maximize annual energy production and yield the largest financial return. Array losses have to be considered in the siting process.

In general, there will be a number of landowners and a developer who will lease an amount of land based on 20 hectares (ha) or 50 acres/MW of planned production. Not all the land will be used for turbines, and in many cases, developers lease land for further expansion. Actual values after construction will be from 12 to 18 ha/MW. Negotiation with a large number of landowners can present some difficulties, for example, one lease of 1640 ha involved 120 landowners.

9.2.1 Long-Term Reference Stations

To determine whether historical data from a site are adequate to describe long-term wind resources at another site, a rigorous analysis should be done. Simon and Gates [16] recommend that the annual hourly linear correlation coefficient be at least 0.90 between the reference site and off-site data. Remember to consider wind shear if the heights are different at the two locations. If the two sites do not exhibit similar wind speed and direction trends and lack similar topographic exposures, they will probably not have sufficient correlation value.

Long-term reference stations should be considered at all locations with wind power potential everywhere in the world. These stations should continue to collect data even after a wind farm is installed. The data will improve siting of wind farms and also provide reference sites for delineating wind resources for single or distributed wind turbines in the region. Wind turbine sizes have increased and hub heights are higher. Because wind speed increases with height in most locations, reference stations are needed 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 duration of 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 farm is installed. However, if a number of wind farms are already in the region, 1 year of data collection may suffice.

For complex terrain, one met station per three to five wind turbines may be needed. Because wind turbines for wind farms are now megawatt size, one met station per two wind turbines may be required in complex terrain. For somewhat homogeneous terrain as in the U.S. Plains, a primary tall met station and one to four smaller met stations may suffice. The tallest met station should be installed at a representative location, not at the best point of a wind farm.

Contour maps are used for locations of wind turbine pads and roads. In general, the wind turbines will be located at higher elevations within the wind farm area. The U.S. Geological Survey has topographical maps that can be downloaded. Topozone (now a subscription service) has interactive U.S. topography maps (at different scales) available online [17]. These maps are very useful for selecting met tower locations, micrositing, roads, and other physical aspects of wind farms.

The key factors for array siting for the Zond wind farms [18] in Tehachapi Pass were an extensive anemometer data network, the addition of new stations during the planning period, a timeframe of 1 year to refine the array plans, a project team approach to evaluate the merits of 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 wind resources over short distances on a complex terrain was greater than expected. The energy output from 2 projects consisting of 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 was an extensive network of met towers.

The money spent on micrositing is a small fraction of project cost, but the value of the information gained is critical for estimating energy production accurately. Many problems with low energy production are the results of poor siting.

Wind turbines have become larger, with rotor diameters from 60 to 150 m and hub heights of 60–100 m and even higher. Very little data show conditions above these heights, but NREL had a program for tall tower data [19]. One problem is that all tower data collected by wind farm developers are proprietary.

Because of wind shear, wind turbines are located at higher elevations on rolling terrain and mesas and on ridges on complex terrain. In the past, turbulence was considered a big problem for siting at the edges of mesas and ridges. However, taller towers allow placement of wind turbines on the edges that are perpendicular to the predominant wind direction. Consider 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. The southern winds in summers allow room for expansion of the wake. Turbulence data for these sites are proprietary, primarily because turbulence affects operation and maintenance.

9.3 DIGITAL MAPS

Digital maps are useful as they give a general overview of wind resource, provide confidence in the data, and provide information about land use and transmission lines, and other features can easily be displayed on the same maps. NREL created higher resolution digital wind maps using terrain enhancement, mesoscale modeling, and geographic information systems (GIS). Again note that the maps are available through EERE, WINDExchange [1].

Wind Site Assessment Dashboard (formerly Windnavigator), a web platform based on Google Maps, is an interactive tool that includes wind resource maps and world data [20]. The map (200-m resolution) provides wind speeds at custom height of 10–140 m and a pointer to locate minimum and maximum mean annual wind speeds. Wind statistics including Weibull values and wind roses, and monthly and diurnal distributions are available. Selectable area maps at 200-m resolution (PDF or GIS data sets) can be purchased. Satellite, hybrid, and terrain views are available for the entire world. The Small windExplorer interactive map is available to the public online [21]. Mean wind speed data for heights of 24.4 m (80 ft), 30.5 m (100 ft), and 36.7 m (120 ft) are available.

A similar interactive wind resource map (map, satellite, hybrid, and terrain views) and data for much of the world, are available [22]. FirstLook, has wind speed data for 20, 50, and 80 m and with Wind GIS Data Layers, resolution is at 90 m. In addition, a solar resource map and prospecting tools are available. Remember, wind speed maps are useful indicators of wind energy and wind power maps are the next step.

9.4 GEOGRAPHIC INFORMATION SYSTEMS

A geographic information system (GIS) is a computer system capable of holding and using spatially oriented data. A GIS typically links different data sets or it displays a base set over which overlays of other data sets are placed. 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.

The two general bases of representing data are raster and vector. In raster-based data, every pixel has a value. Vector-based 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: 16–256 colors or shades of gray. Therefore, pixels and vectors can have different attributes and are linked to a database that may be queried. A GIS allows a user to associate information with a feature on a map and create relationships that can determine the feasibilities of various locations, for example, a hierarchical system for locating anemometer stations for wind prospecting.

An overlay is a new map with specific features placed on top of a base map. An overlay is one form of a database query function. The overlay and base maps can be raster or vector images. 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) and the Digital Line Graph (DLG). They 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 show highways, roads (even trails), lakes and streams, gas and utility transmission lines, and other features. The problem is that the data may have been taken from fairly old maps and may be incomplete. The DEM shows terrain height to 1 m on a latitude–longitude grid with a resolution of 3 arc seconds [pixels around 90 m $\times$ 90 $\times$ cos (latitude) m]. NREL coupled the DEM database with software to produce shaded relief maps of $1° \times 1°$.

A technique of terrain enhancement [23] 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 from the 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 consisting 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

$$\frac{P}{P_a} = \frac{\left(\text{In}\left[\dfrac{H_h + E}{z_o}\right]\right)^3}{\left(\text{In}\left[\dfrac{H_h}{z_o}\right]\right)^3} \tag{9.1}$$

where:

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 and mixed woodland, 0.1–0.3 m; forest, 0.8–1.0 m

Care must be taken when using 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 [24,25]. The DEM (3 arc seconds resolution) and DLG data were used. The original DEM data were in blocks of 1° × 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 showing bin sizes, maximums, and minimums accompanies these functions.

The Panhandle of Texas is part of the Southern High Plains, with rolling hills in the East and flat plains above the caprock. 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 up to 256 colors selectable.

At 256 colors, a DEM map for the entire 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

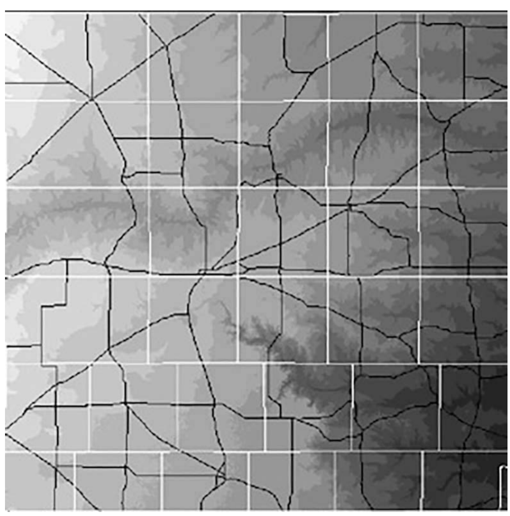


FIGURE 9.7 Digital elevation map (16 shades) of Texas Panhandle showing county boundaries and major highways. Contour lines are 62 m apart.

FIGURE 9.8 Terrain exposure from the average elevation for the Texas Panhandle showing major highways and transmission lines. Light areas have better exposure (range of 16 levels from –195 m to + 168 m).

16 values. The elevation data of the base map can be analyzed by various commands in IDRISI. Instead of the whole area, subsets of the data can be analyzed in the same manner to view more detail. Resolution is limited by the cell size of the original data.

The Panhandle has a large wind energy potential because it has class 3 and 4 winds over the whole area. On the flat open plains covering much of the Panhandle, almost 100% will fall into the same wind power class. In this region, wind speed increases with height; therefore, modest elevation may increase wind power dramatically. Terrain exposure affects areas above and below the average elevation. A 15-km radius was used to determine average elevation and the maximum change from this average was 190 m (Figure 9.8). An orthographic projection with an 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 were put into a higher wind class by this process and low areas were assigned a lower wind class.

GIS was used to screen wind resources based on the criteria of wind power class, terrain type, proximity to transmission line, slope, and aspect. Within these criteria, classes or levels can be selected to exclude or limit an area's suitability for wind plants. A map was generated for the following screening parameters:

- Wind class 3 and above
- Slope of 0 to 3 degrees
- Aspect from 155 to 245° for area where slope exceeds 1°
- Multiples of 8 km from transmission line (69 kV and above)
- Excluded lands: parks, roads, urban, lakes, wildlife refuges

The maps were combined to generate 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 Texas Wind Power (Pacific Northwest Laboratory)

The Pacific Northwest Laboratory (PNL) estimated the capturable wind power for Texas at 50-m height as 134,000 MW from class 3 and above winds and 28,000 MW for the class 4 winds that blow primarily in the Panhandle. The PNL estimate was based on treating total power intercepted

over a given land area as a function of the number of wind turbines, rotor swept area, and available power in the wind. Environmentally sensitive lands, urban areas, and terrains in valleys and canyons were excluded. The following formula was used to calculate the power intercepted by the rotor areas of 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 ($\pi D^2/4$); D = rotor diameter (m); and N = number of wind turbines. The calculation for the number of turbines that can be placed on a 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 from other productive uses and most of the removed land is used for roads. Some wind farm roads are only 5 m wide. The roads at another wind farm with 3 MW wind turbines are over 10 m wide.

If the cost of land is high, the land area for a single wind turbine will be smaller; but the wind plant output will be lower 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 (4D × 8D spacing). For the edges of bluffs and on ridges, 6–15 MW can be installed per linear kilometer (2D to 3D spacing, one row only). With closer array spacing the MW/km^2 would be larger and so would the array losses.

The average intercepted power can be calculated from Equation (9.2) or the intercepted power per unit land area can be calculated from:

$$\frac{P_i}{A_t} = \frac{nP_a}{4 S_r S_c} \tag{9.4}$$

Remember, the calculation is for intercepted power, and capacity factors of 0.30–0.35 are used to estimate capturable wind power.

9.5.2 Estimated Texas Wind Power (Alternative Energy Institute)

The same procedures of terrain enhancement and GIS were used to estimate capturable wind power, also known as wind power potential, for Texas [26]. The selection criteria were class 3 or higher winds from a revised wind map showing terrain exposure, slope of 0–3°, and exclusion of urban areas, highways, federal and state parks, lakes, wildlife refuges, federal wetlands, and land within 15 km of transmission lines carrying 115 kV or more.

The capturable annual power was calculated for the wind turbines with 50 m hub height, 10D × 10D spacing, 30% capacity factor, and no array losses (reasonable for large spacing). 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) and private meteorological sites [27]. The estimates were then used to update the wind map (1-km pixel size) for Texas (Figure 9.9). Class 3 and 5 lands were reduced from the previous estimate and class 4 lands increased. The selection parameters were the same, except for slopes (0–10°) and areas within 16 km of electrical transmission line (≥ 69 kV) for usable land for wind power (Figure 9.10).

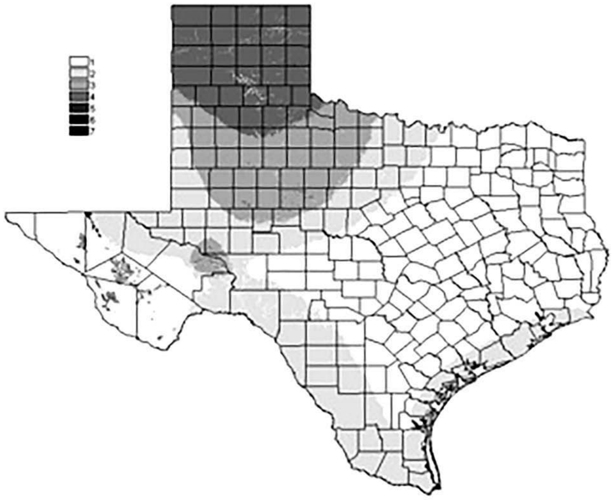


FIGURE 9.9 Texas wind power map, 1995.

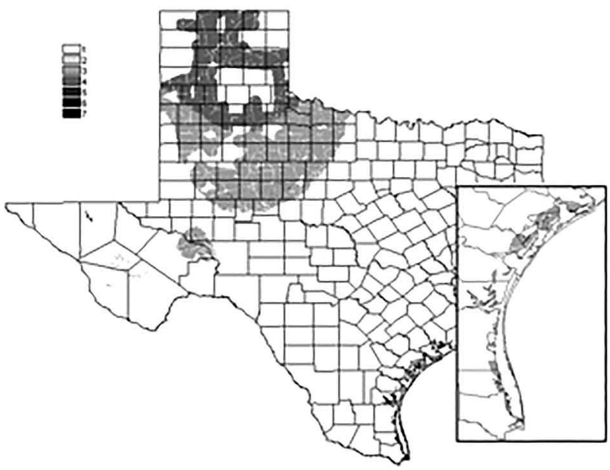


FIGURE 9.10 Texas land suitable for wind farms, 1995.

The estimate for capturable wind power (Table 9.3) is larger also because a spacing of 7D × 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, 172,000 MW (500,000 MW of installed capacity). However, only a fraction will be installed because the total electrical generating capacity of Texas was 120,000 MW (11,500 MW wind) in 2012. Maps and estimates are available from Kenneth Starcher, West Texas A&M University [28].

A number of wind farms have been built on mesas and terrain involving edges and bluffs. In one area of West Texas (Pecos, Upton, and Crockett Counties), 759 MW of wind farms were installed on mesas. Over 3,000 MW (installed from 2005 to 2009) in wind farms are sited along Interstate10 from Abilene to Roscoe and then northwest to Snyder along Highway 84. Some of these are on mesas with exposures from cliffs and bluffs on one side.

The limit of proximity to transmission lines has changed, and wind farms have been built within 40-km of major transmission lines. Also, the Texas Public Utility Commission promoted new

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	62,299	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

transmission lines from West Texas and the Panhandle to connect with major load centers in the rest of the state. This will provide The Energy Reliability Council of Texas (ERCOT) a total of 18,000 MW of wind power—about 10,000 additional MW of wind capacity. Without the constraint of proximity to transmission lines, the estimate for the amount of intercepted wind power is 850,000 MW with capturable wind power around 270,000 MW. If offshore winds are included, the estimate will be even larger.

9.5.3 Wind Power for the United States

Similar estimates have been made for all the U.S. regions and states. Winds of class 4 and above [29] and access to transmission lines are the most common criteria. The *State Wind Working Group Handbook* contains articles and PowerPoint presentations by several authors [30].

9.6 NUMERICAL MODELS

Numerical models for predicting winds are becoming more accurate and useful, especially for areas of the world where surface wind data are scarce or unreliable. Models were derived from numerical models for weather prediction [31]. Remember that a small difference in wind speed can make a large difference in energy production. In the final analysis, surface wind data are still needed for wind farms.

MesoMap: This 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). It simulates sea breezes, mountain winds, low-level jets, changing wind shear due to solar heating of the Earth's surface, 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 utilizing 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 data for wind turbines of any height for selected sites in a region.

WAsP: The Wind Atlas Analysis and Application Program software was developed by Denmark's Risoe National Laboratory to predict 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 to develop the European wind map (Figure 4.3) and is used by other governments and organizations across the world. Other models are available from links listed at the end of this chapter and elsewhere on the Internet.

9.7 MICROSITING

Wind maps, data compiled by meteorological towers, models, and other criteria are used to select wind farm locations. Other considerations for a wind farm developer are the type of terrain (complex to flat plain), wind shear, wind direction, and spacing of turbines based on predominant wind direction and availability, land cost, and requirements such as roads, turbine foundations, and substations. Terrain may be classified as complex, mesa, rolling, or plain. Passes may be classified as one type or a combination. Spacing is generally stated as diameter D of a 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 70–100 m heights? The first answer is yes, for those parameters, but it is not definitive if the inquiry concerns another location in the same region.

In complex terrain, such as mountains and ridges, micrositing is very important. On 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 turbines may be set in a single row. In rolling terrains such as hills, wind turbines should be placed at higher elevations.

In California, the high wind classes arise from the rise of hot desert air and cooler air from the sea traveling through the passes. California has complex terrain at Tehachapi Pass, rolling terrain at Altamont Pass (east of San Francisco), and both ridges and flat terrain at San Gorgonio Pass near Palm Springs. The winds in the passes are predominantly from the west, so the turbine rows are primarily sited north–south. At San Gorgonio Pass, some wind turbines in rows were only 2D apart and rows were spaced 4D to 5D apart because of the high cost of leasing land. Where space is tight, turbines can be placed at different heights. As expected, the array losses are fairly large. Starting in 1998, smaller turbines were replaced with larger ones.

The wind farm near White Deer, Texas, has 80 1 MW wind turbines of 56-m diameter. The wind turbines have 4D spacing within rows and 15D between rows (Figure 9.11). North is at the top of the figure and the lines indicate roads at 1 mile (1.6 km). The buffer zone on the west is because the adjacent 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 occur in July and August, the rows are situated perpendicular to those predominant winds. The low spots are playa lakes that contain water only after rain so no turbines were installed in those locations. Only the west side of the wind farm is visible in the photo; there are more turbines to the east. Examples of wind farms in other terrain are shown in Figures 9.12–9.14. Figure 9.15 shows an offshore wind farm for comparison.

The amount of land taken out of production depends primarily on the lengths and widths of wind farm roads. Values vary from 0.5 to 2 ha per turbine. If county roads exist, the developer will use less land; however, the developer may have to improve the county roads to handle heavier traffic. Roads may be very expensive for a wind farm on a mountain ridge. The access road from the bottom to the top of the Texas Wind Project in the Delaware Mountains cost $1 million in 1993.

FIGURE 9.11 West side of a wind farm in the plains near White Deer, Texas. White lines are roads to show one square mile, which is equal to 260 ha. (Photo courtesy of Cielo Wind Power.)

FIGURE 9.12 Wind farm in rolling terrain, Lake Benton, Minnesota. (Photo courtesy of Wade Wiechmann.)

FIGURE 9.13 Wind farm on Southwest Mesa, near McCamey, Texas. Example of mesa with one row. (Photo courtesy of Cielo Wind Power.)

Civil engineering aspects of a wind farm site include location of assembly area and construction of electrical substation and roads (length, width, and grade over complex terrain). Roads must allow wide turns by trucks hauling the long blades. Many sites erect batch cement plants on-site, especially for construction on complex terrains of ridges and mesas.

A general rule of thumb is that around 5–10 MW/km^2 can be installed on land suitable for wind farms. However, on ridge lines at 2D to 3D spacing, the value would be around 8–12 MW per linear km. The kilometer measure is linear and the ridge is assumed to be 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 the energy output increase as the square of the radius. Most landowners lease blocks or areas of land, not just the places where turbines will be located. It was interesting in the Texas Wind Power Project that land leased for the wind farm included all land

FIGURE 9.14 Wind farm in complex terrain, Northwest Spain.

FIGURE 9.15 Nysted wind farm in Baltic Sea, Denmark. (Photo courtesy of Siemens.)

at the 1,453-m contour and above (elevation of ridges is 1,830 m). The landowner is now trying to determine whether land below the contour has any wind potential.

Satellite and aerial images are used in micrositing and are available from various sources; some are free. Flash Earth (www.flashearth.com) has the option of switching among sources, such as Google Maps, Microsoft VE, and others. The wind farms in the images are fairly distinct, primarily because of the roads at the sites and the areas around the wind turbines. 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 represent section sprinklers (1 square mile, 260 ha), and small circles represent quarter-section sprinklers. The shadows of the wind turbines are more obvious than the wind turbines, and the angle of a shadow may be different from one part of the wind farm to an adjacent part because the images were taken at different dates and times. Images from different sources will also be taken at different dates and times. New wind farms will not appear in satellite images until the images are updated—more than a year may elapse between updates.

Micrositing techniques of wind farm developers are proprietary. However, satellite images show the layout of wind farms, and good information about siting may be obtained from the images and topographic maps. If the type and model of a wind turbine are known, the spacing can be

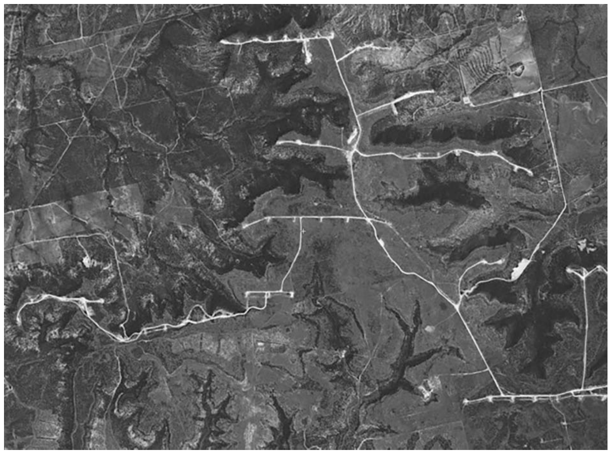


FIGURE 9.16 Satellite image of west side of Trent Mesa wind farm, Texas.

estimated from an image. The image of Trent Mesa, Texas (Figure 9.16) shows about half the layout of the wind farm that contains 100 wind turbines, 66 m in diameter, rated at 1.5 MW.

Economic and institutional issues also affect micrositing. An example is the Waubra wind farm project (192 MW) in Australia [32], which involves environmental, cultural, heritage, and environmental management issues. Since installation, many residents have expressed opposition, claiming health effects caused by wind turbines. One vocal landowner was bought out by the wind farm.

9.8 OCEAN WINDS

Ocean wind observations (see Section 4.4) provide complementary sources 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 allowing observation of large areas without large numbers of meteorological towers.
- All are accessible in archives spanning several years.
- Accuracy is sufficient for wind resource screening.
- They quantify spatial variations.
- They are available at resolutions of 400 m, 1.6 m, and 0.25 degree.
- 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 to 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 [33]. Weibull parameters were calculated from the wind speed data to determine a wind speed distribution from which wind energy production could 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—the same value as 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 [34]. Also, ocean winds, terrain, and predominant wind direction will

indicate regions of wind potential for islands and near shores. For example, ocean winds indicate excellent wind resources for the islands of Aruba, Bonaire, and Curaçao off the northern coast of Venezuela.

9.9 SUMMARY

GIS provides very flexible and powerful tools for terrain analysis relevant to wind energy prospecting. They can help reclassify existing wind maps and identify areas showing potential as possible wind farm sites. In addition, GIS can be used to quantify wind power potential and, in conjunction with numerical models, estimate annual energy production.

After a location is selected, GIS and topographical maps can be used for micrositing. Wind turbines should be located within a wind plant area to maximize annual energy production. However, the normal 90-m resolution may not be detailed enough for micrositing on complex terrain. PNL used a technique of spline interpolation to develop a finer grid from the 90-m data. Of course, if the DEM data at 10-m resolution are available, interpolation is not needed.

A number of numerical models for micrositing are available and most run on personal computers. More powerful programs for weather forecasting and micrositing, which run on large computers or clusters of PCs, are also available. In general, these must be purchased.

PROBLEMS

1. A building is 20 m long, 15 m wide, and 15 m tall. You want to install a 10-kW wind turbine. How tall a tower will you need and how far away from the building should you place it?
2. Several trees 20–30 m tall are near 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 the 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 tower farther away from the building? Show all cost estimates.
4. Is there a small wind turbine in your region? If yes, what are the visual impacts from the neighbor's view and from the public view? Use Tables 9.1 and 9.2 to estimate scores.
5. Using 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. The land is now high priced. Select close spacing and estimate array losses.
8. What land area must you lease for a 50-MW wind farm? Select the size of turbine from commercial turbines available today and calculate spacing. Remember, spacing your turbines too closely will cause array losses. How many megawatts can you install per square kilometer?
9. Array spacing is 4D × 8D, for a 3-MW wind turbine 90 m in diameter. How many can be placed in a square kilometer?
10. The row spacing for 3-MW turbines 90 m in diameter is 2D. How many can be placed per linear kilometer on a ridge?
11. Assume you have complex terrain. What size of land area must you lease for a 50-MW wind farm? Select the size of turbine from commercial turbines available today and calculate the spacing. How many megawatts can you install per square kilometer?
12. In your opinion, what are some advantages and disadvantages of using vector- or raster-based GIS to determine wind energy potential?
13. Check two of the links on numerical models listed in the Links section of this chapter. See whether they contain examples of wind maps. List the website chosen, geographical region of wind map, and map resolution.

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 shown in the figure. Do not forget the spaces between turbines.
16. Go to Zoom Earth (https://zoom.earth) and search for White Deer, Texas (latitude, N 35°, 27 min; longitude, W 101°s, 10 min). The wind farm is just northwest of the town. Zoom in to see the layout of the wind farm. Estimate the number of wind turbines per square mile for the farm. Remember, not all the land within the farm will have wind turbines on it.
17. Go to Google Earth (www.google.com/earth/) and search for the wind farms in San Gorgonio Pass, California, just northwest of Palm Springs. Estimate the spacing for one of the densely packed wind farms.
18. How many meteorological stations, at what height, and over what period are needed to determine the wind potential for a 50 MW or larger wind farm? In general, terrain will not be completely flat. Also remember wind turbines are getting larger, and thus, hub heights are larger. For your selection of number, height, instrumentation, and time period; estimate the costs for obtaining the data.
19. Go to www.remss.com and look at QSCAT data for area off Cape Cod during September 2007. Choose region "Atlantic, Tropical, North." What is the average wind speed and from what direction?
20. In a 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; and (c) other wind farms are in the area.
21. Find a quadrangle map that shows Mesa Redonda (34.9157°N, 107.1337°W) in Quay County, New Mexico (www.newmexico.org/map). What is the elevation of the mesa? You can see all of the mesa in a 1:200,000 view. You will need a 1:50,000 view to read elevations. Can use Topoquest (www.topoquest.com) or Mapcarta (https://mapcarta.com)
22. What is the general rule for calculating megawatts per square kilometer (MW/km^2) in plains and rolling hills? What is the rule for calculating MW per linear km for ridges and narrow mesas?
23. From Table 9.3, estimate MW/km^2.
24. From Table 9.3, use the general rule for 8 MW/km^2, what is the maximum megawatts of wind that could be installed? What is the maximum capturable power?
25. What is the annual wind speed at 100-m height on Mesa Redonda, south of Tucumcari in eastern New Mexico?

LINKS

EMD, WindPro. www.emd.dk/WindPRO/Frontpage Environmental impacts and siting of wind projects, www.energy.gov/eere/wind/environmental-impacts-and-siting-wind-projects.

D.M. Heimiller and S.R. Haymes. 2001. *Geographic information systems in support of wind energy activities at NREL*. REL/CP-500-29164. www.osti.gov/bridge.

MesoMap. software, models. www.awstruewind.com.

EERE, WINDExchange https://windexchange.energy.gov

ReSoft software, models. www.resoft.co.uk/English/index.htm.

RETscreen, free software, decision-making tools. www.retscreen.net.

Trent Mesa Wind Project. www.trentmesa.com.

TRC, CAMET, and MM5 software, models. www.src.com/windenergy/windenergy_main.htm.

WAsP, software, models. www.wasp.dk.

WindFarmer, software, models. Now at DNV GL. www.dnvgl.com/services/windfarmer-3766.

Wind Logics, software, models. www.windlogics.com.

Wind Resource Assessment Handbook. www.nrel.gov/docs/legosti/fy97/22223.pdf.

REFERENCES

1. US DOE, EERE. WINDExchange. https://energy.gov/eere/wind/windexchange.
2. M.N. Schwartz and D.L. Elliott. 1995. Mexico wind resource assessment project. In *AWEA, Proceedings of Windpower Conference,* p. 57.
3. H. L. Wegley et al. 1980. Siting handbook for small wind energy conversion systems. Report PNL-2521. U.S. Department of Energy: Washington, DC.
4. P. Gipe. www.wind-works.org/cms/.
5. P. Gipe. 1999. *Wind Energy Basics: A Guide to Small and Micro Wind Systems*. Chelsea Green: Post Mills, VT.
6. P. Gipe. 1993. *Wind Power for Home and Business*. Chelsea Green: Post Mills, VT.
7. Distributed Wind Energy Association. http://distributedwind.org/home/.
8. U.S. DOE, EERE. *Small Wind Electric Systems: A U.S. Consumer's Guide*. www.nrel.gov/docs/fy07o-sti/42005.pdf.
9. RenewableUK. Small and medium scale wind. www.renewableuk.com/page/smallmediumwind. Also Generate your own power, your guide to installing a small wind system. http://c.ymcdn.com/sites/www.renewableuk.com/resource/resmgr/Docs/generate_your_own_power_cons.pdf.
10. Nobal Wind Map. www.rensmart.com/Weather/BERR.
11. A.G. Dutton, J.A. Halliday, and M.J. Blanch. 2005. The feasibility of building-mounted/integrated wind turbines (BUWTs): achieving their potential for carbon emission reductions. www.eru.rl.ac.uk/pdfs/BUWT_final_v004_full.pdf.
12. Wind Energy Integration in the Urban Environment. www.urbanwind.net/index.html.
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. Public Service of Vermont. Siting a wind turbine on your property: Putting two good things together. http://publicservice.vermont.gov/sites/dps/files/documents/Renewable_Energy/Resources/Wind/psb_wind_siting_handbook.pdf.
16. R.L. Simon and R.H. Gates. 1991. Long-term interannual wind resource variations in California. In *AWEA, Proceedings of Windpower Conference*, p. 236.
17. U.S. Geological Survey. www.USGS.gov; Topozone. www.topozone.com.
18. R.L. Simon and R.H. Gates. 1992. Two examples of successful wind energy resource assessment. In *AWEA, Proceedings of Windpower Conference*, p. 75.
19. M. Swartz and D. Elliott. 2006. Wind shear characteristics at Central Plains tall towers. In *AWEA, Proceedings of Windpower Conference*, CD.
20. UL AWS Truepower. Windnavigator. www.awstruepower.com/products/dashboards/wind-site-assessment/.
21. New York State. Small windExplorer. http://nyswe.awstruepower.com.
22. 3TIER. 3Tier was purchased by Vaisala. www.vaisala.com/en/products/data-subscriptions-and-reports/wind-renewable-energy.
23. M.C. Brower et al. 1993. Powering the Midwest: Renewable electricity for the economy and the environment. Report for Union of Concerned Scientists.
24. L. Shitao. 1994. Wind resource screening in the Texas Panhandle. *Master's Thesis*, West Texas A&M University: Canyon, TX.
25. L. Shitao, J. McCarty, and V. Nelson. 1994. Wind resource screening in the Texas Panhandle. Report 94-1. Alternative Energy Institute, West Texas A&M University: Canyon, TX.
26. V. Nelson. 1995. Wind energy. In *Texas Renewable Energy Resource Assessment: Survey, Overview, and Recommendations*. Report for Texas Sustainable Energy Development Council. www.frontierassoc.com/wp-content/uploads/2017/07/TX-Renewable-Resource-Assessmt-2008-Exec-Summary.pdf.
27. C.M. Yu. 2003. Wind resource screening for Texas. *Master's Thesis*, West Texas A&M University: Canyon, TX.
28. Alternative Energy Institute. 2004 Texas Wind Class Map. Contact Kenneth Starcher, WTAMU, kstarcher@wtamu.edu.
29. USDOE, Energy Efficiency and Renewable Energy. Wind Technologies Office. www.energy.gov/eere/wind/wind-energy-technologies-office.

30. Wind Powering America. Handbook. www.eere.energy.gov/windandhydro/windpoweringamerica/pdfs/wpa/34600_wind_handbookpdf.
31. J. Rohatgi and V. Nelson. 1994. *Wind Characteristics: An analysis for the generation of wind power.* Alternative Energy Institute, West Texas A&M University: Canyon, TX.
32. Waubra Wind Farm. www.acciona.com.au/projects/energy/wind-power/waubra-wind-farm/.
33. C. Jasager et al. Wind resources and wind farm wake effects offshore observed from satellite. Risoe National Laboratory, Wind Energy Department. www.offshorecenter.dk/log/bibliotek/Wind%20resources%20and%20wind%20farm.PDF.
34. M. Swartz, D. Elliott, and G. Scott. 2007. Coastal and marine tall-tower data analysis. In *Proceedings of Windpower Conference*, CD.

10 Applications and Wind Industry

The main applications of wind power are the generation of electricity and water pumping (Table 10.1). Except for the installed capacity of wind farms, the other statistics are best estimates, as data are difficult to acquire. Applications for generation of electricity are classified as utility-scale wind farms, small wind turbines (both remote and stand-alone systems), distributed, community, wind–diesel, village power (generally hybrid systems), telecommunications (high-reliability hybrid systems), and street lighting. Some village power systems use only wind power. In some cases, village power includes diesel or gas backup systems. Stand-alone systems generally use 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 a utility grid are wind-assist systems. Wind turbine sizes range from the utility-scale megawatt turbines for wind farms to small systems (≤100 kW) also connected to grids and 20–300 W remote units for sailboats and households, primarily in the developing world. Small systems are sometimes called micro wind turbines. Be careful of some vendors claiming micro and small wind turbines will produce electricity at less cost than utility-scale wind turbines, all you need is to connect a large number of them. That claim has not been implemented. Just think how many 10-kW wind turbines would be required for a 30-MW wind farm.

10.1 UTILITY SCALE

There were 540 GW (Figure 1.15b) installed by the end of 2017. The estimated energy production for 2018 is 1180 TWh (using a capacity factor of 25%). Major installations were in China, Europe, and the United States and estimated energy production from those installations is 363 TWh, 390 TWh, and 195 TWh, respectively. World growth rate reached 28% per year from 1995–2012 (see Figure 1.15), but has shifted to linear increments. From 2012–2017, the average installed capacity was around 50 GW/yr. For Europe, it was around 10 GW/yr since 2006, with a substantial portion being from offshore installations.

The Wind Power [1] maintains a database of wind farms, wind turbines, manufacturers, developers, and operators. Lists of wind farms with graphs of capacity per year and cumulative capacity are generally available from national wind energy associations and other groups, some of which provide more detailed information such as energy production and capacity factor by year [2]. Also check regional associations such as the Latin American Wind Energy Association for information on installed capacity. Wikipedia has lists of onshore and offshore wind farms. Interactive maps showing locations and information about wind farms based on Google Earth are now available for a number of websites.

In most cases, early goals set for wind power were exceeded. For example, the European 1995 goal was 4 GW of wind by 2000, and in 2003, the goal for 2010 was 75 G; both goals were easily surpassed. Now, the European Union goal is 27% (35%, proposed by the European Parliament) of final energy consumption in 2030 be met from renewable energy. WindEurope [3] updates its capacity scenarios to 2030 every 2 years. The central scenario would be 323 GW in the European Union (EU) by 2030, 253 GW onshore and 70 GW offshore. At 30% CF that would produce 888 TWh of electricity. The high scenario goal would be 397 GW, 298 GW onshore and 99 GW offshore. Of

TABLE 10.1
Comparison of Wind Industry Estimates

	1995	2002	2007	2012	2017
Utility scale, number	22,000	50,000	100,000	180,000	320,000
Installed capacity, GW	4.8	31	94	282	540
Production, TWh/year	0.005	10	30	740	1,180
Small systems, number	150,000	370,000	500,000	820,000	1,400,400
Installed capacity, MW	15	55	200–300	835	1,400
Wind diesel, number			200	250?	250?
Village power, number	10–30	150-?	1,800	2,000?	2,000?
Telecommunication	20–50	150	200-?	3,000-?	3.000-?
Farm windmill[a], number	300,000	305,000	310,000	310,000	300,000
Production/year	3,000	3,000	3,000	3,000	3,000

[a] Farm windmills are being replaced by PV pumps. Production primarily replaces 40- to 50-year old windmills.

course, predictions are always risky, and the predicted megawatts change as projects and legislation are implemented and changed. In Denmark, wind turbines supplied 43% of the electric consumption in 2017 and they even exported some wind power. Note the number of countries included in Europe may differ by cited source and the number in the EU has increased over the years.

In the United States, the Alta wind farm has a capacity of 1,320 MW, Shepard Flats in Oregon has a capacity of 845 MW, and four wind farms in Texas range in size from 523 to 736 MW. John Deere installed clusters of 10-MW wind farms (10-MW size is subject to less regulation). The clusters house enough wind turbines to obtain economies of scale in installation. The American Wind Energy Association has a database of utility-scale projects (member accessed) and publishes quarterly reports (public) of projects commissioned.

States and other entities may also compile information on wind projects, for example, the Kansas Energy Information Network [4] has a list of large wind projects in Kansas, Missouri, Nebraska, Oklahoma, and Wisconsin.

In 2017, about 20,000 wind turbines with a capacity of 52.6 GW were installed worldwide. The average size of a wind turbine is over 2 MW. The Global Wind Energy Council (GWEC) lists installed capacity in 2017 by region (Table 10.2) and by countries within regions [5]. The growth of wind power in China was phenomenal with the installation of 70.5 GW between 2008 and 2017.

TABLE 10.2
Wind Installed Wind Capacity (MW) by Region for 2007, 2011, and 2017

	2007	2011	2017
Africa & Middle East	538	1,135	4,538
Asia	10,091	97,810	228,542
Europe	57,136	109,237	178,096
Latin America & Caribbean	537	3,505	17,891
North America	18,664	65,576	105,321
Pacific	1,158	3,219	5,193
World total	94,123	282,482	539,581

Source: Data from Global Wind Energy Council.

For offshore wind farms, 4C Offshore [6] has extensive information on projects plus map showing size and location. Offshore wind farms installed in Europe [7] have a capacity of over 15 GW by the end of 2017. Early examples are Horns Rev at 160 MW and Nysted at 158 MW in Denmark. The United Kingdom has around 40% of offshore capacity in Europe and also the largest wind farm, London Array, 630 MW. As of 2017, most of the wind farms were in the North Sea. China has 2.8 GW offshore and ambitious plans for more development. In 2017, the first offshore wind farm (30 MW, 6 turbines) was installed in the United States, off of Rhode Island. Other offshore and Great Lakes wind farms are being considered in the United States, Turkey announced plans for the largest offshore project in the world.

Three driving forces for installation of wind farms are economics, policy and incentives at national and state levels, and the negative public perception of nuclear power (especially since the disaster at the Fukishima Daiichi power plants in Japan). Some countries have voted to shut down their nuclear plants. Green power and reduction of pollution and emissions also assist in expanding the wind energy market.

The top ten manufacturers based on total installed capacity in 2016 (Table 10.3) dominate the world market and European manufacturers still maintain major shares. Vestas is still the leader in terms of production and cumulative capacity. The top 10 manufacturers accounted for 78% of the market in 2016. Average size has increased with large 4–8 MW wind turbines deployed offshore. For example, 3,589 Vestas turbines were installed, average size of 2.5 MW, and 3,656 Goldwind turbines were installed, average size of 1.9 MW (both 2017 installations).

The domestic wind turbine industry in China accounted for most of the country's 2016 market. Three Chinese companies are among the top ten suppliers in the world, due to the huge size of the Chinese market. The United States has only one manufacturer (GE Wind) in the top ten. Suzlon of India was the other non-European and non-China manufacturer.

Notice with large megawatt units that the number of units installed is around half the number of megawatts installed. One problem with the data presented is the absence of good information on re-powering wind farms and decommissioning old turbines. The GWEC market projection from 2007 was for 240 GW of wind power by 2012, with many new installations in Asia. That number was essentially reached in 2011. Their projection in 2016 was 800 GW by 2021.

TABLE 10.3
Estimation of Installations in 2016 and 2017 and Cumulative Capacity for Top 10 Manufacturers of Large Wind Turbines

		2011 Rank	2016 Install (GW)	2016 Cum (GW)	2017 Install (GW)	2017 Cum (GW)
1	Vestas (DK)	1	9.0	82.9	7.5	90.4
2	Siemens (GE) Gamesa (SP)	6, 4	7.5	74.9	9.4	84.3
3	GE (U.S.)	3	6.9	60.4	4.8	65.2
4	Goldwind (PRC)	8	6.6	38.1	5.5	43.6
5	Enercon (GE)	2	3.8	44.1	3.6	47.7
6	Nordex (GE)	10	2.7	21.8	2.7	24.5
7	United Power (PRC)	13	2.1	16.6	2.1	18.7
8	Envision (PRC)		2.0	8.9	1.3	10.2
9	Senvion[a] (GE)	11	1.8	15.5	1.6	17.1
10	Suzlon (IN)	5	1.1	16.1	0.9	17.0
	Others			108		120
	World			487		539

[a] Formerly Repower.
DK = Denmark, GE = Germany, SP = Spain, U.S. = United States, PRC = People's Republic of China, IN = India.

Another aspect of utility scale relates to installations of wind turbines by cooperatives and individual farmers that then sell to the grid. This overlap is also known as community wind. Large businesses have also installed utility scale projects, some are independent and others are distributed wind producers.

10.2 SMALL WIND TURBINES

Small wind turbines overlap with village power systems because most wind turbines for village power generate less than 100 kW, as do some of the distributed, community and wind–diesel systems; so the numbers reported for production of small wind turbines will include all areas. In the United States and Europe, much of the small wind turbine capacity is grid connected. In China and other developing countries, most are stand-alone systems for households and generate 50–300 W. Micro wind turbines for sailboats constitute a big market. The trend is to place small wind within distributed wind, however we will continue to discuss small wind.

A very rough estimate of small wind turbines (100 kW or less) is around 1.4 million worldwide with a capacity around 1.4 GW (Table 10.4)—very impressive numbers that show the impact of small wind. These numbers may be an overestimate because they do not reflect replacements, upgrades to larger turbines, abandoned (not repairable) turbines, and operational failures (Table 10.1). The rough estimates are due to questionable accuracy of production figures for China in the past and the difficulties of obtaining data from small manufacturers in all parts of the world. All reported data indicate that average size of units is increasing. Another problem is the reporting criteria. The World Wind Energy Association [8] reports installed units and capacity by country and the distributed wind report [9] primarily shows installed capacity in the United States. Thus, exported units should show up as installations in other countries. Others report annual production or units sold [9].

China is the major producer of small wind turbines followed by the United States and the United Kingdom, and all three are major exporters. For the China estimate we used a reduction of 30% on reported numbers (2002–2011) and then a reduction of 100,000 due to replacements of old turbines at the end of their life cycles. In earlier years there were over 100 companies (state owned enterprises) in China and production numbers reflected goals to be met rather than actual production, sold, or installed. Among approximately 300 manufacturers [8], about 30 are major producers and 17 of those are in China. The largest production was in China, with 78,100 units (capacity = 65.2 MW, average size = 0.82 kW) in 2016; 4,800 units (capacity = 20.2 MW, average size = 4.2 kW) were exported [10], primarily to other Asian countries. In the past, most of the Chinese production consisted of 50–100-W wind turbines for remote households (Figure 10.1). Small wind turbines provide enough electricity for a few lights, a radio, and a small black-and-white TV, and not much more.

The trend for small wind turbines in three major countries (China, the United States, and the United Kingdom) was generally the same, increased numbers and increased size (Figure 10.2). In the United States in 2016, 2,560 units were installed for a capacity of 2.4 MW. 96% of the units were produced in the United States [9]. The export market for U.S. manufacturers in 2016 was 10.3 MW. The Chinese produced 62,600 units (4.17 MW) in 2017, and 5,100 (14 MW) were exported.

TABLE 10.4
Estimation of Small Wind Production as of 2016

	Major Companies	Cumulative(Number)	Cumulative (MW)	2016 Avg Size(kW)
China	17	1,121,000	994	0.8
USA	3	194,000	299	5.0
Europe	? 6	102,000	165	2.6
Other	? 4	24,000	24	
Total		1,441,000	1,482	

FIGURE 10.1 Small wind turbine (100 W) of remote household, Inner Mongolia, China. Note rope on tail for manual control, even though it has a hinged tail for automatic furling.

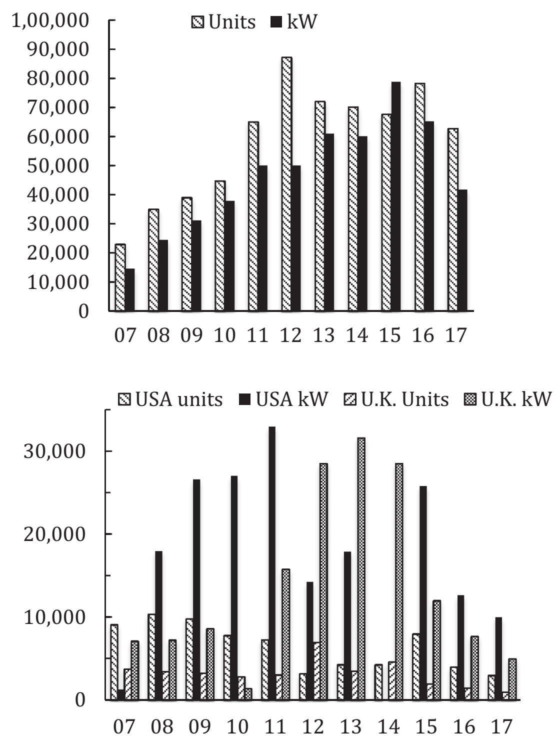


FIGURE 10.2 Production numbers and capacity (kW) of small wind turbines, 2007–2017. Top: China. Bottom: United States and United Kingdom.

In the United Kingdom in 2014, 2,024 units were installed with a capacity of 19.8 MW and an average size of 9.8 kW; 2,614 units were exported. The United Kingdom market report [11] includes wind turbines from 100 to 500 kW. From 2004–2011, 2,549 units were mounted on buildings (10% of the number installed). Italy has become a major market with 112 MW installed from

2012–2016. Kestrel, South Africa, sold over 2,000 wind turbines from 2010 to 2017, and two-thirds were exported to other countries.

The National Wind Technology Center (NWTC), which is under the National Renewable Energy Laboratory (NREL), has a program on distributed wind with research on design modeling, simulation, resource characterization, analysis, and manufacturing [12]. The American Wind Energy Association (AWEA) promulgated a program for the independent certification of small wind turbines, and a working group was established in 2006. In 2008, the Small Wind Certification Council (SWCC) was established [13] to work on problems related to the adoption of small wind turbines:

- Non-standardized performance specifications
- Optimistic and inconsistent claims by suppliers
- Lack of consumer-friendly tools to compare small wind turbines and accurately estimate energy performance
- Need for greater assurance of safety, functionality, and durability for consumers and agencies providing financial incentives
- Inadequate field testing (fewer than half the small models on the market were tested)

The SWCC is an independent body that certifies small wind turbines that meet or exceed the performance and durability requirements of the AWEA standard. The Small Wind Turbine Performance and Safety Standard of AWEA is a common North American framework. SWCC issues labels (Figure 10.3) for rated annual energy output, rated power, and rated sound level, and also confirms that a turbine meets durability and safety requirements.

SWCC also publishes power curves, annual energy performance curves, and measured sound pressure levels. The rated power is at 11 m/s and the rated annual energy is calculated from an annual average wind speed of 5 m/s (11.2 mph) using the Rayleigh distribution (see Section 3.11) and the wind turbine power curve. As of 2017, eight small wind turbines and one medium wind turbine have been certified.

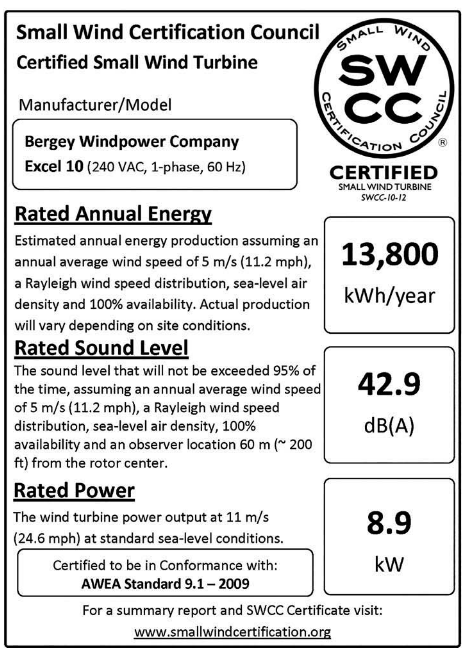


FIGURE 10.3 Certification label for Bergey Windpower's Excel 10.

SWCC also grants time-limited conditional temporary certifications to small wind turbines that meet the requirements of the IEC 61400 series of standards or the British Wind Energy Association (BWEA) standard. The International Electrotechnical Commission developed an international standard, IEC 61400l-2. Part 2 of IEC 614001-2 covers design requirements for small wind turbines. The BWEA Small Wind Turbine Performance and Safety Standard currently supports the microgeneration certification scheme for manufacturers of small wind turbines that wish to sell in the British market.

Field tests can be conducted at independent testing entities or by manufacturers, but self-testing requirements are more restrictive. Towers and foundations are not part of the certified system. Accredited testing organizations include NREL and a few other laboratories in Canada, the United Kingdom, and Germany. Non-accredited organizations undergo SWCC evaluation and approval and include the NREL regional test centers (Kansas, New York, Texas, and Utah). In 2010, NREL provided funding for the centers for certifying two turbines at each site that are or would be sold in the U.S. market. The Texas regional test center at the Alternative Energy Institute was terminated in 2015.

Another market for small wind turbines is for street lighting and telecommunications. While a transmission line may be nearby, the cost of a transformer, connection, meter, and power may exceed the cost of electricity from a combination photovoltaic (PV)–wind system (Figure 10.4 and Figure 10.5). PV–wind system sizes are around 50 W for the PV and 100 W for the wind turbine. It is estimated that there are more than 1,000 telecommunications stations that have small wind turbines as parts of their power supplies (Figure 10.6). In China, there were around 2,500 wind turbines installed for telecommunication sites from 2009 to 2012. The number of telecom sites will be fewer as sites could have more than one wind turbine, for example one site had 16, 1-kW units. This a growing market due to the increased use of cellular phones, especially in remote areas of the world. Check the websites of different manufacturers for information about these two applications.

The market for stand-alone wind turbines, watts to 10 kW, is being displaced by photovoltaics (PV) as the cost of PV cells has decreased dramatically the past few years. Production of small wind turbines in China could decrease by 40–60% by 2020. For the same reason, the grid-tied market for small wind turbines will probably decline in the future, especially in the United States and Europe.

The market for distributed wind, 50–100 kW units and larger, should still be fairly robust. The estimated market potential for distributed wind for the United States is 1.5-GW cumulative capacity in 2030 and 37 GW in 2050 [14].

FIGURE 10.4 Wind and solar (PV) power streetlights and flashing red lights at stop signs on McCormick Road at Interstate Highway 27 between Canyon and Amarillo, Texas.

FIGURE 10.5 Wind–photovoltaic streetlights in China. Wind = 300 W, PV = 120 W. (Photo courtesy of Ryan Rendleman, Verdegy.)

FIGURE 10.6 Two 1.5-kW wind turbines of a telecommunications system in the Philippines. (Photo courtesy of Charlie Dou.)

10.3 DISTRIBUTED SYSTEMS

Distributed systems are defined by a project's location relative to end-use power distribution infrastructure [9]. Installations of wind turbines on the retail side of the electric meter for farms, ranches, agribusinesses, and small industries are used to offset all or a portion of the local energy consumption at or near those locations. Systems connected directly to the local grid support grid operations

and local load. Grid-connected distributed wind systems can be located on the distribution grid or on the customer side of the meter, either physically or virtually. Virtual (or remote net metering) allows multiple energy customers to receive net-metering credit from a shared, on-site or remote system within the customer's utility service area.

Systems range from one or more small units to mid-size (100–1,000 kW) to megawatts for large industries. Two 10-kW units were installed at a liquor store near Amarillo, Texas and in Lubbock, Texas, the American Windmill Museum installed a 660-kW unit and a cottonseed oil plant installed ten, 1-MW units. There is an overlap among small wind turbines for residential use connected to a grid, large wind turbines (over 100 kW) attached as distributed systems (inside the meter), and community wind facilities ranging from small wind turbines to megawatt size turbines. Community wind is covered in the next section of this chapter.

The U.S. market for farm, industrial, business, and community installations was projected to be 3,900 MW by 2020 (2007 estimate). Distributed wind systems will exert impacts on smaller utilities and electric cooperatives [15]. The international market is difficult to measure because much of the market consists of village power and remote systems; however, for farm, industrial, and business uses the market is projected to be 600 MW by 2020. In 2021, it will be interesting to check actual numbers against predictions.

Issues related to distributed wind turbines for farmers, ranchers, and agribusinesses are somewhat similar to the considerations surrounding farm equipment purchases. The barriers and possible incentives for distributed wind applications are:

1. Cost (insufficient products to achieve economies of scale)
   a. Favorable life cycle costs will not sell wind turbines.
   b. Payback has to be 4–6 years.
   c. Wind turbines must compete almost directly with electricity from utilities that costs $0.10 to 0.15/kWh.
2. Lack of infrastructure
   a. Enough units have to be installed to provide sales and maintenance opportunities for local businesses. Within a 250-km radius, a dealer would need $1,000,000/year in sales. At $50,000 per unit, he would have to sell 20 units per year.
   b. To provide operations and maintenance (O&M) services, a business would need a customer base of about 300 units installed within the 250-km radius.
   c. Over time, distributed wind equipment business would be similar to the farm implement business, for example, a large tractor costs over $200,000.
3. In a sense, wind turbines should have modular components. The trend toward larger sizes will continue. Suggested sizes for rural grid-connect systems are:
   Residential: 10 kW
   Farm and ranch residential: 50 kW
   Agribusiness: 100–250 kW
   Large agribusiness: 500 kW to MW
4. Need for total package for agribusinesses
   a. Wind turbine, electrical energy
   b. Demand side management
   c. Service
5. Incentives
   a. Ability to use production tax credit or have feed-in tariff.
   b. Irrigation market requires wind class 3 and above and net energy billing on annual basis for units up to 500 kW.
   c. Benefits for nitrogen oxide (NO_X) and sulfur oxide (SO_X) emission reductions. When carbon trading arrives, distributed wind turbines should be included.
   d. Installation of distributed wind turbines on rural electric cooperative grids.

The Rural Energy for America Program (REAP) provides financial assistance through grants and loan financing to agricultural producers and rural small businesses. Grants can be up to 25% of total eligible project costs and are limited to $500,000 for renewable energy systems. A combination of loans and grants can cover up to 75% of total eligible project costs. All projects must be located in rural areas, must be technically feasible, and must be owned by the applicants. Under the program, 396 wind projects have been funded. These projects are primarily distributed wind and range in size from 10 kW to MW wind turbines. Some are refurbished wind turbines from repowering of wind farms, primarily from California.

A case study for a distributed wind and solar system is Cross Island Farms, Wellesley Island, New York. The system consists of a 10-kW wind turbine, a 5.5-kW PV unit, and a 17-kW propane generator [16]. The costs were $73,000 for the wind turbine, $40,000 for PV equipment, and $13,000 for the propane generator. The first developer received $9,000 for wind resource assessment and siting and concluded that the economics indicated an inadequate return. A second developer, more experienced in wind operations, recommended a taller tower 25–37 m (80–120 ft) and the payback was estimated at 5 years for the wind turbine and 10 years for the PV.

One problem of distributed and/or community wind is the higher surface roughness leading to lower annual capacity factors if a wind turbine is located in a city. For example, the capacity factors for the 660-kW unit at the American Windmill Museum ranged from 13 to 18%, even though the wind turbine was located in an exposed area. Expected capacity factors were 25–30%. A taller tower would have improved performance, but zoning laws limited tower height.

10.4 COMMUNITY WIND

The definition of community wind varies, and again there are overlaps in reported numbers of turbines and capacities for utility scale, small wind, and distributed wind. The AWEA defines community wind as "projects that incorporate local financial participation and control." Types of community wind projects are:

- Nonprofit municipal electric utilities
- Rural electric cooperatives
- Owners of wind generation facilities
- Purchasers of wind power from local residents
- Local owners of wind turbines who sell power to for-profit utilities
- Schools or colleges using power from their wind turbines
- Large farm operations using power from their wind turbines
- Other businesses using power from their wind turbines

The last two entities on the list are also distributed wind systems. Another definition of community wind applies to projects that use turbines over 100 kW and are completely owned by villages, towns, cities, commercial customers, and farmers (excluding publicly owned or municipal utilities). Based on this definition, the three 100-kW wind turbines at North Texas University and the eight 60-kW units at three school districts near Lubbock, Texas, would be classified as distributed wind, not community wind.

Community wind projects leverage local distribution grids for the economic and environmental benefit of the local community and provide investment opportunities by allowing community members to become financial partners. As with larger wind farms, community wind brings rural economic development with local participation.

10.4.1 United States

WINDExchange has handbooks for small and large community wind [17], information on how a community can get wind power, and community-scale 50-m wind maps by state. Small community

projects are defined by costs between $10,000 and $100,000, and a large community wind project has one or more 1.5-MW wind turbines. In 2016, the average installed cost for a small wind turbine was $5,900/kW and in 2015 the average installed cost for projects ≤5 MW was approximately $3,412/kW. The Community Wind Working Group formed by AWEA developed policies. An AWEA database on community wind has been incorporated into WindIQ, however, it is only accessible by members. Some older case studies are given for three projects, and photos and project summaries are given for some other projects [18]. Northwest Wind Resource & Action Center has four case studies for community wind [19].

Windustry has information on community wind [20], which includes overviews, projects, and a toolbox that offers practical information for farmers and rural landowners looking to develop commercial-scale projects. The core content came from the *Community Wind Development Handbook,* [21] developed on behalf of the Rural Minnesota Energy Board. *Community Wind 101* [22] is a primer for policy makers and clean energy advocates which looks at economic benefits, examines obstacles facing community wind developers, and describes examples.

10.4.1.1 Minnesota

In 2005, the Minnesota legislature passed an energy bill that promoted community-based energy development (C-BED) to facilitate community wind projects without placing excessive burdens on utilities. The bill requires utilities to create a new tariff which utilizes a net present value rate for electricity and provides the option of front-loading the rate in the first half of the contract's lifespan. Community wind projects average 10–20 MW and other states are adopting the mechanism to promote rural economic development. Dan Juhl [23] was an early proponent and by 2012 he had completed 21 projects (1,905 MW), most in Minnesota.

The Minwind arrangement consists of nine farmer-owned projects near Lucerne, Minnesota, and the case study [24] describes ownership criteria. Early wind projects were farmer-owned, most under 2 MW, with one or two large turbines. The state provided a production incentive of $0.015/kWh for the first 10 years. For two projects, 66 farmers raised 30% of the $3.6 million cost of four turbines (950 kW). The remaining 70% was raised through local banks. Later projects were larger, and were based on economics of scale, especially for the installation phase.

10.4.1.2 Schools, Colleges, and Universities

The Wind for Schools Project [25] has 147 systems installed across 12 states. The primary goals of the project are to (1) educate college juniors and seniors regarding wind energy applications; (2) engage communities in wind energy applications, benefits, and challenges; (3) introduce students and teachers to wind energy; and (4) improve wind energy workforce development though wind-focused deployment and educational activities. One of the things they do is to install small wind turbines at rural elementary and secondary schools and develop Wind Application Centers at higher education institutions.

A number of Enertech wind turbines (13.5 m diameter, 40 or 50 kW) have been installed at schools, colleges, and universities. See Section 10.4 for detailed data on Enertech 44 performance. Later versions were built by Atlantic Orient, Entegrity, and Seaforth. At Natoma Rural High School in Kansas, an Entegrity unit produces 60,000 kWh/year. Units in the Texas Panhandle should produce around 100,000 kWh/year. Entegrity installed 10 units in Texas and 5 in Kansas.

In Texas, stimulus money from the American Recovery and Reinvestment Act of 2009 provided funds for wind projects at three schools and two universities. A 50-kW unit was installed in 2012 by the Alternative Energy Institute at the feedlot of the Nance Ranch, West Texas A&M University. Three 100-kW units are expected to produce around 8% of the electricity used at the Eagle Point grid, which includes a residence hall and football stadium at the University of North Texas [26].

Northern Power [27] wind for school programs provides a web-based interface for students and teachers to view turbine performance and provides curriculum resources. The student view covers energy production, wind speed data, and historical trends. The company lists case studies that include two for schools.

Other states utilize programs and/or policies for promoting wind turbines at schools. A U.S. DOE report [28] describes early examples. In Iowa [29], nine schools utilized installations ranging from 50 kW to 750 kW. Spirit Lake [30] installed a 250-kW turbine in 1993 and a 750-kW wind turbine in 2001 and they now supply 46% of the school's electricity. Some colleges with wind energy training programs for wind energy make large wind turbines available for their students. Examples are Mesalands Community College in New Mexico, Spirit Lake Community Schools in Iowa, and the Texas State Technical Institute in Sweetwater.

10.4.1.3 Electric Cooperatives

The Golden Spread Electric Cooperative [31] consists of 16 member rural electric cooperatives serving a large area (182,000 km^2 or 69,700 sq. miles) across West Texas (92% of the area) and the Oklahoma Panhandle. Electricity was previously purchased from investor-owned utilities. The cooperatives now generate some of their power, natural gas (1732 MW), and wind (84 MW). The Panhandle Wind Ranch with 34 wind turbines (3.2 MW) was commissioned in 2012 and generated an average 279 GWh/year (2012–2017), value close to $12 million/year ($0.043/kWh).

The Fox Islands Electric Cooperative [32] installed three 1.5-MW wind turbines because its 2008 rates were about $0.28/kWh, two to four times the national average, and its undersea cable was becoming unreliable. In 2010, the wind project generated 12.1 GWh, which was in line with the projected 11.6 GWh/year.

The Basin Electric Power Cooperative [33] added 719 MW of wind energy through joint projects and purchase agreements. Crow Lake (162 MW) has 108 wind turbines of 1.5-MW size and 100 more (Prairie Winds SD 1) are owned by Basin Electric. One turbine was sold to the Mitchell Technical Institute, and seven are owned by a group of local community investors. Prairie Winds ND 1 is a 115-MW wind farm; other Basin Electric small projects use nine turbines around 10 MW.

Other electric cooperatives pursue smaller projects and purchase wind power from independent producers or are considering wind power options. The Iowa Lake Electric Cooperative has two 10.5-MW projects involving seven 1.5-MW wind turbines. The Farmers' Electric Cooperative of Clovis, New Mexico, purchases 18 MW from a wind farm in Curry County.

10.4.1.4 Municipal and City Operations

The Berkshire Wind Power Project [34] is a 15-MW, 10-turbine wind farm atop Brodie Mountain in Hancock, Massachusetts. The project is owned and operated by the nonprofit Berkshire Wind Power Cooperative consisting of the Massachusetts Municipal Wholesale Electric Company and 14 consumer-owned municipal utilities. The capacity factor is nearly 40%, which generates around 50 GWh/year.

Hull, Massachusetts [35] installed its first wind turbine of 40 kW in 1985. It operated until 1997, when damage from a 70-mph windstorm caused malfunctions of the tip brakes on the blades. In 2001, a 660-kW unit was installed and a 1.8-MW unit was added in 2006. Hull's website shows kilowatt-hours generated, connect hours, and capacity factors for each turbine. As of June, 2013, statistics for the two units are 17,211 and 25,600 MWh, 60 and 57% connect times, and capacity factors of 26 and 23%.

Lamar, Colorado installed four 1.5-MW wind turbines and Springfield, Colorado installed a single 1.5-MW wind turbine in 2004. Three turbines are owned by Lamar Light and Power and the other two are owned by Arkansas River Power Authority. The Lamar utility operates all five wind turbines from its power plant control room. This project is one of the case studies cited by Flowers [18].

The Jersey-Atlantic wind farm [36] utilizes five 1.5-MW wind turbines to supply electricity to a wastewater treatment facility, and it sells excess power to the grid. The project cost in 2005 was $12.5 million, and the wind farm saved $3.17 million between January, 2006 and May, 2012. Web data includes monthly values for energy produced and revenue generated. Real time monitoring is available for the wind farm and solar array along with energy flow data.

Other municipalities and cities are considering wind power, and large municipal utilities have commitments to purchase power from wind farms as part of their goals for increasing renewables. For example, Austin Energy has 1,667 MW of renewable capacity with 1,254 MW from wind farms across Texas. Its goal is 35% from renewable energy by 2020. The website [37] shows current percent generation from renewables and the type percentage. For example on 3/9/2018, 9:49 AM, 40.3% renewable, of which 68.5% was from wind. CPS Energy of San Antonio, Texas, is the largest municipally owned utility (gas and electric) in the United States. Renewable energy (wind, solar, and landfill gas) accounts for 9%, and most of that comes from 1,059 MW of wind power from West Texas and coastal wind farms. CPS plans to achieve 1,500 MW of renewable energy or 20% of generation by 2020. In 2017, Georgetown, Texas, went 100% renewables through the use of wind and solar.

10.4.2 Other Countries

Wikipedia publishes articles regarding community wind energy in Europe, Australia, and Canada. Most community and cooperative wind projects are in Denmark and Germany. In Denmark, to encourage investment in wind power, families were offered tax exemptions for generating their own electricity within their own or an adjoining community. While this could have required a family to purchase a turbine, families often purchased shares in wind turbine cooperatives that then invested in community wind turbines.

At the end of 2005, individuals or cooperatives owned 83% of the 5,293 installed wind turbines in Denmark. Privately owned wind turbines accounted for 77% of the capacity. Capacity percentage decreased with the installation of more offshore wind farms, but over 100 cooperatives still owned 75% of the wind turbines in 2011.

A famous example of a community project is the Middelgrundens offshore wind farm [38] in the harbor of Copenhagen, Denmark. The Middelgrundens Wind Turbine Cooperative owns 10 of the 20 Bonus 2-MW wind turbines. Each share corresponds to 1/40,500 of the partnership (8,552 electric consumers, most of whom reside in Copenhagen). Weekly and monthly energy production figures and instantaneous values of power output, wind speed and direction, and other parameters can be followed online.

On Lolland Island, Denmark, wind power produced 50% excess energy. In 2007, the Lolland Hydrogen Community test project was formed. Excess wind power is used to electrolyze water, producing hydrogen and oxygen. The hydrogen powers two cells (2 kW and 6.5 kW) for producing heat and power. The oxygen is used at the municipal water treatment plant to accelerate biological processes. The 4,200 residents of the island of Samsø own shares in 20 of the 21 wind turbines installed on two wind farms (one offshore) [39]. The turbines produce more energy per year than used on the island and the excess is exported to the mainland.

Germany had only two wind cooperatives in 2006. The number increased to 111 by 2011 [40]. In the community-owned Hilchenbach wind farm, 88 people hold shares, and five wind turbines produce around 23.5 GWh/year. The city of Hilchenbach then purchased Rothaarwind and two-thirds of the shares belong to local residents. The district of North Frisia has more than 60 wind farms producing about 700 MW, and 90% of them are community owned. In 2017, in North Rhine-Westphalia, there were 324 community projects of which 85 are wind.

In The Netherlands, 25 wind cooperatives were formed from 1986 to 1992, but 11 disbanded or merged with others. About half the onshore capacity is owned by local farmers, investors, and cooperatives. A large project is a 122-MW wind farm (36 3.5-MW wind turbines) partnership of Nuon and 63 farmers that constitute the De Zuidlob wind turbine consortium.

The Baywind Energy Cooperative, the United Kingdom's first community wind project is run by its 1,300 members who receive annual returns around 7%. Energy4All is a nonprofit company that supports community renewable energy projects. It set up a number of community wind projects and detailed information wind projects in the United Kingdom is available online [41]. Falck

Renewables owns and operates wind farms in the U.K., France, Spain, and Italy (total of 760 MW) and gives individuals living close to a wind farm the opportunity to own a share in its wind farms. The cooperative investment scheme was developed in collaboration with Energy4All, which first introduced community-owned turbines in 2012 into its commercial wind farms. There are currently around 3,000 investors in the Falck co-ops.

EOLOP involved the installation of a wind turbine (2.35 MW) with shared ownership among citizens who voluntarily provide the investment. Their web site has information on 42 cooperative projects in six countries [42]. Sweden has around 25 MW of community wind projects. Note that some web sites that promote community wind are maintained by developers of commercial wind farms.

The Hepburn Community Wind Park [43] in Australia restricts shareholders to members (1,900) of the cooperative, and members receive dividends in proportion to investment. The project went on line in June, 2011 and has generated 16.8 GWh since then (monthly production reports are available). The Denmark Community Wind Farm [44] utilizes two 800 kW wind turbines.

10.5 WIND–DIESEL GENERATION

For remote communities and rural industries, the diesel generator is the standard for generation of electricity. Remote electric power is estimated at over 50 GW and diesel generators range in size from 5 to 1,000+ kW. Canada utilizes more than 800 diesel generation sets with a combined installed rating of over 500 MW. In the Province of Chubut, Argentina, village systems use diesel generators ranging from 75 kW in small villages to 1,250 kW in larger ones. Because the systems are subsidized, it is difficult to determine the actual cost of electricity at provincial and national levels. Costs for electricity were in the range from \$0.20 to \$0.50/kWh, with variability driven by the cost of diesel.

Diesel generators are inexpensive to install but expensive to operate and maintain, especially in remote areas. Major maintenance is needed every 2,000–20,000 h, depending on the size of the diesel genset. Many small village systems generate electricity only in the evenings. More than 300 remote communities (about 200,000 people) in Canada use diesel-generated electricity. Australia, Argentina, northeast Brazil, Chile, China, Indonesia, Philippines, coastal sub-Sahara Africa, and other countries with populations in isolated villages and on islands have the potential to use wind–diesel systems. The techniques for designing, modeling, and simulating wind–diesel systems have improved as the industry has accumulated more on-site operational experience.

Wind–diesel systems were developed and tested at the Risoe National Laboratory in Denmark, The Netherlands Energy Research Center in Petten, the Wind Energy Institute of Canada (formerly Atlantic Wind Test Site) on Prince Edward Island, the U.S. National Renewable Energy Laboratory in Colorado, in the United Kingdom, and in other locations. Primary work focused on developing wind–diesel systems for the retrofit market. This market would be for installing existing diesel generators in windy locations where wind power would exceed 50% of the installed capacity

Wind–diesel [45] systems have potential because of the high costs of generating power from isolated diesel systems. By 1986, more than a megawatt of wind turbines were combined with existing diesel systems. Simulation models for wind–diesel systems are available. A problem common to all new applications is that early prototypes may not be operational over the long term. For example, 13 of the early wind–diesel projects in remote communities in Canada were no longer operational by 2011.

Wind turbines can be installed at existing diesel power plants (Figure 10.7) at a low (fuel saver as the diesel does not shut down), medium, or high penetration (wind supplies more of the load, which results in better economics as diesel engines may be shut down).

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. Among the problems of integrating a wind turbine and existing diesel generator are voltage and frequency control, frequent stops and starts of

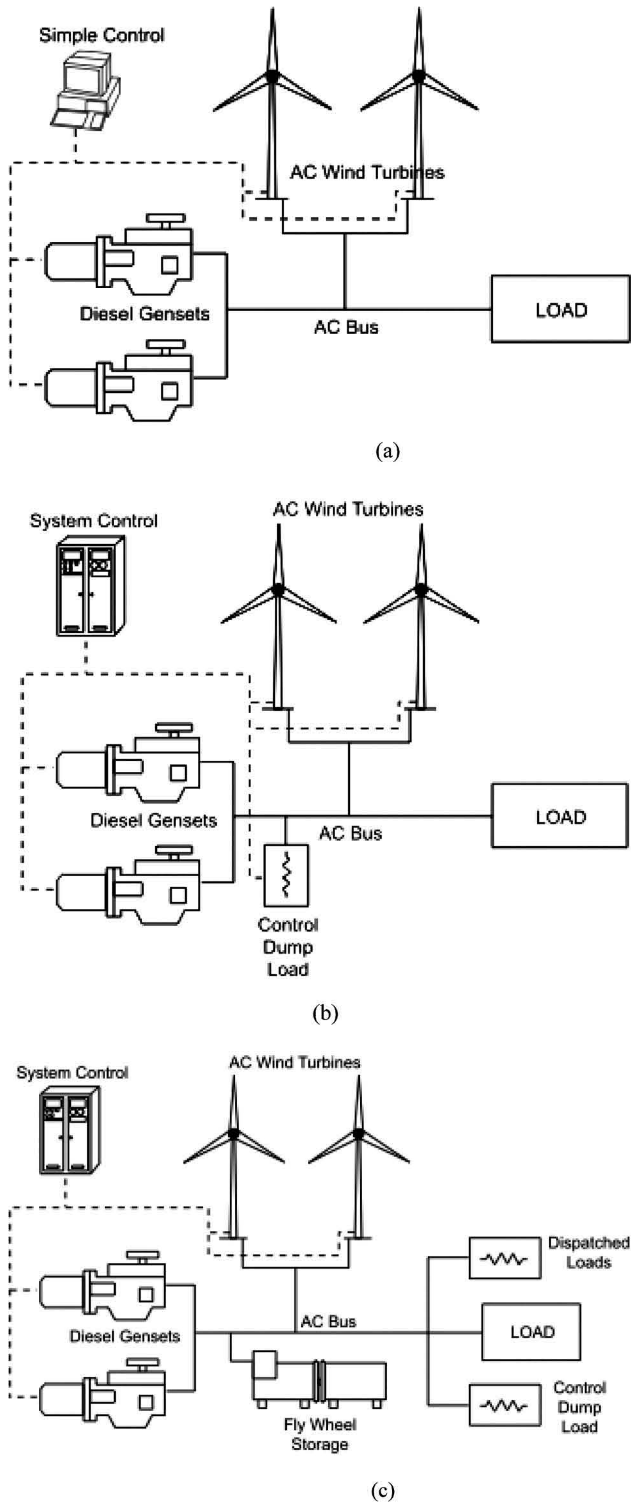


FIGURE 10.7 (a) Low penetration diesel without storage. Diesel governor and voltage controls maintain system power quality. (b) Medium penetration with system control and dump load for high winds and medium diesel power. (c) High penetration with flywheel storage.

the diesel, utilization of surplus energy, and the use and operation of new technologies. These problems vary by the amount of penetration. Wind turbines at low penetration can be added to existing diesel power for large communities with few problems because the wind segment is essentially a fuel saver. One solution for high wind penetration to use flywheels or battery storage.

Based on data for Alaska wind–diesel systems, a dump load or storage is needed to reach predicted energy production from the wind turbine, even for low penetration. Otherwise, the capacity factors will be lower than predicted. One company recommends wind turbine capacity at 130–150% of engine power to provide 70–80% wind penetration. If the surplus energy from the wind and heat from the diesel engines is utilized for central heating, ice storage, and electric cars, wind penetration can reach 90%. Other options are adding desalination or hydrogen production packages to wind–diesel systems.

Rough estimates indicate that there are around 270 wind–diesel system in the world, with wind turbines ranging in size from 100 kW to megawatts. Wikipedia has an incomplete list of 46 wind–diesel installations that produce 50 MW of wind power. Reports on wind diesel are available from the 2009 International Wind–Diesel Workshop [46].

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. Average penetration was 14–24%. Tower height was limited to 30 m because of local crane capacity. In 2003, the addition of two large wind turbines (900 kW), controllable electric boilers, and a synchronous condenser increased the average penetration from 43 to 64% [47]. Fuel consumption was reduced significantly, with a savings of approximately $1 million/year. Wind penetration ratios exceeding 40% usually have stability problems but in this case 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% along with some problems. Three of the systems were not working by 2005. By 2013, renewable energy produced 20% of the electricity from 28 MW of wind and 7.5 MW of PV [48]. The goal is to achieve 100% renewables by 2030. Other systems are Alto Baguales-Coyhaique, Chile (2-MW wind) and wind–hydro–diesel systems (1.4-MW wind) on Flores and Graciosa Islands in the Portuguese Azores. A database of wind- and solar-diesel plants on islands has photos, capacity, turbine, status, and type of system [49].

Data from the Alaska Energy Authority [50] show that from 2007 to 2012, 63.8 MW (144 turbines at 27 locations) were installed. Online data for wind turbines also cover manufacturers, rated power, commissioning dates, and costs. Installed costs ranged from $3,000 to over $20,000/kW. Diesel fuel cost was about $1.20/L ($5/gal) or $0.38/kWh assuming 3.4 kWh/L (13 kWh/gal) generation. The 48.5 MW installed in 2012 came primarily from 11, 1.5-MW wind turbines at Fire Island and 12, 2-MW turbines at Eva Creek.

At Kodiak, AK, renewables supply almost all of the electrical energy. The System consists of hydro, six 1.5-MW wind turbines, two 1.5-MW battery storage systems, two 1-MW flywheels (for the rapid variable power for cranes at the port), and diesel gensets. Diesel gensets are only turned on when hydro is being maintained and for regular checkups. The wind turbines displace around 10×10^9 L/year (2.8×10^9 gal/year) of diesel worth around $8.4 million. Hydro supplies around 76% of the energy and wind supplies the rest.

There are 17 wind–diesel and wind–diesel smart grid projects, and two surplus wind to heat water projects partially funded by the Alaskan Energy Authority [51]. From 2009 to 2016 these projects generated 514 GWh of electricity and 6.2×10^{12} J (5,400 MMBtu), which resulted in 130×10^6 L (35.5×10^6 gal) of displaced diesel worth 88.3 million dollars. At Unalakleet Valley Electric Co-op there was a problem with line losses (>15%) due to poor power factor (capacitor problems) from the wind turbines (6, 100-kW), which results in an annual power loss equal to one of the turbines.

Wales, Alaska's high-penetration system (Figure 10.8) utilized battery storage. The system has not worked properly since 2006 because of high-penetration issues and it essentially needs to be reworked. The University of Alaska at Fairbanks wind–diesel applications center [51] produces a

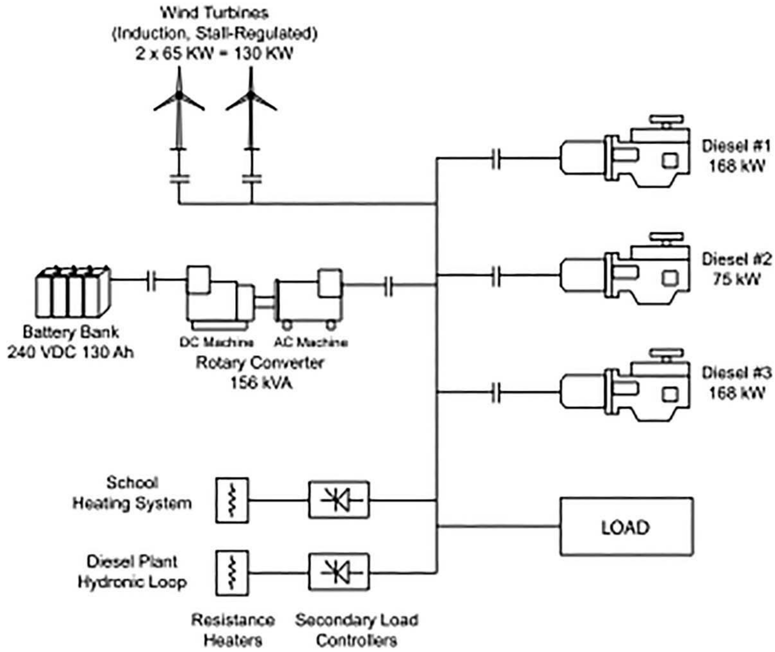


FIGURE 10.8 High penetration wind–diesel system with battery storage in Wales, Alaska.

best practices guide and uses a wind hybrid simulator consisting of two 200-kW diesel gensets, a 100-kW wind turbine, wind turbine simulator, grid simulator, battery bank, secondary load control, synchronous condenser, inverter, controls, and data acquisition equipment.

Three 250-kW wind turbines were added to the diesel system (four 1,200-kW generators) on King Island, between Tasmania and Australia. Wind 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 [52] to produce around 50% of electrical demand. A large-flow vanadium redox battery reduces the variability of the wind energy. That battery went out of service in 2012 and was replaced with an advance lead acid battery in 2014. The system has reduced diesel consumption from 4.5 to 2.6 million liters per year, primarily via the wind turbines. Their Web site has live data showing input from wind, PV, battery, and diesel (two with flywheels).

ABB (which purchased Powercorp) [53] has case studies of five wind–diesel installations. To handle the instabilities of integrating wind power with diesel, a flywheel that can absorb or release 1 MW of power within 0.5 ms is part of the system. Two wind turbines were installed in 2003 at the Mawson Research Station in Antarctica. Ross Island, Antarctica, installed three 330-kW wind turbines in 2009 which provide 22% of the electricity and 11% fuel saving 122,312 gallons/year (463,000 L/year).

Vergnet [63] has installed over 900 midsize turbines ranging in size from 12 to 275 kW. The company has case studies for hybrid, solar, wind, independent power producers, mining, and utilities. Examples are Devil's Point, Vanuatu, (13, 275-kW wind turbines), Coral Bay, Australia (3, 275-kW wind turbines with flywheel storage), Maddens Wind Farm, Nevis (8, 230-kW wind turbines), and Aleipata Wind Hybrid Farm, Samoa (2, 275-kW wind turbines).

Danvest Energy [55] lists nine projects indicating a total of over 6 MW of wind power and fuel savings of 50–85% per year. The site has downloads describing wind–diesel facilities, service and controls, desalination, dump load controls, and other topics. Ramea (population 700) on Northwest Island off the coast of Newfoundland, Canada, has a wind–diesel project consisting of six remanufactured Windmatic turbines (total 390 kW).

Wind–diesel and wind hybrid systems are now available for village power, so the wind constitutes an integral part of the original design. A number of wind turbine manufacturers offer wind–diesel or wind hybrid options. These range from simple, no-storage systems to complex integrated systems with battery storage and dump loads.

Wind–hydrogen systems are similar to wind–diesel devices if hydrogen is used to power a genset. An added advantage is that fuel does not have to be transported to remote locations. The hydrogen can also be used as a fuel for heating and cooking. In 2009, wind–hydrogen capability [56] was added to the Ramea project. The system consists of 300-kW wind and a 250-kW hydrogen genset. Hydrogen is produced by electrolysis of water. Seven projects using wind for hydrogen production, including Ramea, were discussed at a workshop [46]. In a pilot project on the island of Utsira in Norway [57], ten households receive power from two 600-kW wind turbines, a 5-kWh flywheel storage system, an electrolyzer with a peak load of 48 kW, and a 55 kW engine.

The Wind Energy Institute of Canada [58] maintains a wind–hydrogen village at its North Cape test site (formerly the Atlantic Wind test site). A 300-kW electrolyzer is powered independent of the grid by wind turbines. The 150-kW hydrogen genset supplements or replaces wind power when wind speeds are too low. A Wind Technology Center research project known as WIND2H2 [59] used two wind turbines (100 and 10 kW) and converted variable output DC to produce hydrogen via an electrolyzer.

Installations of wind–diesel systems and associated R&D have continued for several years. Many configurations were devised but little consensus and replication resulted. The technology is more mature than it was in 2007, but the number of installations of village power systems is insufficient despite the huge market potential.

10.6 VILLAGE POWER

Around 1.1 billion people lack electric service because they are too far from the transmission lines of conventional electric power plants. Extension of the grid is too expensive for most rural areas, and extended facilities exhibit poor cost recovery. Efforts are ongoing to bring renewable energy from wind, sun, mini- and micro-hydro, and biomass to these villages. Other components required to supply limited reliable energy include controllers, batteries, and conventional diesel and/or gas generators. In windy areas, wind is the lowest cost component of a renewable power supply.

Village power systems provide power from a central source or a mini grid. Village hybrid power systems [60] can range from small micro grids (<100 kWh/day, about 15 kW peak) to larger communities (tens of MWh/day, hundreds of kWp). One or multiple wind turbines (10–100 kW) may be installed and software programs are available for modeling hybrid systems [61]. The main difference between village power and wind–diesel generation is system size although the categories overlap.

A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries, which acts as a single controllable entity. Two important criteria are: (1) whether the microgrid is ever connected to a larger grid and (2) the type of dispatchable generation. Generation from renewables plus storage are now part of the design and operation of microgrids. Low levels of renewable contribution (up to 30%) reduces the cost of power. For middle levels (30–80%), the cost is essentially the same/kWh. High levels of renewable contribution requires excess renewable energy capacity with large storage, which substantially increases the cost of energy. Microgrids and minigrids may be installed and connected to large grids.

Manufacturers' websites may show case studies; for example, Bergey Windpower case studies show different types of installations that include village power [62]. The island of Eigg, Scotland, is almost all supplied by renewable energy; hydro 110 kW, wind 24 kW, PV 32 kW, diesel 128 kW, and battery 212 kWh. Most mini grids using renewables being installed today are with photovoltaics. Renewable systems for villages include:

- Fuel saver system (adding renewable energy system to existing diesel power plant (see Section 10.4)
- Single or hybrid renewable energy source with battery storage (Figure 10.9)
- Single or hybrid renewable energy source with diesel or gas generator
- Single or hybrid renewable energy source with diesel or gas generator and battery storage

The advantages of village power systems using renewable energy are:

- Generation of AC or DC power for remote areas (AC is standard)
- Available electricity for productive uses
- Modular equipment
- Reduced or no fuel costs
- Lowest life cycle cost of electricity
- Local ownership and operation

The disadvantages of village power systems using renewable energy are:

- High initial capital cost compared to diesel generators
- Equipment complexity (sophisticated controllers, power conditioning, batteries)
- High growth in demand (may require load management and limitation)
- Little supplier support (few systems installed)
- Need for infrastructure (trained staff, billing structure, administration)

Institutional issues are more important than technical issues, especially for demonstration projects. Many demonstration projects may become very political, and the social issues may dominate technical issues. Institutional issues are:

- Pre-installation planning which includes local residences
- Cost, subsidy, and maintenance requirements
- Ownership
- Operation and maintenance
- Operator training (after acquiring technical proficiency, operator may leave for the city)
- Financing possibilities: world (multilateral), national aid agencies (lateral), and nongovernment organizations and national, state, local, and private organizations
- Tariff design, metering, ability and willingness to pay

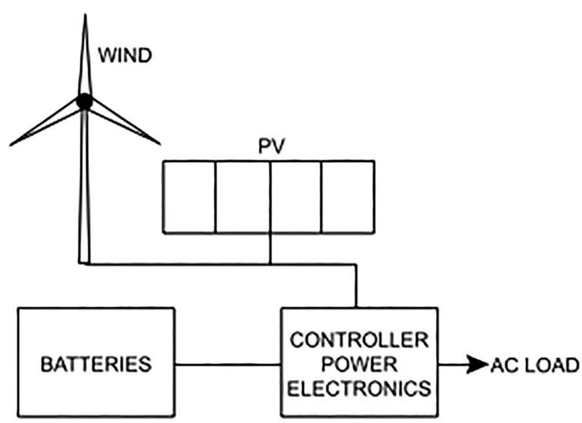


FIGURE 10.9 Hybrid wind–PV system with battery storage.

- Load growth
- User education
- Service quality
- Economic development versus social services (schools, clinics)
- Cultural response
- Institutional cooperation: local, state, national, electric utilities, financing

10.6.1 China

Among the estimated 2,000 renewable village power systems in the world, more than 1,250 are in China. About 100 renewable village power systems, from 5 to 200 kW, were installed in China by 2000 but more than 21,000 villages and 7 million households still lack electric service [63, Chap. 2]. China now leads the world in installation of renewable village systems (100 include wind). One example is the electrification of five villages in Bulunkou Township in the Xinjiang Uigur Autonomous Region [63, Chap. 5].

China started a Township Electrification Program in 2002 and its 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 six wind systems. Because the projects required some funding from the townships, not all the planned projects were installed.

Note the large difference in average sizes (780 kW versus 22 kW) of the mini hydro, PV, and PV–wind systems. In 2005, 66 PV–wind hybrid systems were visited to check on performance. A large hybrid village system (Figure 10.10) in Gansu Province had a projected load of about 235 kW. Mazhongshan Township is 158 km from the nearest utility grid. The village power system consists of 210-kW wind power and 90-kW PV, divided into three groups. A group consists of seven 10-kW wind turbines, a 30-kW PV cell, a battery bank of 240 V, 3,000 Ah, and a 100-kW DC–AC inverter. A system provides electricity to one part of the township.

10.6.2 Case Study: Wind Village Power System

Huaerci [63] is a village in the mountainous area of eastern Xinjiang Province, China, with 90 households and 360 inhabitants. The primary economic activity is 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 poor. Lighting at night was provided by candles. Most families used two candles per night so the children could do their homework. Renewable resources are wind (annual mean wind speed, 8.3 m/s) and solar (annual average, 3,100 h).

The system configuration chosen consisted of 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 5-year loan at 3% interest.

FIGURE 10.10 Fourteen of the 21 wind turbines (10 kW each) at Mazongshan Township, Gansu Province, China. (Photo courtesy of Charlie Dou.)

The system provides 24-h power for the 90 households, village offices, a school, and a TV transmitting station. All light bulbs are energy saving types, and since installation of the system, ten color TVs, 30 black-and-white TVs, and a CD player have been purchased. The peak residential load is about 5 kW, and energy consumption is around 300 kWh monthly with an additional 45 kWh/month for the institutional loads.

A village power management committee is composed of village officials, 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. Cash flow should be sufficient to allow replacement of the battery bank, but this village power system is not fully commercialized. The system has a part-time operator. No productive loads are served to date due to limited system capacity. The lessons learned are:

(1) Load analysis and prediction are important. Proper system configuration to match load is a critical factor for cost recovery.
(2) Six renewable energy village power systems have been developed in Barkol County. They provide a great opportunity to develop a multiple project management entity and introduce a commercialized model to ensure sustainability.
(3) Productive loads should have been established at the beginning.
(4) A skillful technical operator should 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 is powered by a wind turbine system, and another two large villages are powered with a 30-kW wind system.

10.7 WATER PUMPING

Water pumping and sailboat propulsion are the oldest and most consistent uses of wind power. Two common examples of mechanical water pumping are the historical Dutch windmill for pumping large volumes of water from a low lift and the American farm windmill for pumping small volumes of water from a high lift [64–66].

For mechanical windmills and wind turbines, important considerations are: (1) wind power and (2) the method of transferring power. This means that the characteristics of a wind turbine (primarily the rotor) and the characteristics of the pump are combined into a single 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. Farm windmill efficiency depends on the load matching of the rotor to a positive displacement device, generally a reciprocating (piston) pump.

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. About 80,000 operating windmills are estimated to operate in the Southern High Plains of the United States. World production of farm windmills is estimated at 3,000/year, primarily for replacing old units installed 30 to 40 years. The American farm windmill is well designed for pumping small volumes of water for livestock and residential use, and the design has not changed since the 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 15–18 slightly curved blades (vanes); see Figure 10.11. The large number of blades provides the high starting torque needed to operate the piston pump. Most units have back gearing (reduction in speed), which transfers the rotating motion of the rotor to a reciprocating motion for

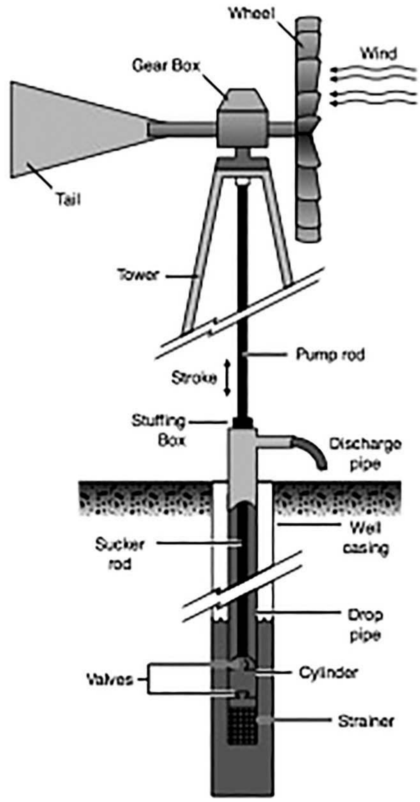


FIGURE 10.11 America farm windmill.

pumping water. All wind turbines have characteristics that reduce efficiency and prevent capture of all the energy possible at high winds. On a 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 5–6% (see Section 8.5).

In the 1970s and 1980s, several research groups and manufacturers attempted to improve the performance of farm windmills [64, Chap. 5] and reduce costs. Many of these projects were designed to pump water in developing countries. Designers believed that the performance could be increased by making the following changes:

1. Reduce the solidity (number of blades or area of blades) to achieve higher rotor rpm.
2. Change pump characteristics by using variable stroke or variable volume to match rotor characteristics.
3. Develop a windmill for the low wind regions of the tropics.
4. Counterbalance the weight of the rods, pump, and water column.

The Agricultural Research Service of the U.S. Department of Agriculture (USDA) and the Alternative Energy Institute at West Texas A&M University (WTAMU) tested some of these concepts in their cooperative program on wind energy for rural applications but the USDA withdrew

from the program in 2012 and AEI was terminated in 2015. A company in South Africa developed a windmill with a rotating helix pump [67].

Costs can be reduced by using local materials, buying from local light industry manufacturers, and considering new windmills designed for developing countries. One option is the use of a Savonius rotor for low-volume, shallow water. Another option is a wind turbine that drives an air compressor and airlift pump. However, the problem is still the same: The rotor must be connected to a constant-torque device.

10.7.1 Design of Wind Pumping System

The requirements for applications differ in that water for livestock and residential use requires a low-volume storage tank. Villages require potable water and a low- or high-volume storage tank, depending on the size of the village. Irrigation requires large volumes of water, usually without a storage tank. The steps to consider when designing or sizing a water pumping system are:

1. Water demand: residence, livestock, village, irrigation
2. Water resource: surface, well; also available volume
3. Hydraulic power: volume times dynamic head
4. Wind resource
5. Comparison of other power sources
6. Design considerations

Other design considerations are economics, O&M costs, institutional issues, equipment life, and future demand requiring addition or expansion of the system. The average daily demand (m^3/day) is estimated for the month of highest demand or the wind design month (month with lowest average wind speed). Demand must also consider growth during the design period, which should be at least 10 years.

Water demand for livestock can be up to 90 L/day. Open storage tanks are subject to evaporation loss, especially in windy and dry areas, and will require even more water. Also, animals travel only limited distances from a water source, so one water source is required for each 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 near the water supply.

Domestic water needs depend on the number of people, usage, and type of service. What is considered necessary in some countries or regions is considered a luxury in others. In addition, people will consume more water during hot, dry periods. Local water consumption is the best guide but remember that usage per person will probably increase if availability improves. Village water supplies must include clinics, stores, schools, and other institutions. Growth in demand will depend primarily on water availability, growth in size of herds or flocks, and population growth in villages. Growth in population should be estimated from local trends.

Water demand for irrigation (low or high volume) is based on local conditions, season, crops, and evapotranspiration. These data are generally available from regional or national government agricultural agencies.

10.7.2 Large Systems

Large systems have been considered for pumping water for irrigation and villages. These can be classified as wind-assist and remote, stand-alone systems. Wind-assist water pumping involves a wind turbine and another power source that work in parallel to provide power on demand. Wind-assist is essentially a fuel-saving mode of operation, because it does not require changes in irrigation applications.

Wind-assist systems are of the indirect and direct connection types. The advantages of an indirect connection 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 produces more power than is needed by the load.

A direct mechanical connection to a gear head has also been tested with a conventional electric or diesel power source [68,69]. The disadvantages of the mechanical connection are the need to place the wind turbine near the well and the use of the wind turbine only when water is needed.

The wind–electric water pumping system is a major improvement over the farm windmill in the areas of efficiency and volume of water. The annual efficiency is double that of a farm windmill. Because wind turbines are available in larger sizes (1–10 kW), wind–electric systems can pump enough water for irrigation and for villages.

A 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. The wind turbine output and the centrifugal pump constitute a good match because both have power proportional to rpm value cubed. Another advantage is that the wind turbine can be located some distance from the well or pump.

Two 10-kW wind–electric systems were installed in Naima, Morocco, in 1989, to supply water for villages and animals [70]. The spring is a large distance from the villages. The first wind turbine pumps water from the collection tank to a large storage tank on top of a hill (Figure 10.12). There is gravity flow to two other storage tanks and a second wind turbine pumps water to another village. The wind–electric systems replaced inoperable diesel pumping systems. In 1997, two more 1.5-kW wind–electric systems were installed.

The Kestrel website shows examples of wind–electric water pumping. A 3-kW wind turbine is used to pump water for cattle from a well and then from one dam to another. The system delivers 2,500 L/h and 1,300 L/h. At another location, a 1-kW wind turbine pumps 1,800 L/h from a 50 m depth.

10.8 WIND INDUSTRY

After the oil crisis in 1973, the first step was the development of small wind turbines (<100 kW). Most companies in the United States began by importing wind turbines, finding abandoned units to refurbish and 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 types because of their simplicity and ease of construction. Electricity consumption also increased over the small demand of the 1930s. Larger wind turbines were needed because 5 m diameter rotors could not meet the demands of farmers and ranchers. In addition, many more uses of electricity required larger wind turbines.

Because the electric distribution system covers the entire United States, there was a market for wind turbines that were fully compatible with utility systems: 120, 240, or 480 V, alternating current (AC). Inverters with solid-state electronics connected direct current (DC) units and alternators to utility lines. Enertech and Carter were early proponents of induction generators, which could be connected directly to utility grids.

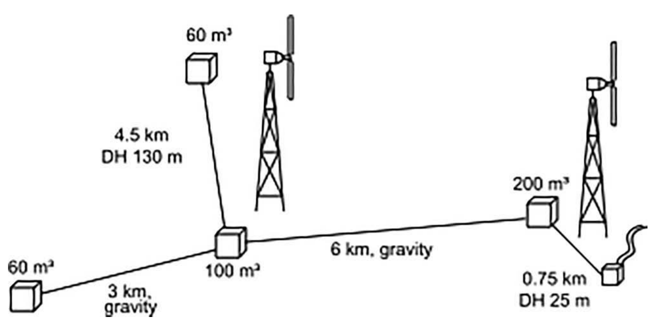


FIGURE 10.12 Layout of water supply for three villages at Naima, Morocco. DH = dynamic head.

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 increased by 1980 to $67 million. The federal program for development of wind turbines was geared to large units that connect to utility grids (Figure 10.13). These units were to produce power at $0.02 to 0.04/kWh. The program was managed by NASA–Lewis [71] starting with the MOD-0 (100 kW) and MOD-0A (200 kW) and progressing to megawatt-sized wind turbines. Five of the MOD-2s 2.5 MW were built (Figure 10.14), and the original design of the MOD-5 was reduced from 7.2 to 3.2 MW. All these units had two blades.

During the 1980s, other large wind turbines were developed and installed in the United States and Europe. The Hamilton Standard WTS-4, Wind Turbine Generator, Bendix-Schachle, and Alcoa units were developed mainly through private funds. However, a group of wind enthusiasts convinced

FIGURE 10.13 Top left: MOD-5B, Oahu, Hawaii. Top right: WTS, Medicine Bow, Wyoming. Top of MOD-2 is visible at lower right. Bottom: Westinghouse 600, Oahu, Hawaii. MOD-5B is visible at right.

FIGURE 10.14 MOD-2 wind turbines at Goodnoe Hills, Washington, near the Colombia River. Turbines were place in a triangle to aid research on wake interference. (Photo courtesy of NASA-Lewis.)

federal officials to support a program for small wind energy conversion systems (SWECS). The SWECS prototype program awarded contracts in 1978 and 1979. By 1980, more than 50 companies produced 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 [72].

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 electric grids without penalty, and for payments to producers for electricity sold to utility companies. The value of that electricity was determined by the avoided cost concept implemented by the states.

10.8.1 1980–1990

The 5 years from 1980 to 1985 are considered the nascent phase of wind industry development. The boom of wind farms in California drove the exponential growth of the industry from 3 to 900 MW. The California wind market expanded from tax shelters (solar and investment tax credits) along with avoided costs and standard contracts set by the California Energy Commission. As with many new industries, a lot of manufacturers appeared. Only small wind turbines (<100 kW) were available commercially, and they had reliability problems.

From 1980 to 1990, four features that evolved from the installations in California characterized the wind industry: (1) rapid growth, (2) development of intermediate-sized wind turbines (100–600 kW) without government funding, (3) the withdrawal from the market of U.S. aerospace companies, even those that received government funding for design, development, and prototypes, and (4) strong foreign competition, primarily from Europe. Foreign manufacturers, with Denmark leading the way, became important factors. Vertical axis wind turbines from Flowind and VAWTPower were installed on California wind farms, although most U.S. installations were horizontal axis types.

The 5 years from 1986 to 1990 involved consolidation and shakeout within the industry. The United States tax credit program ended in 1985, although earlier contracts meant wind turbines were still being installed in California, but not at the earlier fast pace. The United States had fewer than 10 manufacturers in 1990; the only major producer was U.S. Windpower.

U.S. federal R&D support for wind energy fell to a low of $8 million in 1988. However, Europe increased their support for wind energy. Japanese companies, especially Mitsubishi, entered the world market and were determined to be major manufacturers. Many of the earlier, large megawatt units were prototypes developed with U.S. government funding, but by the end of the decade, development was driven by the market as wind turbines increased in size above 100 kW.

Over half of the federal funding for wind energy from 1973 to 1990 ($350,000,000) was spent on the development of large wind turbines. This program was largely a failure because it proceeded to the next stage without fully developing the wind turbines from the previous stage. Design of wind turbines was much more difficult than aerospace engineers anticipated, and the aerospace industry was more interested in cost-plus government contracts than in developing commercial products. All the DOE prototypes were dismantled because of failures or excessive O&M costs.

10.8.2 1990–2000

World energy production in 1995 was estimated at 5 TWh/year, from over 22,000 wind turbines with an installed capacity of around 4 GW. The AWEA set a very optimistic goal for the United States of 10 GW by 2000. This was not achieved, although wind energy activity in states other than California increased due to the new production tax credit (PTC) incentive. The PTC was $0.015/kWh for 10 years, with an inflation factor for wind farms installed in later years. The PTC has been extended a number of times. (from 2017 to 2019, with phase-out schedule of 80-60-40%).

The Sandia National Laboratory manages the DOE program for VAWTs. A 34-m VAWT test bed, 500 kW, was tested at the USDA site at Bushland, Texas, from 1988 to 1998 (Figure 10.15).

FIGURE 10.15 Vertical axis wind turbine, 34-m test bed at USDA-ARS at Bushland, Texas. The VAWT is rated at 500 kW, peak power 625 kW. (Photo courtesy of USDA-ARS.)

The DOE program, managed by the NWTC, changed its focus to assistance and R&D to allow U.S. industries to meet foreign competition through the Advanced Wind Turbine Program (AWTP) [73–75].

Another measure in the United States was the EPRI/DOE Wind Turbine Performance Verification Program that was to provide a bridge from utility-grade development programs to commercial purchases. The 1995 goal of the AWTP was to develop wind turbines for class 3 wind regimes (5–5.5 m/s average at 10 m height) to produce electricity at $0.03 to 0.04/kWh, with O&M costs of $0.005/kWh. Another DOE R&D project goal was to achieve wind energy cost to $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 the industry and installation of wind turbines. More consolidation occurred and some manufacturing shifted from Denmark. The manufacturers of two-blade, light-weight systems (Carter, for example) went out of business. Vergnet in France and Wind Energy Solutions (formerly Lagerwey) in The Netherlands are selling commercial machines, and prototypes are still being tested. No VAWTs were produced for the wind farm market. This period was characterized by:

1. Continued rapid growth of the wind industry. Sizes of wind turbines increased from 200 kW to MW. Countries outside the United States and Europe installed wind farms; India installed 1,220 MW by the end of 2000.
2. European manufacturers dominated the market for large wind turbines.
3. Offshore wind farms were installed in Europe.
4. Large wind turbines with no gearboxes were developed.
5. The major United States manufacturer of large wind turbines (Kenetech) went out of business. The remaining manufacturer (Zond) was purchased by Enron and renamed Enron Wind.

The Utility Wind Integration Group in the United States published a number of brochures [76] on all aspects of the wind industry. This information is primarily for planners who work for utility companies and for policy makers in state governments.

10.8.3 2000–2010

Wind turbines were considered during the planning processes for new electric plants in many countries. Europe continued to lead in installed capacity, development of multimegawatt turbines, and

manufacturing. Global producers of equipment for electric power plants, General Electric (Enron) in the United States, and Siemens (Bonus) in Germany, became manufacturers by purchasing wind turbine producers. Vestas absorbed NEG-Micon and remains the leading manufacturer of large wind turbines. The large three-blade, full-span, variable-pitch, upwind machines dominated the market.

The most economical sizes for wind turbines have not yet been determined. The trend for the wind farm market has been larger machines. However, in many locations, especially on islands and at other remote areas, the lack of cranes limits the installation of megawatt wind turbines. Larger wind turbines are now being developed for offshore use.

The U.S. production tax credit and the Renewable Portfolio Standard in Texas led to a resurgence of wind farm installations. In 2006, Texas (Figure 10.16) surpassed California in installed capacity, and a number of other states have passed renewable portfolio standards. The late passage of the production tax credit meant that few wind turbines were installed that year (Figure 10.16). Because no wind turbines from the DOE program became major players in the commercial market, the research thrust by 2006 changed to assist manufacturers through a program called the Low Speed Wind Technology Project. The cost-shared R&D projects included a 2.5-MW wind turbine of Clipper Windpower, a modular power electronics package that can be scaled for small to megawatt wind turbines, a 1.5 MW direct-drive generator from Northern Power Systems, and a prototype multimegawatt low-wind-speed turbine from GE.

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: solar, wind, hydro, and biomass. Many of these sources will require hybrid systems with batteries and diesel for firm power. Large lending institutions like the World Bank and national government aid programs now understand that they have alternatives to large-scale projects for producing power. Also, more U.S. companies make small wind turbines and China expanded its production of small wind turbines.

Landowners now harvest wind much as they harvest the sun to produce crops. Because financing large wind power plants requires millions of dollars, landowners usually lease the land and receive royalties from the energy produced by wind turbines, similar to the practice in the oil and gas industry. The difference is that wind resources can be determined before large amounts of money are invested. Most importantly, the resource will not be depleted.

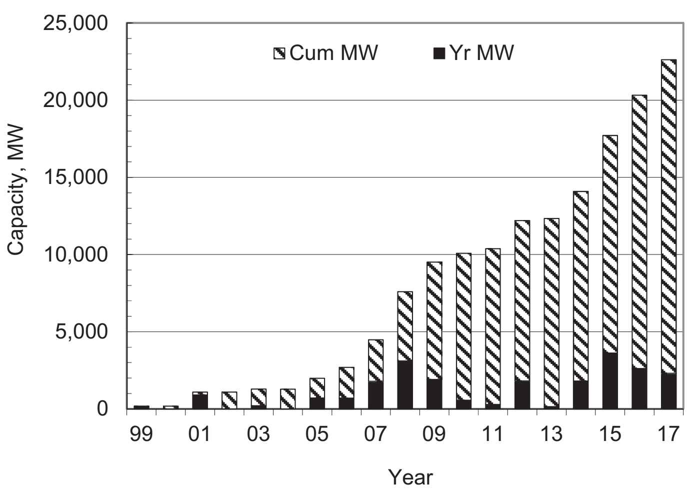


FIGURE 10.16 Wind farm capacity in Texas. Bars represent capacity installed for year. Stripes represent cumulative capacity.

10.8.4 2010–Onward

From information available through 2016, the major change has been the rapid growth of wind farms in China to 188 GW. Over the same period, Europe installed 168.5 GW and the United States installed 86.5 GW. The number of wind farms increased markedly in other parts of the world, for example, New Zealand now has 19 wind farms with a combined capacity of 690 MW [77]

Vestas continues to lead in cumulative production. Due to the huge market in China, three Chinese manufacturers ranked among the top 10 in terms of cumulative production (Table 10.3). Note that the 10 manufacturers have almost 80% of the market and Siemens-Gamasa replaced Vestas as the leading manufacturer in 2017. More megawatt wind turbines with direct drive and permanent magnet generators have been installed. Sizes, especially for offshore, and hub heights continue to grow. Vestas is installing 3.45-MW wind turbines in Thailand with a hub height of 162 m (530 ft) for a low wind regime and Max Bögl Wind is installing four wind turbines with a hub height of 178 m (584 ft).

The U.S. NREL research program for support of wind energy in the early part of the decade focused on offshore wind, mid-size and small wind turbine development, and gearbox reliability. In 2017 it was land-based, distributed, and offshore wind plus grid integration and market acceleration. Each area has subset work [78]. Sandia is focusing on increasing the viability of wind technology by improving performance and reliability, reducing cost, and enhancing blade design and manufacturing techniques [79]. For offshore wind, they are designing a segmented ultralight morphing rotor (200 m blade) for a 50-MW turbine. A Wind & Water Power Newsletter is available. Pacific Northwest National Laboratory research areas include distributed wind, atmospheric remote sensing, modeling, and wildlife & wind interactions [80].

The Internet makes a lot of information available about the development and commercial production of wind turbines of 5–10 MW. In 2012, Vestas introduced an 80 m blade for the V164 8.0-MW offshore unit. Siemens makes a 75 m blade (Figure 10.17) for its 6-MW offshore unit. Alstom uses an LM Wind Power 73.5 m blade on its 6-MW offshore unit. As of 2018, MHI-Vestas V164 (9.5 MW) has the largest rated power while the Adwen AD-180 has the longest blade at 88.4 m (www.windpowermonthly.com/10-biggest-turbines). Some analysts predict wind turbines up to 20 MW primarily for the offshore market, with others working on the design of wind turbines with rated power of 50 MW and a blade length of 200 m. Denmark has a national test center for large turbines with 7 pads to be expanded to 10 pads [81]. Turbines under test range from 2 to 7 MW and a 9-MW turbine was under test offshore. Community wind will increase as local investors and entities install small wind farms and/or smaller units in areas of less demand. Distributed wind will also continue to grow, primarily due to incentives by nations and states.

FIGURE 10.17 Mold for a Siemens 75-m blade. (Photo courtesy of Siemens.)

Small wind production is still dominated by China, followed by the United States and Europe, in terms of capacity (Figure 10.2). Although no large VAWTs are used in commercial facilities, many small VAWTs are on the market. From 2018, small wind will be challenged by the cost comparison of PV. It is also easier to operate and maintain small PV systems.

Two markets that have not expanded as expected were wind–diesel and village power. Despite the large number of wind–diesel systems installed in Alaska in 2012, the number in the rest of the world has not expanded much. The primary problems of village power are the nascent aspect, financing, and lack of infrastructure. Without massive government support, that market will consist mainly of prototypes and demonstration projects.

The United States had a strong market for utility scale wind farms; at the end of 2017 there was 89 GW from over 54,000 turbines (data includes Guam and Puerto Rico), and 13.3 GW is under construction. Texas still led the nation with 22.6 GW and had 4 GW under construction, primarily due to construction of high voltage transmission lines from windy areas to load areas of the state (see Section 11.8).

10.9 STORAGE

Much of the material in this section was taken from *Introduction to Renewable Energy* [82, Chap. 13]. Energy on demand comes from stored energy. The most common storage methods are dams, batteries, and biomass. Fossil fuels store solar energy from past geological ages. If a way could be found to store energy cheaply, we would have no need to construct new electrical power plants for some time. Storage is a billion-dollar idea and anyone who devises an economical method to store energy will be richer than Bill Gates.

Economic storage would allow energy in existing power plants to be stored during periods of low demand [83], and wind farms could provide some firm power. In general, the efficiency of storage systems is around 60–70%. Energy cannot be created or destroyed, it can only be transformed from one form to another. In reality, energy can be stored only as kinetic energy or potential energy. Kinetic energy storage can be achieved by flywheels or as heat (thermal storage). Dump loads (resistance heating of water) for storing heat are generally used in wind–diesel systems in cold regions. Compressed air is a mixture of mechanical and thermal change. Super (high rpm) flywheels made of composite materials to ensure strength have been used in wind–diesel systems, uninterrupted power supplies, and as prototypes on buses.

Potential energy arises from interactions such as gravity, electromagnetic forces, and weak and strong nuclear reactions.

We will now consider gravitational and electromagnetic concepts for storage systems. Most potential gravitational energy comes from water sources (dams, tidal basins, and pumped storage). Electromagnetic interactions include chemical reactions, phase changes, magnetic systems such as superconductor magnetic energy storage (SMES), electric devices (capacitors), and mechanical methods (springs). Chemical storage is through batteries, photosynthesis, and production of methane, hydrogen, fertilizers, and other compounds. Gas storage requires high pressure, conversion to liquid state, or inclusion in a chemical compound, for example, storing hydrogen in metal hydrides. Of course, solar energy is stored in chemical compounds such as foods and fibers. Solar energy is also converted into sugars, starches, and cellulose that are liquid precursors for biofuels.

The main components to consider in designing a storage system are (1) energy density, (2) efficiency and rates of charge and discharge, (3) lifetime (number of cycles), and (4) economics and application. Different storage technologies can accommodate power and/or energy. Energy density, size, and weight are important factors for some applications (Figure 10.18). Liquid fuels have large energy density while hydrogen gas has low energy density.

Storage efficiencies generally range from 50 to 80%, and lifetimes vary widely from 100 years for dams, to 5–10 years for lead acid batteries in a PV system and less than an hour for non-rechargeable batteries (Figure 10.19). The maximum rate and best rate of charging and discharging

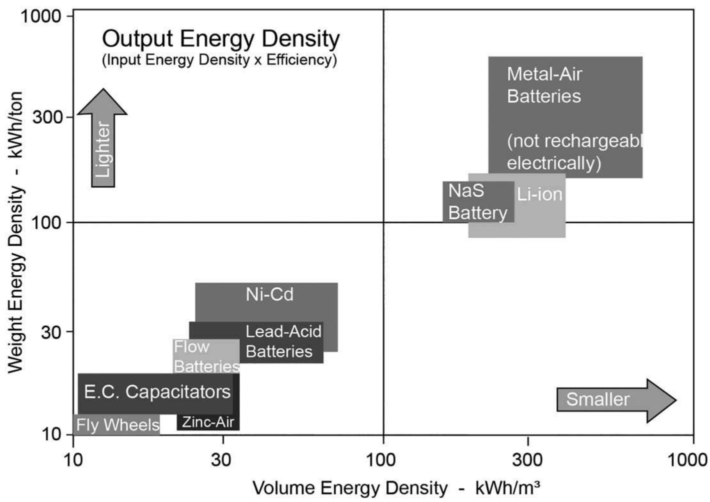


FIGURE 10.18 Energy density by weight and volume for electric storage. (From the Electricity Storage Association. With permission.)

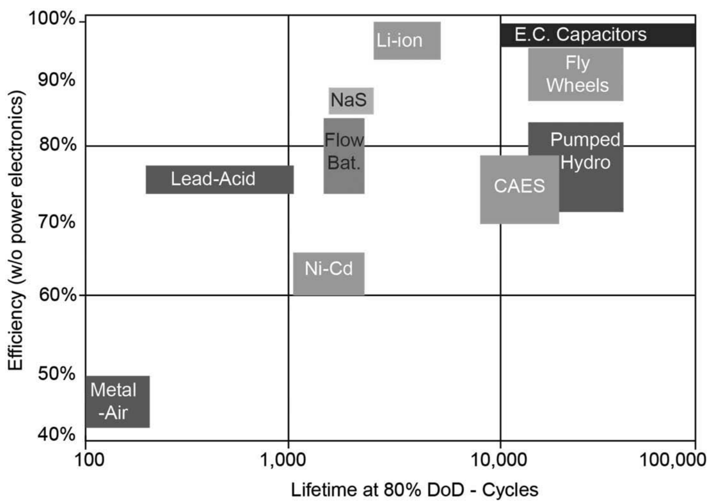


FIGURE 10.19 Efficiency and lifetime for various electric storage systems. CAES efficiency is for the storage only. (From the Electricity Storage Association. With permission.)

storage relate to the type and use of storage (Figure 10.20). The inclusion of energy storage in an application and the type of storage are driven by economics and specific power and energy (Figures 10.21 and 10.22).

Fast charging stations, which can charge an electric car to 80% in 30 minutes are now available on some interstate highways in the United States (you can make a cross-country trip in your Tesla with careful route planning). This demonstrates how versatile liquid fuels are for transportation. Also, the requirements for storing high power for a short time differ from the requirements for storing energy for a few days. For utilities, large storage systems are limited to pumped storage and compressed air energy systems (CAES). However, battery systems for power shaving, conditioning, and reducing the variability from renewable energy sources have been installed on wind and solar systems. Pumped hydro and compressed air have long lives over many cycles.

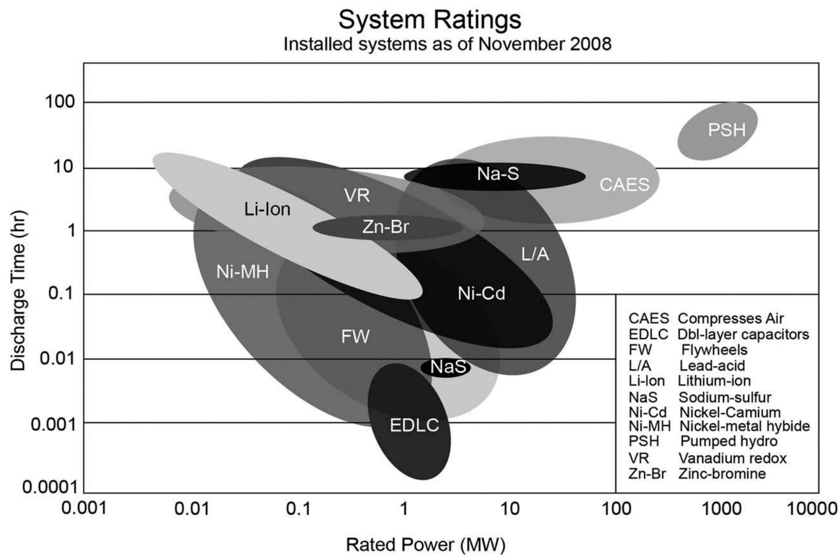


FIGURE 10.20 Discharge times and rated power of installed electric storage systems. (From the Electricity Storage Association. With permission.)

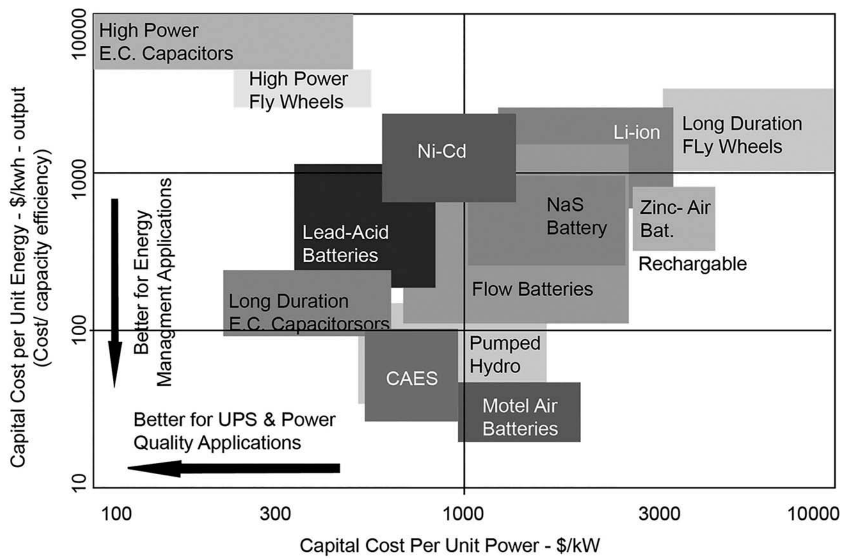


FIGURE 10.21 Capital costs for electric storage systems. (From the Electricity Storage Association. With permission.)

Batteries are the most common storage devices for remote village power systems and stand-alone systems. A comprehensive report on energy storage solutions and applications for island communities [84] discusses case studies and various scenarios and strategies. It also contains estimates of size ranges and costs, capital cost (dollars per kilowatt), levelized cost of storage (dollars per kilowatt-hour), and annual operating costs (dollars per kilowatt per year). The levelized cost for battery storage ranged from a low of $0.05 to $0.15 for sodium–sulfur (NaS) batteries to $0.30 to 0.45/kWh for lithium ion batteries.

The electricity produced by a generator cannot be stored. Energy in minus energy losses is the demand. Generation supplies that amount of demand, which varies by time of day and season.

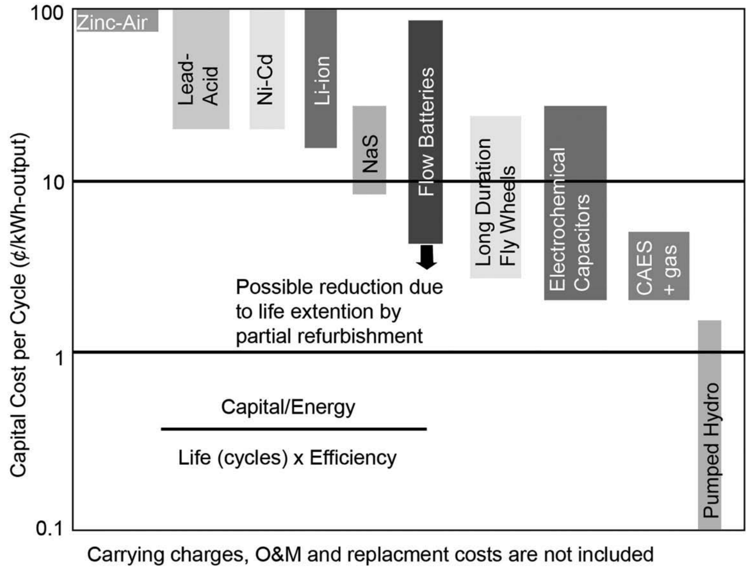


FIGURE 10.22 Carry charges for electric storage systems. (From the Electricity Storage Association. With permission.)

In addition, utility systems must meet peak demands and have spinning reserves for unforeseen conditions. If demand exceeds capacity, users are taken off the grid. In some parts of the world, rolling blackouts occur or electricity is available only for certain time periods. Finally, extreme events may force the shutdown of a total grid.

The U.S. DOE has a global energy storage database (interactive) on grid connected projects and relevant state and federal policies (www.energystorageexchange.org). As of 2016, there were 194 GW in 1,676 projects, most of it being pumped storage. The United States had the largest number of projects, 541, while China has the largest installed capacity, 32 GW.

An interesting storage system is the water battery of Max Bögl Wind. The bottom of the concrete cast tower serves a passive water reservoir for a pumped storage hydro power station situated in the valley below. Four turbines, 3.4 MW each, have hub heights from 155–178 m, the tallest as of 2018. The water battery reservoirs have 70 MWh of storage capacity and are connected by an underground penstock to the hydro power station in the valley below.

10.9.1 Compressed Air Energy Storage

Compressed air energy storage (CAES) is a peaking power plant that consumes 40% less natural gas than a conventional gas turbine that uses about two-thirds of the input fuel to compress air. In a CAES plant, air is compressed during off peak periods and then utilized during peak periods. Compressed air can be stored in underground mines or salt caverns that take 1.5–2 years to create by dissolving the salt. CAES has relatively low efficiency with a cost over $1,000/kW of storage.

10.9.2 Flywheels

Flywheels store rotational kinetic energy, which is proportional to the mass and the square of the rotational speed

$$E = 0.5 \times I \times \omega^2, \text{ J} \tag{10.1}$$

where I = moment of inertia (kg m^2) and ω = angular velocity (rad/s). For mass M and radius R, the moment of inertia for a ring is $I = M \times R^2$, and for a homogeneous disk, $I = 0.5 \times M \times R^2$.

Increasing the rpm increases the energy density so high-speed flywheels have rpm values in the tens of thousands. Low-speed flywheels are made from steel, and high-speed flywheels are made from carbon fiber and/or fiberglass. High-speed flywheels are housed in a low vacuum and use magnetic bearings to reduce or eliminate frictional losses. Advances in power electronics, magnetic bearings, and materials have resulted in direct current (DC) flywheels. In case of a material failure, the container has to retain the energy inside. Cycle efficiency is around 80%.

Installed cost of a flywheel depends on type and ranges from $150 to 400/kW. Another application for flywheels is for cranes at ship and rail yards, where they provide short-time high energy for lifting. Energy is returned to the flywheel as objects are lowered.

10.9.3 Batteries

Batteries are common all over the world for small power and energy applications. Batteries convert chemical energy into electrical energy using electrodes immersed in a medium (liquid, gel, or solid) that supports the transport of ions or electrolyte reactions at the two electrodes. Individual cells are placed in series for higher voltage and in parallel for higher current. Internal resistance and other factors cause losses during charging and discharging a battery.

The power is the product of the voltage and current, but batteries are generally specified by volts and storage capacity C_B which is related to stored energy. C_B is the amount of charge that a battery can deliver to a load. It is not an exact number because it depends on the age of the battery (number of cycles), temperature, state of charge, and rate of discharge. If you discharge a lead–acid battery to zero a few times, you have drastically reduced its lifetime. As a first approximation, the energy is

$$E = V \times C_B\,, \text{ J} \tag{10.2}$$

where V = voltage and C_B = battery capacity in amps-hour.

Example 10.1

A 12 V battery rated at 100 Ah could deliver 5 A for 20 h. $E = 12 \times 10$ Wh or 1.2 kWh. However, at a faster discharge rate, the values would be lower: 85 A for 10 h, 70 A for 5 h.

Decreased temperature results in less battery capacity and for a lead–acid battery, storage capacity decreased around 1% for every 1°C drop in temperature. Remember those very cold mornings when the battery just had enough juice to start your car? Explosions from short circuits, generation of hydrogen, and disposal of used batteries and toxic chemicals are problems.

10.9.3.1 Lead Acid

Lead acid batteries are low cost and widely used technologies for power quality, uninterrupted power supply (UPS), and some applications for spinning reserves. However, their use is limited for large amounts of energy storage for utilities, primarily due to their short cycle lives. As noted, rates of charge and discharge (Figure 10.19) affect capacity (fast rate, fewer volts) and depth of discharge affects life (Fig. 10.20) so the trade-off is between the cost of new batteries and lifetime. Even with that disadvantage, lead–acid batteries are common energy storage facilities for remote village power and stand-alone and remote wind systems. Examples of lead–acid systems are a 10 MW 4 h system in Chino, California; a 20 MW, 40 min system in San Juan, Puerto Rico; and a 3.5 MW, 1 h system in Vernon, California.

Some useful battery practices for small renewable systems are:

- Do not add new batteries to old sets.
- Avoid more than two (three at most) parallel strings.
- Do not use different types of batteries in the same set.
- Keep cable lengths the same.
- Keep all components clean and all connections tight.
- Follow the manufacturer's recommendations for charging and equalization.
- Do not wear jewelry when working on batteries.
- Use insulated tools.
- Wear protective clothing and eye protection when working on batteries.
- Do not smoke or generate sparks around batteries.
- Maintain a battery log.

In general, car batteries are not suitable for storage in renewable energy systems, although they are available and have been used for some small wind systems.

The 5 min ramp rate at the Hampton Wind Farm (1.3 MW), New South Sales, Australia, is smoothed with an advanced system composed of lead acid batteries and capacitors. Advanced lead acid batteries (1.6 MWh) replaced a flow battery system at King Island, Tasmania, Australia.

A battery system consisting of modules of power cells (12 V, 1 kWh, dry cell battery) was installed at the Notrees Wind Farm in Texas to mitigate the variability of the wind power. The storage system consists of 24, 1.5-MVA/1-MWh modules for total of 24 MWh. The cost of the system was $43.6 million (2012 information). In 2016–2017 the lead-acid batteries were replaced with lithium ion batteries. Two other systems based on the same technology were installed in Hawaii. A 15-MW/10-MWh battery system was installed at the 30-MW Kahuhu wind farm on Oahu, and a prototype 1.5-MW/1-MWh system was installed to control the ramp rates of 3 MW of wind turbines at a 30-MW wind farm on Maui. The systems provide responsive reserves and ramp control (rates to 1 MW/min) to reduce curtailment and increase energy delivered by 70%. The system in Kodiak, Alaska has diesel (10 MW), hydro (23 MW), wind (9 MW), and battery storage (3 MW) for frequency control. Lead acid batteries are now being replaced by lithium ion batteries. Eigg Island, Scotland is almost all supplied by renewable energy; hydro 110 kW, wind 24 kW, PV 32 kW, diesel 128 kW, and battery 212 kWh.

10.9.3.2 Lithium (Li) Ion

The main advantages of Li ion batteries compared to other advanced batteries are (1) high energy density (300 –400 kWh/m^3, 130 kWh/ton), (2) high efficiency (almost 100%), and (3) long cycle life (3,000 cycles at 80% depth of discharge [DOD]). Li ion batteries have captured 50% of the small portable market and hybrid and electric vehicles are the main drivers behind their increased use.

The Tehachapi wind energy storage demonstration project is a 8 MW/32 MWh Li ion battery system to improve grid performance and integration with the large wind farms in the area. The cost of the project is around $54 million. A 2 MW system to enhance stability of the grid is installed near the Elbow Creek Wind Farm in Texas.

10.9.3.3 Sodium–Sulfur

Performance factors for commercial NaS battery banks are (1) capacity of 25–250 kW per bank, (2) 87% efficiency, and (3) lifetime of 2,500 cycles at 100% DOD or 4,500 cycles at 80% DOD. The cost is around $2,500/kW.

NaS batteries of over 270 MW at 6 h storage have been demonstrated at numerous sites in Japan. The largest installation is a 34-MW/245-MWh unit for a wind farm in Northern Japan. U.S. utilities have deployed around 20 MW for peak shaving, backup power, wind farm, and other applications. Presidio, Texas, frequently experienced power outages due to a long connection to the main grid via

a single, 60-year-old transmission line. A 4 MW/32 MWh NaS battery that stores enough electricity for the whole town was installed. The cost of the battery and substation was estimated at $23 million.

Xcel energy installed 1-MW battery storage next to an 11-MW wind farm. The 20, 50-kW modules store about 7.2 MWh—enough to power 500 homes for seven hours. For basic generation storage, the battery was discharged during on-peak periods and charged during off-peak periods at a rate proportional to power output of the wind farm. The optimal ratio of storage to wind for this operation should be 200–400 kW storage per megawatt of installed wind. The other operations tested were economic dispatch, frequency regulation, wind smoothing (ramp control), and wind leveling.

In Italy, a 35-MW battery stores the oversupply of wind energy generated in the south for the large power users in the north, thereby reducing transmission congestion and the curtailment of wind generation in the Italian grid.

10.9.3.4 Flow Batteries

A flow battery converts chemical energy into electricity. Electrolytes containing one or more dissolved electroactive species flow through an electrochemical cell. Additional electrolyte is stored externally, generally in tanks, and is usually pumped through the reactor, although gravity feed systems are also used. Power and energy ratings are independent of each other. Flow batteries can be recharged rapidly by replacing the electrolyte liquid while simultaneously recovering the spent material for reenergization.

Vanadium can exist in four different oxidation states. Vanadium redox batteries [86] use this characteristic in a battery that contains only one chemical electrolyte instead of two. Hydrogen (H^+) ions (protons) are exchanged between two electrolyte tanks through a permeable polymer membrane. The net efficiency of this battery can be as high as 85%. Current installations include:

- 1.5 MW, UPS system in a semiconductor fabrication plant in Japan
- 4 MW, 6 MWh output balancer, Tomaanae Wind, Hokkaido, Japan
- 0.25 MW, 2 MWh load leveler, Castle Valley, Utah
- 0.3 MW/1 MWh vanadium redox flow battery, 2 MWh lithium ion battery at community wind farm, Braderup, Germany
- 0.25 MW/1 MWh at Las Positas College, Livermore, California

10.9.4 Other Types of Batteries

Other types of batteries are metal–air, nickel–cadmium (Ni-Cd), zinc–bromide (Zn-Br), and even organic compounds. Metal–air batteries may be less expensive, but they are at the preproduction stage at which the consumed metal is mechanically replaced and processed separately. Recharge using electricity is under development, but metal–air batteries have lives of only a few hundred cycles and efficiency around 50%.

A Zn-Br battery has two different electrolytes that flow past carbon–plastic composite electrodes in two compartments separated by a microporous polyolefin membrane. Battery systems are available on transportable trailers (storage plus power electronics) with unit capacities of up to 1 MW (3 MWh for utility-scale applications). Some electric utilities are installing 5-kW/20-kWh systems for community energy storage.

10.9.5 Hydrogen Fuel Cells

A lot of information cites hydrogen as the fuel of future and discusses hydrogen storage [87, Chap. 11]. Although hydrogen has low environmental impact and can be produced by renewable energy sources, its major disadvantage is the low energy density per volume. Hydrogen has one-third the

energy content of methane. However, existing natural gas pipelines could carry about the same capacity because hydrogen has lower viscosity.

Fuel cells are much more efficient than internal combustion engines, but the infrastructure for producing fuel cell cars is at the nascent stage. If hydrogen is produced by wind energy systems (see Section 10.5) through electrolysis, transportation and storage become major factors. Hydrogen can be stored as a compressed gas or liquid (cooled to 20°K in non-pressurized containers) or by an extraction process. Storage in materials may involve adsorption (activated carbon), chemical compounds, compounds that can be reversibly transformed into other substances of higher hydrogen content, and metal hydrides that change hydrogen content with temperature.

Metal hydrides may be used in storage of hydrogen for vehicles powered by fuel cells. As a comparison, 100 kg of hydride can store around 500 MJ and 100 kg of gasoline provides 4,700 MJ of energy—a large difference. However, the efficiency of a hydrogen fuel cell is around 60% and that of a gasoline engine is around 20%. Hydrogen would produce fewer emissions and is essentially nondepletable. The production of hydrogen from water using wind and sun would be problematic in arid and semiarid areas that already lack water. Some considerations for hydrogen storage systems are:

- Ratio of mass of hydrogen to overall mass of storage and retrieval system
- Ratio of mass of hydrogen to total volume of storage and retrieval system
- Cycle efficiency
- Retention (amount of hydrogen remaining over long period)

Of course, as with other storage systems, economics (installed cost, O&M, replacement costs) are paramount. Other considerations are safety, ease of use, and infrastructure for transportation.

10.10 DECOMMISSIONING AND REPOWERING

Almost all commercial turbines installed in the 1980s and early 1990s had small rated capacity and they have or are reaching the end of design life. Nonoperational turbines should be decommissioned and dismantled. In general, for wind farms, the older turbines are removed and replaced by new turbines. This act is referred to as repowering. Sometimes the wind turbines have been refurbished for the distributed market. Reasons for dismantling are increased O&M, technological condition prohibits continued operation, little or no support from the original equipment manufacturer (spare parts unavailable or difficult to obtain), the need for space for repowering, or better production and economics of larger replacement turbines. The estimated O&M of turbines increases by 1.6% per usage year. Due to damage from an ice storm to units and transmission line, the Texas Wind Power Project (109 units) and the Delaware Mountain Wind Farm (38 units) were dismantled in 2014. Even though it is one of the best wind sites in Texas, there has been no plan to repower the site.

Decommissioning also includes site restoration that complies with permitting requirements. This includes removal of roads, ancillary structures, transmission lines, and may require removal of foundations to plow depth. The salvage value will pay for part of the decommissioning and restoration. The three MOD-2s (Figure 10.14) were taken down by placing explosives at the tower base. For small wind turbines, the attachment to the foundation is released, a cable is attached near the top, and the turbine is pulled over. We have seen some small wind turbines, especially prototypes, which are not working and should be taken down, however the owner does not want to pay the cost of removal.

Repowering means removing and replacing old turbines or upgrading components in existing turbines [88–90]. The new wind turbines are larger and are installed at greater heights, which gives much more production with fewer turbines. Economics in the form of subsidies are one of the major drivers for repowering in the United States (wind farm has reached or is past the 10-year limit for production tax credit) and Europe (feed-in tariff). In the United States, full repowering has occurred mainly in California, as those were the older wind farms with small capacity wind turbines.

Common partial repowering includes longer blades and upgrades to the gearbox, hub, main shaft, and main bearing assembly. Remember, energy production is proportional to the square of the diameter. Expected gain in energy production is 20–25% and could add another 20 years to the lifetime. Replaced components must be resold, recycled, or disposed. Although it is not repowering, upgrades to software, forecasting, and wake steering can increase performance.

In Europe, an estimated 76 GW of wind power will reach the end of operational life between 2020 and 2030. Therefore, repowering will be a major business. For example, in Germany repowering needs could reach 1 GW/year. A combination of subsidies and a substantial number of older turbines have made Germany and Denmark today's leading repowering nations. However, in Denmark, the total market will not be large as the total installed capacity is small.

In 2011 Denmark accounted for around 52% of the total global repowered capacity and Germany for 43%. Both had specific repowering incentives.

Denmark's first wind repowering program ran from 2001 to 2003. Owners of turbines smaller than 100 kW were able to install three times the capacity removed and receive a bonus on top of the normal feed-in-tariff for the first 5 years. For units of 100–150 kW, owners could install twice the capacity removed and receive the same treatment. Under this program, 1,480 turbines (122 MW) were replaced with 272 turbines (332 MW). The second Danish repowering scheme ran from 2008–2011 and offered a premium on top of the normal tariff for replacing up to 175 MW of old turbines with new machines that had at least double the capacity. At Rejsby Hede in Southern Jutland, 395 Vestas turbines rated at 600 kW were installed in 1996 and the plan is to replace them with 21–30 turbines rated at 3.2 MW or greater. By 2020 the Danes will be replacing 200 MW of old turbines with 1 GW of repowered capacity annually.

One of the larger German projects is at Schneebergerhof in the Rhineland-Palatinate region. Juwi replaced five Enercon E66 1.5-MW turbines with five 7.5-MW turbines. The new turbines produce more than six times the energy of the old turbines. The Tauern wind farm located in Austria is at 1,900 m above sea level. The wind farm had 13, V66 (1750-kW) turbines, which were replaced with nine V112 3.45-MW turbines. This will increase the capacity of the wind farm from 22.75 MW to 31.05 MW.

The Noordoostpolder wind farm (Figure 10.23) in the Netherlands consists of three projects (86 turbines, 429 MW) and three development parties [91]. NOP Agrowind and Westernmeerwind consist of around 100 agricultural entrepreneurs from the surrounding area and the third party is the sustainable energy company, innogy. Each party is responsible for the development, construction, and management of their part of the wind farm.

FIGURE 10.23 Repowering and decommissioning of Noordoostpolder wind farm. Notice small turbines in foreground to be decommissioned and empty pads from units taken down. Also, there are small units in the background. (© Innogy Noordoostpolder, Credit Klaas Eissens.)

- NOP Agrowind, 195 MW: 26 Enercon wind turbines (E-126, 7.5 MW) on land along the Westermeermeer and Noordermeer dikes.
- Westermeerwind, 144 MW: 48 Siemens wind turbines (3.0DD-108, 3 MW) in the water along the Westermeer dike (2 rows) and the Noordermeer dike.
- Innogy, 90 MW: 12 Enercon wind turbines (E-126) on land along the Zuidermeermeer dike (8) and the Westermeer dike (4).
- 50 300-kW Windmaster turbines that were installed along the dike in 1991 were removed.

10.10.1 United States

In California, by 2012, over 1,500 old turbines were removed and replaced with new turbines. At the Shiloh IV farm in California, 50 new turbines replaced 235, 100-kW turbines for an almost four-fold power increase. At Altamont Pass, 780 turbines were replaced with 34, 2.3-MW machines, and 9.5 km of electrical lines and 13 km of road were removed.

In 2017, MidAmerican Energy in Iowa repowered around 1,000 MW with new gearboxes and longer blades. MidAmerican estimates that the new turbines will generate between 19 and 28% more energy. GE Renewable Energy repowered three wind farms (162 units, rated at 1.5 MW) in Texas with longer blades and gearboxes and performance is expected to increase by 25%. NREL estimated that the U.S. repowering market could grow to $25 billion by 2030.

10.11 COMMENTS

Beside the emerging market of distributed systems, two other factors increased the market: green power and reduction of pollution. People can purchase green power at a premium, and a lot of that power is generated by wind turbines (Figure 10.24) or wind farms. A number of urban areas are in non-attainment areas for clean air, and one way to reduce pollution is by producing electricity from renewable energy.

The reduction of carbon dioxide emissions per the Kyoto Treaty is included in many nations' regulations, and policies have been updated due to the Copenhagen Accord. If trading in CO_2 becomes regulated in the United States, electricity produced by wind turbines will become more valuable and will eventually become the most cost-competitive power source on the market.

FIGURE 10.24 Two Vestas V47 660 kW on a ridge of the Hueco Mountains east in El Paso, Texas. Electricity is sold under a green power program. Notice the car at the base of the turbine. (Photo courtesy of Cielo Wind Power.)

Some wind applications are of interest because of prototype testing and commercial availability, for example, hydrogen production, compressed air storage, pumped hydro, stand-alone electric–electric systems for making ice and desalination plants. Wind hybrid systems are used for telecommunications and remote military installations. Many of these sites are accessible only by helicopter, so fuel costs are high.

An ultraviolet water purifier powered by renewable energy was tested by the USDA's ARS and AEI [88]. A controller was developed and five configurations were tested—two with photovoltaic cells (100 W), two with wind (500 W), and one hybrid wind–photovoltaic system. The photovoltaic-only system was more efficient and cost-effective than the wind-only system. However, the wind–photovoltaic system demonstrated more reliable power production. 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 ozone produced from electricity from wind–photovoltaic hybrid systems. These small systems use 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 photovoltaic energy, a small battery bank, and an inverter.

PROBLEMS

1. What is a wind-assist power system?
2. Go to Global Wind Energy Council (www.gwec.net). Which country has the largest installed capacity of wind power? How much capacity is installed?
3. Estimate the wind installed capacity 5 years in the future for the world and for your country.
4. Estimate the world capacity of offshore wind farms today.
5. Are there any small wind turbines in your region? If yes, how many? What is rated power? Stand-alone, or grid-connected?
6. Are there any wind distributed or community systems in your region? If yes, provide number of turbines and rated power for one project. If no, find information on the Internet for one system.
7. Should distributed wind systems receive incentives? If yes in your opinion, what incentives should they receive?
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 are the center's current R&D programs?
10. Go to the National Wind Technology Center NREL website. What are the center's non-R&D programs?
11. In your opinion, what are the major advantages and disadvantages of renewable village power?
12. Compare the annual efficiency of a farm windmill and a wind–electric system.
13. What factors contributed to the initial wind farm boom in California?
14. Which manufacturer is the largest supplier of megawatt wind turbines?
15. Go to two or three manufacturers' websites. State diameter, rated power, and tallest tower for their largest commercial wind turbines.
16. Does the utility from which you buy electricity have wind farms on its transmission lines? If yes, determine the number of turbines and rated power for one wind farm.
17. What are some applications of small wind turbines? Bergey Windpower has examples of applications, or use an example from the text.
18. In your opinion, why does the United States not have more manufacturers of large wind turbines?
19. Find two examples of wind–diesel projects on the Internet. State specifications of the systems.

20. Compare two criteria for flywheel and battery storage systems.
21. What is the general efficiency of large storage systems for wind farms?
22. Find an example of a large battery system for wind farms. What are the general specifications and cost?
23. List two advantages and two disadvantages of hydrogen storage for wind farms.
24. Find the closest community wind project to your area. List size, general specifications, and performance data.
25. Go to the Small Wind Certification Council website. How many companies produce certified wind turbines?
26. What are the two primary objectives of the U.S. Wind for Schools program?
27. Go to any website for community and/or distributed wind installations that publish performance online. How much energy has the project produced over what time period?
28. Suppose you want to partially repower a wind farm to increase production by 25%. Units are 1.5 MW with rotor diameter of 66 m. How much longer are the new blades?
29. State two reasons for repowering.
30. Google wind repowering. Pick an example, give brief description of project. Do not use examples from this text.

LINKS

Windfair Newsletter. Weekly email, http://w3.windfair.net).

U.S. DOE, EERE. WINDExchange Newsletter. Twice/month email, https://energy.gov/eere/office-energy-efficiency-renewable-energy.

North America Clean Energy. www.nacleanenergy.com.

The Wind Power. Month. www.thewindpower.net/index.php.

R. Nolan Clark. 2014. *Small Wind, Planning and Building Successful Installations.* Academic Press, New York.

P. Gipe. 2016. Wind Energy for the Rest of Us. www.wind-works.org/cms/.

HOMER Energy. https://www.homerenergy.com. Developer and distributor for HOMER software, microgrid and distributed energy system design.

Global Wind Energy Council. www.gwec.net . In addition to global statistics has an interactive map of capacity by country over time.

Islanded Grid Resource Center. http://islandedgrid.org.

Electricity Storage Association (http://energystorage.org). Check out the energy storage section.

World Bank, sustainable Energy for All (SE4ALL). https://datacatalog.worldbank.org/dataset/sustainable-energy-all.

Xiao Qing Dao Village Power Wind–Diesel Hybrid Pilot Project. www.nrel.gov/docs/fy06osti/39442.pdf.

REFERENCES

1. The Wind Power. Wind turbines and wind farm database. www.thewindpower.net.
2. Australia Wind Power. Wind power and wind farms in Australia. http://ramblingsdc.net/Australia/WindPower.html.
3. WindEurope. 2017. Wind energy in Europe: Scenarios for 2030. https://windeurope.org/wp-content/uploads/files/about-wind/reports/Wind-energy-in-Europe-Scenarios-for-2030.pdf.
4. Kansas Energy Information Network. Kansas wind energy. www.kansasenergy.org/wind_projects.htm RenewablesUK. Wind: state of the industry 2012. www.renewableuk.com.
5. Global Wind Energy Council. Global wind statistics 2017. http://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf.
6. 4COffshore. www.4coffshore.com.
7. WindEurope. 2017. Offshore wind in Europe. https://windeurope.org/about-wind/statistics/offshore/.
8. World Wind Energy Association. 2017. Summary, small wind world report. www.wwindea.org/wp-content/uploads/filebase/small_wind_/SWWR2017-SUMMARY.pdf.

9. U.S. DOE, EERE. 2016. Distributed wind market report. www.energy.gov/eere/wind/downloads/2016-distributed-wind-market-report.
10. C. Dou. 2017. China medium/small wind industry. Austrian Small Wind Conference 2017. Power Point provided by C. Dou.
11. RenewableUK. 2015. Small and medium wind report. www.renewableuk.com/news/304391/Small-and-Medium-Wind-UK-Market-Report-2015.htm.
12. National Wind Technology Center. Distributed wind research. www.nrel.gov/wind/distributed-wind.html.
13. Small Wind Certification Council. www.smallwindcertification.org.
14. E. Lantz, et al. 2016. Assessing the future of distributed wind: Opportunities for behind-the-meter projects. NREL/TP-6A29–67337. www.nrel.gov/docs/fy17osti/67337.pdf.
15. Utility Wind Integration Group Distributed Wind Impacts Project. www.uwig.org/ug.htm.
16. NREL. Distributed wind case study. www.nrel.gov/docs/fy12osti/53626.pdf.
17. EERE, WINDExchange, community wind. https://windexchange.energy.gov/markets/community.
18. L. Flowers. 2012. Community wind: one size doesn't fit all. www.awea.org/files/FileDownloads/pdfs/CW-Case-Study-PPT.pdf.
19. Northwest Wind Resource & Action Center, Community-scale 7 distributed wind. www.nwwindcenter.org.
20. Windustry. Community wind. http://windustry.org/community-wind.
21. Community wind development handbook. www.auri.org/2008/01/community-wind-study.
22. P. Mazza. 2008. Community Wind 101: A Primer for Policymakers. www.climatesolutions.org/sites/default/files/uploads/communitywind_101.pdf.
23. Juhl Energy. http://juhlenergy.com/our-projects#windprojects.
24. Windustry. Minwind III-IX. www.windustry.org/resources/minwind-iii-ix-luverne-mn-community-wind-project.
25. U.S. DOE, EERE, WINDExchange. Wind for Schools Project. https://windexchange.energy.gov/windforschools.
26. University of North Texas. http://studentaffairs.unt.edu/sustainable.
27. Northern Power Systems. Knowledge Center. www.northernpower.com/aboutus/knowledge-center/.
28. U.S. Department of Energy. America's schools use wind energy to further their goals. www.nrel.gov/docs/fy04osti/35512.pdf.
29. T. Galluzzo and D. Osterberg. 2006. Wind power and Iowa schools. www.iowapolicyproject.org/2006docs/060307-WindySchools.pdf.
30. Wind Powering America. Spirit Lake School District case study. www.nrel.gov/news/program/2012/1950.html.
31. Golden Spread Electric Cooperative. www.gsec.coop.
32. Fox Islands Wind Project. www.foxislandswind.com/index.html.
33. Basin Electric Power Cooperative. www.basinelectric.com/Facilities/PrairieWinds-1.
34. Berkshire Wind Power Co-op. Using wind wisely. www.berkshirewindcoop.org.
35. Hull Wind. www.hullwind.org.
36. Atlantic County Utilities Authority. www.acua.com/green-initiatives/renewable-energy/windfarm/.
37. Austin Energy, Environment. https://austinenergy.com/ae/about/environment/renewable-power-generation.
38. Middelgrundens Vindmφllelaug. www.middelgrunden.dk/middelgrunden/?q=en.
39. Energy Academy, RE-Island. https://energiakademiet.dk/en/vedvarende-energi-o/.
40. German Wind Energy Association. Community wind power: local energy for local people. www.wind-energie.de/fileadmin/redaktion/dokumente/dokumente-englisch/publications/bwe_broschuere_buergerwindparks_engl_10-2012.pdf.
41. Energy4All. Community ownership. https://energy4all.co.uk/community-ownership/.
42. EOLOP, World wind cooperative projects. www.viuredelaire.cat/en/the-project/world-wind-cooperative-projects.html.
43. Hepburn Wind. http://hepburnwind.com.au.
44. Denmark Community Windfarm, Western Australia. http://denmarkcw.wixsite.com/home.
45. R. Hunter and G. Elliot. 1994. *Wind Diesel Systems: A Guide to the Technology and Its Implementation*. Cambridge University Press: Cambridge, U.K.

46. International Wind–Diesel Workshop; Wind–2009. www.pembina.org/pub/wind-diesel-workshop-2009.
47. G. Seifert and K. Myers. 2006. *Wind–Diesel Hybrid Power, Trials and Tribulations at Ascension Island*. Paper presented at Proceedings of European Wind Energy Conference. http://slideplayer.com/slide/4554740/.
48. K. Muhel. 2013. Synergies towards a renewable energy system in Cape Verde-the case of informal settlements of the capital city, Praia. *Masters Thesis*, Aalborg University. http://projekter.aau.dk/projekter/files/260119885/Kata_Muhel_MasterThesis_SusCi2017.pdf.
49. THEnergy. Sustainable consulting. Renewable on Islands. www.th-energy.net/english/platform-renewable-energy-on-islands/database-solar-wind-power-plants/.
50. R. Stromberg. 2013. Alaska wind energy barriers, Alaska Wind Energy Workshop; Unalakleet wind–diesel data analysis; Alaska Energy Authority overview.
51. Alaska Energy Authority. 2018. Renewable Energy Fund Status Report. www.akenergyauthority.org/Portals/0/Programs/RenewableEnergyFund/Documents/2018-REF%20Status%20Report.1.27.18.pdf.
52. Hydro Tasmania's King Island Renewable Energy Integration Project. www.kingislandrenewableenergy.com.au.
53. ABB. Microgrid references. www.pcorp.com.au.
54. Vergnet. www.vergnet.com.
55. Danvest. Hybrid power: wind–diesel www.danvest.com/home.pp.
56. Canada Natural Resources. Ramea Island. www.nrcan.gc.ca/energy/renewable-electricity/wind/7319.
57. StatoilHydro. Experiences from the wind-hydrogen plant at Ursira. www.globalislands.net/greenislands/docs/norway_14Nakken.pdf.
58. WEIcan. Wind–Hydrogen village. www.treehugger.com/clean-technology/prince-edward-island-wind-hydrogen-village.html.
59. NREL Wind to Hydrogen Project. www.nrel.gov/hydrogen/wind-to-hydrogen.html.
60. V.C. Nelson et al. 2001. *Wind Hybrid Systems Technology Characterization Report*. West Texas A&M University and New Mexico State University: Canyon, TX and Las Cruces, NM. www.researchgate.net/profile/Robert_Foster6/publication/267362970_WIND_HYBRID_SYSTEMS_TECHNOLOGY_CHARACTERIZATION/links/54c7d0ab0cf238bb7d0b5318/WIND-HYBRID-SYSTEMS-TECHNOLOGY-CHARACTERIZATION.pdf.
61. National Wind Technology Center. Energy analysis: HOMER. https://www.homerenergy.com.
62. Bergey Windpower. http://bergey.com/global-projects.
63. C. Dou, Ed. 2008. Capacity building for rapid commercialization of renewable energy in China. CPR/97/G31, UNDP/GEF, Beijing.
64. V. Nelson, R.N. Clark, and R. Foster. 2004. *Wind Water Pumping*. West Texas A&M University: Canyon, TX. CD. Contact kstarcher@wtamu.edu.
65. J. A.C. Kentfield. 1996. *The Fundamentals of Wind-Driven Water Pumpers*. Gordon & Breach: Amsterdam.
66. J. van Meel and P. Smulders. 1989. *Wind Pumping: A Handbook*. Technical Paper 101. World Bank: Washington, DC.
67. Turbex. http://turbextrading.co.za.
68. R.N. Clark and F.C. Vosper. 1984. Electrical wind-assist water pumping. In *Proceedings of Third ASME Wind Energy Symposium*, p. 135.
69. R.N. Clark. 1985. Wind–diesel hybrid system for pumping water. In *AWEA Proceedings of Windpower Conference*, p. 221.
70. M. Bergey. 1990. Sustainable community water supply: A case study from Morocco. In *AWEA, Proceedings of Windpower Conference*, p. 194.
71. R. Thomas and D. Baldwin. 1981. The NASA–Lewis large wind turbine program. SERI/CP-635-1340. In *AWEA Proceedings of Fifth Biennial Wind Energy Conference and Workshop*, p. 39.
72. V. Nelson. 1984. A history of the SWECS industry in the U.S., *Alternative Sources of Energy*, March/April, p. 20.
73. A.S. Laxson, S.M. Hock, W.D. Musial et al. 1992. An overview of DOE's wind turbine development program. In *AWEA, Proceedings of Windpower Conference*, p. 426.
74. R. Lynette. 1992. Development of the WC-86 advanced wind turbine. In *AWEA, Proceedings of Windpower Conference*, p. 450.

75. C. Coleman. 1993. Northern Power Systems advanced wind turbine development program. In *AWEA, Proceedings of Windpower Conference*, p. 152.
76. Utility Wind Integration Group. www.esig.energy.
77. New Zealand Wind Energy Association. Wind farms operating and under construction. www.windenergy.org.nz/operating-&-under-construction.
78. NREL Wind. www.nrel.gov/wind/research.html.
79. Sandia National Laboratory. Wind energy. http://energy.sandia.gov/energy/renewable-energy/wind-power/.
80. PPNL. Wind research. https://wind.pnnl.gov.
81. Technical University of Denmark. Wind energy. www.vindenergi.dtu.dk/english/test-centers/oesterild.
82. V. Nelson and K. Starcher. 2016. *Introduction to Renewable Energy*, 2nd ed. CRC Press: Boca Raton, FL.
83. Energy Storage Association. http://energystorage.org/energy-storage.
84. International Renewable Energy Agency. 2012. Electricity storage and renewables for island power: A guide for decision makers. www.irena.org/DocumentDownloads/Publications/Electricity%20Storage%20and%20RE%20for%20Island%20Power.pdf.
85. R. Foster, M. Ghassemi, and A. Cota. 2010. *Solar Energy: Renewable Energy and the Environment*. CRC Press: Boca Raton, FL.
86. PowerPedia. Vanadium redox batteries. https://peswiki.com/powerpedia:vanadium-redox-batteries.
87. A. Vieira da Rosa. 2009. *Fundamentals of Renewable Energy Processes*, 2nd ed. Academic Press: New York.
88. J. Tchou, G. Howard Larsen, and E. Moroz. 2017. Seven considerations when deciding to repower (or repair). North American WindPower. https://issues.nawindpower.com/article/seven-considerations-deciding-repower-repair.
89. U.S. EIA. 2017. Repowering wind turbines adds generating capacity at existing sites. www.eia.gov/todayinenergy/detail.php?id=33632&src=email.
90. L. Buchsbaum and S. Patel. 2016. Wind turbine repowering is on the horizon. *Power Magazine*. www.powermag.com/wind-turbine-repowering-horizon/?pagenum=1.
90. B.D. Vick et al. 2003. Remote solar, wind, and hybrid solar/wind energy systems for purifying water. *Journal of Solar Energy Engineering,* 125, 107.
91. Windpark Noordoostpolder. www.windparknoordoostpolder.nl/en/.

11 Institutional Issues

The interconnection of wind turbines to utility grids, regulations covering installation and operation, and environmental concerns are the main institutional issues. The U.S. National Energy Act of 1978 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) rated 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 among small power producers, independent power producers, and utilities.

The National Energy Strategy Bill of 1992 covered wheeling power over utility transmission lines. The Federal Energy Regulatory Commission (FERC) can order the owners of transmission lines to wheel power at costs determined by FERC. Utilities are allowed to recover all legitimate, verifiable economic costs incurred in connection with the transmission and necessary associated services including an appropriate share of costs incurred for enlargement of transmission facilities.

From a wind power view, this legislation is very important because the Great Plains region is a major source of wind energy. Transmission to major load centers is needed for that power to be utilized. In 1997, FERC opened transmission access.

The state deregulation of the electric utility industry changed the competition for renewable energy. Deregulation means that integrated electric utility companies are split into the areas of power generation, transmission, and distribution and consumers are free to 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 (now in place). He conducted a paper study of a 2-GW wind farm in Kansas that could have a capacity factor of 60%. The first large wind plant (initially 40 MW, expanded 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 (project decommissioned in 2014). In 2010, the Electric Reliability Council of Texas (ERCOT) formed competitive renewable energy zones (CREZ). As a result new transmission lines increased the transmission of power, primarily wind.

11.1 AVOIDED COSTS

Avoided costs were established by the public utility regulatory bodies in all states. The Federal Energy Regulatory Commission (FERC) defines avoided cost as the incremental or marginal costs to an electric utility of energy or capacity that the utility would have to generate or purchase from

another source if it did not buy power from a qualifying facility. Avoided cost reflects the cost of new power plants, not the average cost of plants already installed. The avoided cost includes both present and future costs.

However, many utilities claimed they did not need new generation. In those cases, avoided costs were only fuel adjustment costs. A utility may set a standard purchase rate for qualifying facilities under 100-kW capacity. Contact your public regulatory body for more information about small or independent 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 10 years, while Standard Offer 1 was variable, depending on the cost of fuel. One of the reasons that wind farms started in California was the high avoided cost set by the PUC.

The fuel adjustment cost (avoided 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 Xcel Energy). Until 2008, the avoided cost was still the fuel adjustment cost. In 2008, the fuel adjustment cost increased to around $0.05/kWh due to the increased price of natural gas. Since then, the fuel adjustment cost has declined due to the boom in natural gas produced from shale formations.

In 2011, the reduction in the price of natural gas made the economic justification for new wind farms more difficult because the value of fixed contracts for wind power from independent producers declined. However, the wind market continued to grow, for example in 2016, wind provided 20% of the energy for Xcel as they had 6.3 GW of wind on their system. The cost of wind power has declined as turbine technology has improved so Xcel is planning for an additional 3.7 GW by 2021. Due to renewable portfolio standards, primarily by states, utilities are actively using or building wind farms and some utilities consider wind a hedge against future volatility of natural gas costs. Because natural gas emits less carbon dioxide than coal, it is touted as the fuel for electricity and transportation and as a bridge toward renewable energy.

11.2 UTILITY CONCERNS

A few wind turbines on a large utility grid would present no problems with the amount of power. The power would be considered a negative load—a conservation device equivalent to turning off a load. For large penetration, 20% and greater, other factors such as the variability of the wind and dispatching become important. Utilities are concerned with safety and the quality of power from wind turbines on their grids.

11.2.1 Safety

Safety is a primary consideration particularly from energizing dead utility lines, grounding equipment, and lightning. The safety issue has been resolved and large numbers of wind turbines have been connected safely to utility lines. Induction generators have to be energized by the utility line and they do not operate when a fault occurs on the line. Inverters have sensors that disconnect them from utility lines in case of a loss of load.

Of course, safety during installations and operations is a concern, as it is for any industrial enterprise. High voltages, rotating blades and machinery, large weights, and work at heights of 50 to 100 m make for a hazardous workplace. Safety is the first consideration for working around wind turbines. One rule is to never climb a meteorological or turbine tower if you are the only person at a site. Although the large wind turbines have taller towers, climbing inside a tubular tower is easier than climbing on a truss or met tower, especially in inclement weather.

The Caithness Wind Farm Information Forum in the U.K. developed a summary and list of wind turbine accidents up to June 30, 2018, that shows accident type, turbine, date, and location [5]. The summary notes 2,265 accidents that include 184 fatalities.

The most common causes are falls from turbines. Of the fatalities, 112 were industry workers, and 72 were public fatalities, most of which resulted from accidents during transportation of wind turbine components. Surprisingly, four people were killed when an airplane crashed into a wind turbine during a fog. The largest number of accidents arose from blade failure; the second most common cause was fire. Because of turbine height, a fire cannot be extinguished. It can only be watched until it burns out.

Safety data, especially early data, are not comprehensive. For example, the Alternative Energy Institute (AEI) at West Texas A&M University and the U.S. Department of Agriculture (USDA) tested more than 80 prototype or first production wind turbines and noted a number of failures, from lost blades to complete destruction, that are not included in the database. The longest distance for a blade failure was 56 m from a small (4-kW) wind turbine, which is quite a bit shorter than the documented 400 m noted in the summary. A fatality that was included on the database occurred when the top of a forklift hit a high-voltage line while moving a rebar cage for a wind turbine foundation and Patrick Acker, the worker holding the cage, was electrocuted.

Wind-Works has a section on accidents and safety [6] plus a database tracking fatal accidents (80 through 2014) in the wind industry. It shows mortality of 0.025 deaths per TWh, which is a significant decline from the 0.4 deaths/TWh for the mid-1990s and 0.15 deaths/TWh by the end of 2000. Of course, some of the deaths related to the transport of wind turbines. The mortality statistics for the wind industry need to be compared to those of other energy industries such as coal.

11.2.2 Power Quality

Power quality involves harmonics, power factor, and voltage and frequency control. A number of wind turbines on the end of a feeder line may require extra equipment to maintain quality of power. Utility companies have to supply reactive power for induction generators, and in general, capacitors on wind turbines or at wind farm substations are required to maintain power factors.

11.2.3 Connection to Utility

A 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 (1) wind turbine specifications, (2) block diagram of electrical system, (3) and descriptions of controls for handling loss of load by utility. Even if the arrangement is net energy billing, the utility may require a meter to measure energy flow in both directions.

Liability for damage is another concern of a utility. Most utilities want to be insured against all damage arising from wind turbine operation. Of course, a small power producer wants to be insured against wind turbine damage resulting from utility operations but that is impossible to obtain. Insurance should be available as part of a homeowner or business policy. Some electric cooperatives required proof of a $500,000 liability policy before allowing connection of a wind turbine to their systems.

A utility interconnection study will cost $30,000 to $100,000 and determines the effects of wind farm operation on transmission lines and existing generators. The American Wind Energy Association has information on utilities and wind power [7].

An example of onerous regulation of small wind turbines comes from the State of Washington, where the Department of Labor and Industries will not approve small wind systems without Underwriters Laboratory (UL) listing for all components. The state now requires a few specially registered electrical engineering firms to certify all existing and planned wind systems that are not UL listed at a cost of around $2,000. This action brought small wind equipment sales to a halt in Washington.

States that provide incentives and/or rebates for small wind installations require or will require certification. See Section 10.2 for more information about small wind turbine certification in the United States.

11.2.4 Ancillary Costs

Wind farms, especially as they provide more generation capacity on the grid, create other costs for utilities. Wind variability can increase operating costs for 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 to 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 [9].

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 subtracted from the amount Northwestern Energy pays the wind farm for power and thus reduces the utility payment for wind-generated electricity.

A major storm in Spain with winds above the cut-out wind speed caused a major drop in output from wind farms of 7,000 MW compared to the predicted input to the utility grid operation for that day. In another case, wind farms produced 53% of the total demand in Spain for 5 hours (November 2009) when there was ample wind and low demand on the grid during early part of the day. In April 2017, the ERCOT system in Texas set a record wind power output of 16,141 MW—39.5% of the load. Because more wind power is being added, new records will be set.

11.3 REGULATIONS

Regulations for renewable projects vary by country, region, and state from simple reviews by a single agency to multiple complex reviews by various agencies and even multiple levels of government. Sometimes agencies pass conflicting regulations. National laws and policies may restrict connection of a renewable energy system to a utility grid. Most large projects require consideration of environmental impacts, although enforcement practices may vary widely.

In the United States, federal permitting requirements range from environmental restrictions to Federal Aviation Administration regulations on lights for tall towers and wind turbines taller than 200 ft (60 m). Industry maintains that regulations now represent major shares of their costs of doing business. In most cases, industry claims it cannot meet proposed regulations because they are uneconomical.

Permits are required for construction in residential areas 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, for example, because of a thrown blade, is the most common objection, even though risks from cars and utility lines are accepted. Signs, trees, and even utility poles have failed in high winds or under conditions of icing.

Tower access and access to high voltage equipment must be controlled. One certain fact is that any incident that interferes with television reception will be unacceptable to the public. When the metal blades on the MOD-0A interfered with reception on Block Island, Rhode Island, the Department of Energy (DOE) had to install cable for the residents. Most locations have no specific zoning regulations for wind turbines. Before installing a small wind turbine, be prepared to educate public boards and residents [10].

11.4 ENVIRONMENT

Environmental issues surround all large projects and vary by location. Some may apply to small wind turbines. An expensive environmental impact analysis and/or study, particularly related to impacts on fish and wildlife will be required for any project (even small wind turbines) receiving federal funding in the United States. At the end of a project lifetime, the decommissioning, recycling, and disposal (especially of toxic components) must be considered. The goal of the U.S. Fish and Wildlife Service is to protect wildlife resources, streamline site selection, and attempt to

avoid environmental problems after construction. The service issued guidelines on minimizing the impacts of land-based wind farms on wildlife and habitats [11].

Land areas that are excluded from use because of environmental considerations include national and state parks, wetlands, and some wildlife refuges. In the United States, environmental impact statements are required and the Environmental Protection Agency has jurisdiction over many aspects of wind farm location. Some states and even counties have environmental requirements that must be met before a wind turbine or farm can be constructed. The first step is to check local requirements.

A developer should consider the environment, permits, licenses, and regulatory approvals as well as threatened or endangered species, wildlife habitats, local avian and bat species, wetlands and other protected areas, and locations of known archaeological and historical resources. Geographical Information Systems are excellent tools for depicting environmental and land use constraints. Regulations on archeological sites differ by state and may not apply to private lands. A search for archeological site information should be performed for a medium or large wind farm site even if it is not mandatory.

After the first analysis of environmental issues, a more detailed analysis should address possible impacts and their mitigation. After a project is operational, mitigation of the impacts must be monitored regularly. Biological concerns are habitat loss, alteration or fragmentation of habitats, bird and/or bat collisions with wind turbines, electrocution of raptors, and effects on vegetation. Water, especially wetlands, soil erosion and water quality must be considered. For wind farms, the clearing of scrub brush for roads, sites, and laying underground wires is welcomed by ranchers. However, the cleared areas such as road shoulders must be seeded and monitored for growth, erosion, and noxious weeds. Another possibility in complex terrain is that maintained roads may be welcomed by land owners/operators and they can serve as firebreaks.

The main environmental issues are visual impacts, noise, birds, and bats. The visual impact can be detrimental, especially in locations near scenic areas, and people are in favor of renewable energy as long as it is "not in my backyard." Turbines should be painted with nonreflective paint in drab colors.

Some people are adamantly opposed to wind farms, most are neutral, and the rest are in favor. For those opposed, the visual impact is generally the greatest concern [12]. The photo gallery of Stopillwind has before-and-after photos of wind farms. Wind farms produce economic returns both directly and indirectly. A wind farm developer should educate the local community as soon as a project is planned. Economic development in rural areas is very powerful from a political standpoint.

Noise measurements have shown that wind turbines fall below the ambient noise levels. However, the repetitive sound from the blades is obvious and no one would want to live in the middle of a wind farm. The whine from gearboxes on some units is also noticeable. However, much noise has been reduced by larger wind turbines at higher hub heights and new airfoils. Farmers who live near the wind turbines at the White Deer wind farm in Texas (80 1-MW turbines) report that noise is not a problem. Some residents near the Waubra wind farm in Australia report health problems caused by living among wind turbines.

The rotor area for a 90 m diameter wind turbine is over 6,300 m^2, 10 rpm rotor speed, and blade velocity differs from the root to the tip. Large wind turbines revolve more slowly than small wind turbines, but their tip speed ratios are similar. Both blades have sufficient velocity to kill a bird.

Parameters related to birds include fatalities caused by wind turbines, species, season, threats, and possible mitigation measures [13]. Collision rates per turbine per year vary from 0.01 to 23. The 23 collision figure was for a coastal site in Belgium that had a large population of gulls, terns, and ducks. Annual average collision rates for other coastal sites in northwest Europe ranged from 0.01 to 1.2 birds per turbine. None of these examples has been associated with significant population declines. 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 but increased their distances from the wind turbines. Overall, fewer than 1% of the ducks and geese flew near enough to the turbines to be at any risk of collision [14].

In general, migratory birds fly well above the heights of wind turbines although overcast and ground clouds may lower flight paths. Two large wind farms near the Texas coast, south of Corpus Christi, use radar to monitor migrations of birds. The turbines are shut down if they pose threats to the birds.

Avian mortality became an issue at Altamont Pass, in California, after wind turbines killed some raptors. Transmission line poles were capped to prevent the birds from using them as perches, extending their wings between the lines, and being electrocuted. Xcel Energy agreed to evaluate 90,000 miles of transmission lines in twelve states to fix any equipment likely to kill birds.

The primary areas of concern are (1) possible litigation resulting from killing even one bird 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 [15] have been funded since 1994 to determine the effects of rotating blades on raptors and find methods to make them repel birds. Truss towers make natural perches since wind farms lack trees. Most large turbines now have tubular towers. WINDExchange has a section on wildlife impacts [16].

Southern Spain is another area that experiences bird problems [17]. Tarifa is a temporary roosting area for birds migrating to and from Africa. Biologists believe the problem of avian mortality at the site is partly due to aerodynamics. Soaring birds travel the air currents that propel them up the ridges where the wind turbines are. Large birds do not have the maneuverability of smaller birds.

Based on the situation at Tarifa, it is obvious that some locations should be off limits to wind farms. Wind farms should not be located next to refuges for endangered bird species such as whooping cranes. Although thousands of birds are killed by communication towers, buildings [18], hunters, and even cars, the Sierra Club and other environmental groups will become adversaries if bird species are threatened. 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 covering bird and bat impacts were developed. Wildlife–wind research, tools, and fatality estimators are available from the National Wind Coordinating Collaborative [19]. One provides guidance on preconstruction utilization counts for making predictions and conducting post-construction fatality studies [26].

As expected, fatality rates for birds vary by the characteristics of a wind farm and the surrounding area. In Altamont Pass, raptors suffered the highest fatality rates. Outside California, studies at 12 wind projects estimated fatality rates from 0.63 to >10 per turbine per year at a fragmented mountain forest site in Tennessee. Bat fatality rates are estimated from a low of 1.5 per turbine per year for most of the United States to a high of 46 for the eastern United States [20].

National Wind Coordinating Collaborative (NWCC) members are from utilities, state legislatures, state utility commissions, consumer advocacy organizations, wind equipment suppliers and developers, green power marketers, environmental organizations, and state and federal agencies. Permitting publications are available from NWCC.

The issues of regulatory framework, environment, and impact analysis and mitigation are covered in AWEA's *Siting Handbook* [21]. The information applies to projects of five or more megawatts but is still useful for smaller projects. Early in the siting process, a developer should conduct a critical analysis of the environmental issues such as permits, licenses, and regulatory approvals; threatened or endangered species and habitats; avian and bat species; identification of wetlands and other protected areas; and locations of known archaeological and historical resources. A constraints map is a useful tool for depicting environmental and land use constraints.

Regulations from federal to local levels play parts in every project. Federal permitting requirements for wind energy projects range from environmental to aviation matters. There is coordination at the federal level for recommendations and regulations [22]. A check on archeological sites is generally imperative during planning for wind farms. Regulations differ by state and some states exclude private land. A developer would be wise to learn about archeological requirements. NREL, in collaboration with the National Association of Counties, created a helpful guide for county commissioners [23].

Visual impacts for large wind farms are very different from the impacts of from those of small wind turbines because of the numbers and heights of towers. Wind farms may be visible from 20 km

and they are visible from all directions in the U.S. Plains (Figures 11.1 and 11.2). Only the curvature of the Earth limits viewing distance. At close range, wind turbines dominate the landscape (Figure 11.3).

In mountainous areas, wind turbines are arranged in lines on the ridges, but in general they are not visible from all angles because most roads are in the valleys and the views are blocked. The moving rotors make wind turbines more visible. The requirements to install lights on towers over 60 m make the turbines 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 a turbine.

The Denmark requirements include a limit on wind turbine shadow flicker on neighboring houses not to exceed 10 hours per year. If the shadow limit is exceeded, a turbine owner may be required to shut down the wind turbine in critical periods. In a pasture with no trees in the summer, a rancher noticed that yearling calves at the New Mexico Wind Energy Center lined up in the shadows of the towers and moved to remain in the shade as the shadows moved. For information about the visual impacts of small wind turbines see Section 9.1.2.

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 caused by the movements of the blades and also from components, primarily gearboxes.

FIGURE 11.1 Visual impact of various sizes of wind turbines at different distances. Photo taken in late afternoon looking south. Foreground: 3.2 km to 1 turbine, diameter 90 m, 3 MW, tower height 80 m. Middle at left: 6.4-km distance to 8 turbines, diameter 64 m, 1.25 MW, tower height 72 m. Background: 9.5-km distance to first row, 14.5 km to back row, wind farm with 38 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.

FIGURE 11.3 Turkey Track wind farm, south of Sweetwater, Texas, on Highway 153. Wind turbine diameter 77 m, 1.5 MW, tower height 80 m. Near wind turbine is around 1 km away and the wind turbines in the background on the horizon are on another wind farm.

One issue that is often overlooked is traffic from the large trucks hauling the wind turbines and cranes to the project, and then the numerous pickups both during and after construction. Routes from source and delivery ports become important, and invariably local roads have to be improved, and the question is: Who pays for the improvements? For mesas and complex terrain, most ranchers like the new roads because they are maintained by wind farms.

The amount of activity and number of people involved in the construction phase and the amount of space and equipment required are surprising to rural communities. During construction, cattle guards may have to be installed because opening and closing gates take too much time. Livestock may be injured or killed and damages will have to be paid. Finally, solid and hazardous wastes generated during construction and operation must be managed. At the end of a project's life, environmental problems may arise during dismantling.

For protection against liability, a developer should perform a screening assessment or an environmental site assessment before acquisition of a property. The American Society for Testing and Materials has screening tools and standards for environmental site assessment [24].

11.5 POLITICS

Every endeavor produces political issues and activities. To change a behavior, especially in 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 subsidies for that type of energy. Subsidies take the form of taxes, tax breaks, and regulations and all these generally require legislation. Every company wants incentives for itself and penalties for its competitors. Industries also want governments to fund their research and development and even assist with commercialization.

Incentives are usually in the form of tax breaks, subsidies, mandates, and regulations. Public utility commissions now demand that utilities use integrated resource planning and must consider renewables and conservation in their planning processes. Can utilities make money on kilowatt-hours saved? Should the consumers or shareholders take the risks? Three Mile Island in the United States, Chernobyl in Russia, Fukushima in Japan, and the nuclear utility industry in general are good examples of political impacts from the local to the national level. The federal Price–Anderson Act limited the amount of liability from nuclear accidents. Without that legislation, the nuclear industry could not have sold plants to utilities.

Penalties are generally in the form of taxes and regulations. U.S. environmental groups have already shown that utility planners will be held accountable for the risk of a carbon tax if they plan new coal plants. In other words, the environmental group opinion is that shareholders, not consumers, should shoulder the risks.

Education creates public awareness of the possibilities and options and should provide a realistic cost and benefit comparison over the lifetime of an energy system. Entrenched industries try to paint adverse science as questionable or theoretical, for example, cancer caused by tobacco use and global warming caused by greenhouse gases. No one can fool "Mother Nature," and humans will pay one way or another.

Politics will continue to influence which and how many different energy sources are subsidized. Present energy policies include taxes or limitations on greenhouse gas emissions, rebates on equipment, and incentives for electrical energy produced from renewable energy, renewable portfolio standards, set prices for renewable energy (feed-in tariffs), and tax credits.

11.6 INCENTIVES

Energy subsidies produce serious effects and generally favor 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 paid to conventional energy sources without accounting for the costs of infrastructure, safeguards, and military actions [25].

The privatization of the electric industry, along with the restructuring into generation, transmission, and distribution opened some doors for renewable energy. For 2011, the estimated incentives were $88 billion for renewable energy and $523 billion for fossil fuels. It would be interesting to know what incentives benefitted nuclear power. The International Energy Agency has been measuring fossil fuels and electricity subsidies for over a decade. The estimate is $260 billion for 2016 for the world with China having the largest subsidy [26].

11.6.1 United States

The major impetus to the wind industry came from 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 methods of financing.

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 Internal Revenue Service Code: This applies if the investor: (1) owns a wind facility that was placed in service between December 31, 1993 and July 1, 1999; (2) produces electricity at the wind facility; and (3) sells the electricity to an unrelated party.

The credit applies to production through the first 10 years of operation. It is intended to serve as both a price incentive and 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 after 1989. Both values will be adjusted for inflation. The credit can be carried back 3 years and carried forward 15 years to offset taxes on income from other years. The PTC was extended several times and was a major factor in the large increase in wind power in the United States starting in the 1990s. The 2015 extension for wind is $0.024/kWh for 2015–2016 and then at 80–60–40% through 2019. Rules allow wind projects to qualify if they complete a significant amount construction before the end of the period. For wind farms that have reached the 10-year limit, repowering can meet the requirements if at least 80% of the property's value is new. It is estimated that 6 GW will be repowered under this provision.

The provision of direct payments (Renewable Energy Production Incentives) to public utilities, co-operatives, and Native American tribes is equivalent to the PTC arrangement. Congress must fund the incentive program every year. The funds provided may be less than requested and wind projects must compete with other renewable projects.

In 1973, the federal funding for wind was $300,000, and that increased steadily to $67 million in 1980. During Reagan's term, the amount was reduced every year, and in 1988 the amount budgeted was $8 million. Increases have been granted since then and the budget for wind for the 2012 fiscal year was $93 million (not including projects funded by the American Recovery and Reinvestment Act). A major part of the funding went toward development of large HAWTs. Now the funding is through EERE, Wind Energy Technologies Office. Funding for 2017 was $90 million. For a chart showing the funding by year since 1975, go to www.energy.gov/eere/wind/wind-energy-technologies-office-budget.

The tone or direction is set by the administration and changes under every president. The early direction was R&D plus demonstration projects that were 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 topics such as aerodynamics and wind characteristics. Funding increased slightly during the George Bush term, and the advanced technology program was initiated in an attempt to recapture some of the market acquired by foreign wind turbine manufacturers.

Under Clinton, interest in renewable energy increased and the direction was commercialization. The Climate Change Action Plan moved DOE's focus on technology development to an active role

in renewable energy commercialization. This initiative was backed with $72 million for fiscal year 1995 ($18 million for wind) and a total of $432 million through 2000. The DOE started looking to wind to achieve emissions reductions from renewables since this was and is the most economical resource.

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 became part of the package. However, a mandated increase in fuel efficiency for the automotive industry (the CAFE standards) did not pass until the last year of the G. W. Bush presidency. Under Obama, the funding increased from $54 million in 2009 to $107 million in 2015. Under Trump, so far, there is more support for coal and nuclear than there is for renewable resources such as wind power.

When money is available, every university and federal laboratory wants some. New institutes and consulting groups proliferate. 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 Wind Energy Research Center at Rocky Flats was in charge of the small wind systems program. The location was chosen because of politics, that is, because of too much publicity about environmental problems at the plutonium facility. Early in the program, the center purchased units for testing and started a field evaluation program [27] to install two units in every state and each territory—definitely a political plus. After 40 units were installed, the program was abandoned due to costs and also because wind turbines from small wind manufacturers were not ready.

The small wind machine program was transferred to the Solar Energy Research Institute (SERI). NASA–Lewis retired from the large HAWT program, transferring what was left to SERI. In 1991, President George H. W. Bush designated SERI as the National Renewable Energy Laboratory (NREL), on an equal footing with the other national laboratories originally created to study the development of nuclear weapons and high-energy physics. The expected outcome was that NREL would absorb all the other programs associated with renewable energy, although Sandia continued its VAWT program. As always, political infighting ensued. Today, NREL's National Wind Technology Center performs R&D and administers most wind energy programs.

A 1999 initiative was Wind Powering America [28], whose goals were to meet 5% of U.S. energy needs with wind (79 GW installed) by 2020; double the number of states with 20 MW of wind capacity to 16 by 2005; triple it to 24 by 2010; and increase wind's contribution to electricity production to 5% by 2010. Subsequently, the secretary accelerated the DOE 5% commitment to 2005. Rural economic development where wind resources are the greatest has been substantial. That goal was surpassed in 2015, and in 2017 installed capacity is 89 GW, 18 states have over 1 GW, and around 6% of U.S. electricity was produced by wind.

11.6.1.1 State Incentives

States compete for renewable energy as a way to offset importation of energy and also to create jobs. The Database of State Incentives for Renewable Energy (DSIRE) is a comprehensive source of information about state, local, utility, and selected federal incentives that promote renewable energy [29]. Overview maps and tables are classified by incentive types 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 legislature

to store waste from its Prairie Island nuclear facility in dry casks outside the plant. In 2017, Xcel (includes other states) had over 6,300 MW of wind power on its system. After the success of the Renewable Portfolio Standard in Texas, 29 states passed similar measures by 2012 and another eight passed renewable portfolio goals.

Texas legislation allowed the Lower Colorado River Authority to acquire renewable energy from plants located on state lands outside the authority's service territory. This paved the way for a 35-MW wind farm (1995) in the Delaware Mountains of the Trans-Pecos region, with an extension for another 200 MW; another project of 30 MW was installed on the same ridge. Due to high maintenance costs and long transmission lines, both projects were decommissioned in 2014.

Some states mandated deregulation of the electric utility industry. Besides giving the consumers choices of producers, most states impose a system benefits charge (SBC) that lets utilities recover stranded costs of power plants, primarily 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 costs 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 as part of electric restructuring. The mandate was for 2,000 MW of new renewables by 2009. Because so much wind power was installed, the RPS was increased in 2005 to 5,880 MW by 2015, with a goal of 10,000 MW by 2025. The RPS also mandated 500 MW from other renewables. The amount to be produced by wind was surpassed in 2008, as wind farm capacity was 7,611 MW and the goal of 10,000 MW by 2025 was surpassed in 2011.

Another aspect of electric restructuring in Texas was that electric retailers must acquire renewable energy credits (RECs; 1 REC = 1 MWh) from renewable energy produced in Texas or face penalties of up to $50/MWh. These are compliance RECs. Anyone may participate in the REC market; traders, environmental organizations, and individuals. The RECs are good for the year created and bankable for 2 years. The market opened in January, 2002, and early prices were around $5/REC. In 2008, RECs sold for $5 to $8 but by 2017 they declined to less than $1, primarily due to the large amount of wind installed.

The price for voluntary RECs at the national level averaged around $0.35 in 2017. Compliance RECs varied by states or regions. For example, in 2017, the price for New Hampshire was $25 [30].

As always, industries seek tax breaks at every level. States and local entities give tax breaks for economic development. Wind farm developers want property tax breaks or abatements on installed costs because taxes and installations are both major costs. Conventional power producers can deduct the cost of fuel, whereas renewable energy producers have no deductions because their fuel is free. Tax abatements have become common.

11.6.1.2 Green Power

Green power is the result of a voluntary decision by retail electricity customers to purchase electricity supplied from renewable energy sources or contribute funds for utilities to invest in renewable energy development. Green power is an option in some state policies, and also has been driven by responses of utilities to customer surveys and town meetings.

In the early 1990s, a small number of U.S. utilities began offering green power options to their customers. A consumer had to pay a premium of about $3 per month for a 100-kWh block or $0.03/kWh. This represented a powerful market support mechanism for renewable (mainly wind) energy development. By 2007, more than half of all U.S. electricity customers had options to purchase green power from more than 750 utilities (about 25%) nationally. Now, every electricity customer in the United States can buy green power through unbundled RECs and power purchase agreements (PPA).

The voluntary green power market consists of the following: utility green pricing programs, utility renewable contracts, unbundled RECs, competitive suppliers, community choice aggregations (CCA), power purchase agreements, and community solar. In 2016, voluntary green power was about 28% of all U.S. renewable energy sales, excluding large hydropower [30,31]. Utility green

pricing programs ranged from \$0.001/kWh to \$0.05/kWh, with the average residential premium being \$0.018/kWh.

In some states, customers can choose their electricity service from a competitive supplier and many of them offer green power, from partial to all.

Author's Note: Previously, I (Nelson) chose voluntary green power, \$3 per month for 100 kWh from wind power, and after restructuring I chose 100% wind power. Now that I have 7.5 kW of PV on my home, I have renewable net metering still backed by wind power. Texas wind is the primary source of green power for the national competitive supplier market.

Seven states have passed legislation that allows CCA. A CCA aggregates electricity for customers to purchase electricity (total or partial) and RECs from an alternate electricity supplier.

Corporations and other large non-residential customers make large green power purchases to meet internal renewable energy goals, generally through power purchase agreements. Wind farms account for a significant amount of green power at the national level. For example, Google has 3 GW of mostly wind and some solar to offset its energy usage.

The Green Power Partnership is a voluntary program that encourages organizations to use green power [32]. As of 2017, there were 1,500 organizations in the program. The web site breaks down partners by industry, usage, loads, resource mix, and product type. They also list rankings of the partners for different entities. There are also green power communities, a few of which have opted for 100% renewables.

It is interesting that some utilities lowered the rate premium on green power as traditional fossil fuel costs increased. As green power becomes cheaper than regular power, will those consumers who purchased green power pay less than the regular rate? NREL ranks the utility green power programs annually [33].

11.6.1.3 Net Metering

If the renewable energy system produces more energy needed on-site, the utility meter runs backward; if the load is greater, the meter runs forward. The bill is determined at the end of the time period—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 states have net metering that ranges from 10 to 1,000 kW, with most in the 10- to 100-kW range [29].

In general, net metering did not increase sales of wind turbines because the small 10- to 50-kW turbines are not cost competitive with retail electricity. Larger wind turbines can be cost competitive for users with large loads where all the electricity is used on-site. Because the value set for avoided cost is generally only equal to the fuel adjustment cost, a company wants to use that energy on-site because it 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 producers. This is especially true for irrigation that creates large demand in the summer when most of the United States experiences low winds.

Of course, utility companies do not like net metering because it increases the billing problem. Utilities claim that one group of customers is subsidizing another group. With electric restructuring, utilities are worried that large customers will find cheaper electricity and 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, most emphasized megawatt wind turbines. The programs had little success. 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 a major share of the world wind farm market. Chinese manufacturers are also major producers primarily due to their large domestic market.

Different policy options for renewable energy apply in the European Union (EU) [34–36]. The effectiveness and efficiency of current and future support for renewable energy for producing electricity were analyzed [37]. 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 may 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 (feed-in tariff) and (2) quota or capacity-based (Table 11.1). The quota concept is similar to a renewable portfolio standard. In general, feed-in tariffs led to the most installations. Both models ran from 15 to 20 years with adjustments for inflation and possible sliding scale with time.

Paul Gipe of WindWorks wrote several articles about electricity feed laws and feed-in tariffs that discuss renewable tariffs by country, reviews of books about feed-in tariffs, and relevant links [38]. Electricity feed laws (EFLs) permit the interconnection of renewable sources of electricity with utilities and specify how much will be paid for the electricity and for how long. EFLs are widely used in Europe where they resulted in large amounts of installed wind power, most notably in Germany and Spain. Advanced renewable tariff values are classified by technology, application, project size, and/or resource intensity.

Denmark's windmill law requires electric utilities to purchase energy from private wind turbine owners at 85% of the consumer price plus ecotax relief of about \$0.09/kWh. Electric utilities receive about \$0.015/kWh as a subsidy for wind power. The development of wind power was tied to the Energy 21 goal of reducing CO_2 emissions 20% by 2005.

Germany accounted for half the European market after 1995. It adopted the Electricity Feed Law (EFL) in 1990 as a measure to protect climate, save fossil fuels, and promote renewable energy. The law requires utilities to buy renewable energy from independent power producers at a minimum price defined by the government. The minimum price 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 to set a regional cap of 5% for renewable electricity. Since the Renewable Energy Sources Act was enacted, electricity generation from renewable sources in Germany increased from 6% in 2000 to 25% in 2012, and much of that is generated by wind.

Earlier programs for promoting wind (100 MW and expansion to 250 MW) mandated kilowatt-hour support. Because so much wind was installed, the figure was changed in 2004

TABLE 11.1
Models of Utility Compensation in Europe

Country	2003 €/MWh	2011 €/MWh
Feed-In Tariff		
Netherlands	9.2	8.0
Germany	6.6-8.8	9.0
France	8.4	3.0
Portugal	8.1	7.0
Austria	7.8	10.0
Spain	6.4	6.6–7.9
Greece	6.4	8.7–10
Italy		13.5
United Kingdom		4.7–9.9
Quota		
Italy	13	
United Kingdom	9.8	

to €0.085/kWh for 5 years and €0.055/kWh for the following 15 years. A decrease of 2.5% per year meant in 2010 that the price would be €0.079/kWh for 5 years and then €0.05/kWh for 15 more years. Some states in Germany also implemented 50% investment grants 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. Germany switched from feed-in tariffs to auctions, 5 year rate then for another 15 years [39]. The auction bids in 2017 for onshore wind average €38/MWh with the lowest bid of €22/MWh.

China now ranks first due to favorable government policies and a law that requires energy companies to purchase all the electricity produced by the renewable sector. The feed-in tariff was for $52–62/MWh for 20 years. Starting from 2017, the values were reduced for onshore by region, intertidal, and offshore wind. The wind industry relied on financing through the Clean Development Mechanism (Kyoto Protocol), which presented some problems for new projects.

As in other countries, transmission must be upgraded from windy areas to the load centers. Some regions experienced curtailments up to 20%. Presently, China mandates that 70% of the components of wind turbines erected in the country be produced by factories in the country. To meet the goal of 3% of electricity from non-hydro renewables by 2020, 100 GW of wind must be installed. That goal was reached in 2014, and by the end of 2017, China had 188 GW of wind.

India ranks fourth in installed capacity based on a favorable fiscal environment and policy measures. Wind power development in India has been promoted through R&D, demonstration projects, programs supported by government subsidies, fiscal incentives, and liberalized foreign investment procedures. The central government provides income tax holidays, accelerated depreciation, duty-free imports, energy capital, and interest subsidies. State government measures include buybacks, power wheeling and banking, sales tax concessions, electricity tax exemptions, demand cut concessions for industrial consumers that establish renewable power generation units, and capital subsidies. Tamil Nadu and several other state boards purchase wind energy at about $0.064/kWh. In 2017, one GW auction for wind went for $40.9/MWh. Thus, some states in India that offer higher-cost feed-in tariffs stopped signing contracts with new wind projects.

In the last 10 years, Brazil has installed around 13 GW of wind, which is 73% of the total installed capacity for Latin America (Mexico not included) and the Caribbean. Even though hydropower provides around 90% of the electricity in Brazil, severe droughts have promoted the government to diversify their energy resources. Besides mandates for the national electric company, financing is provided in the form of subsidized loans from the development bank. Only those companies that use local content of about 65% qualify for a full loan. Brazil has had renewable energy auctions since 2009, with average prices for wind ranging from $27/MWh to $60/MWh (2009–2014). In August, 2017, Brazil's electricity regulatory agency cancelled nine solar projects (249.7 MW) and 16 wind farms (307.7 MW) because of the large number of projects contracted in Brazil's first reserve energy auction that remain unbuilt or are idle. However, the latest auction in December, 2017, for 1.4 GW of wind, had an average price of $29.7/MWh for 20-year contracts starting 1/1/2023.

11.7 EXTERNALITIES

Externalities are defined as social or external costs and benefits attributable to an activity, the costs of which are not borne by the parties involved in the activity. Externalities are not paid by producers or consumers and are not included in market prices, although someone will pay or be affected by them at some point.

Social benefits (called subsidies) are paid by a third party and accrue to a group. An example is the 1936 Rural Electrification Act, which brought electricity to the rural areas of United States. An example of a positive externality (social benefit) is the cleaner air resulting from the installation of wind farms. A good example of a negative externality is the use of coal in China. Every city of with a population of 100,000 or more has terrible smog because of all the coal used for heating, cooking,

industrial production, and generation of electricity. China will face huge public health costs in 20 years when today's children are adults.

External costs can be classified as (1) hidden costs borne by governments including subsidies and R&D programs, and (2) costs associated with pollution arising from health problems, environmental damage from acid rain, destruction of the ozone, unclean air, and lost productivity. Although global warming due to CO_2 emissions is disputed by many in industry, a few scientists, and some politicians; it will have far-reaching effects. Government and other mechanisms for including externalities into the market fall into several categories:

Regulation—This historical approach created inefficient and monopolistic industries and made them inflexible and highly resistant to change. Current philosophies are 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 that include externalities.

Pollution taxes—Governments can impose taxes on pollution generated. European countries utilize such taxes. Another possibility is allowing renewable energy credits for producing clean power. Pollution taxes and avoidance of pollution have the merit of simplicity. They exert only marginal effects on energy costs, but they are not true integrations of external costs into market prices. The taxpayer pays instead of the consumer. The pollution tax could be added to consumer bills and could be paid based on energy use.

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—These measures promote R&D and production advances.

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 for a range of fuel cycles [40]. In the 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, U.S. companies have been trading sulfur dioxide (SO_X) and nitrogen oxide (NO_X) emissions. Both compounds are precursors of acid rain and contributors to ground-level ozone and smog. Essentially, industries trade allowance units that may be bought, sold, or banked for future use. Carbon dioxide trading does not exists in the United States, but some states are passing laws to reduce CO_2 production and even some cities have policies to reduce CO_2 emissions. Who knows when there will be trading in CO_2 emissions for the United States, as the Trump policy is against the science behind global warming. The largest emitters of carbon dioxide are China and the United States [41].

U.S. emissions from generation of electricity are primarily due to the burning of coal (Table 11.2). The emission factors in the table were adjusted somewhat to show total values of metric tons calculated by the Energy Information Administration [42]. For example, the average value for sulfur dioxide from coal is 3.0 kg/MWh and the worst coal plant in the United States produces 18 kg/MWh. New coal plants are equipped with scrubbers, but almost 40% of coal plants do not follow the same pollution control standards because they were online before enactment of the Clean Air Act of 1970.

The average carbon dioxide emission is around 720 kg/MWh for all fuel types, and of course coal emissions are higher, around 1,000 kg/MWh. Wind turbines reduce carbon dioxide emissions by one metric ton per megawatt hour when displacing coal generation, Furthermore, wind turbines do not require water to generate electricity. Natural gas production of electricity has increased in market share. Carbon dioxide emissions per megawatt hour are smaller, so the average has decreased. A Minnesota group (connected with the utility industry) estimated the external costs for carbon dioxide from coal as only \$0.34 to \$3.52/ton. The EU emission trading is a cap and trade program and the cap is reduced over time so that total emissions fall [43]. In Europe, carbon dioxide emission reductions at one time were worth €30/ton in some countries. In 2017, the values on the trading market ranged from €4 to 12/ton.

TABLE 11.2
2009 Values of U.S. Generation of Electricity and Air Emissions

		Carbon Dioxide		Sulfur Dioxide		Nitrogen Oxides	
	MWh 10^6	**kg/MWh**	**tons 10^6**	**kg/MWh**	**tons 10^6**	**kg/MWh**	**tons 10^6**
Coal	1764	950	1676	3.0	5.3	1.5	2.6
Oil	931	710	661	2.7	2.5	0.7	0.6
Natural Gas	284	480	136	0.003	0.001	0.6	0.2
Total	2979		2473		7.8		3.4

Note: MWh and metric ton data from U.S. DOE, EIA. Emission factors estimated from various sources.

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 planned and constructed (estimated at 10 to 20 years). A number of large transmission projects have been proposed in the United States. New transmission lines will have to be constructed for the major wind farm developments in the Great Plains.

NREL's transmission integration performs research on integrating renewable and other technologies into the bulk-power system [44]. A National Interest Electric Transmission Corridor is a geographic region designated by the DOE to help acquire rights of eminent domain for transmission lines.

For states that have electric restructuring, transmission is now a separate company and the question is jurisdiction (who pays for new lines). If curtailment is needed, who is curtailed and what are the curtailment priorities? Curtailment happens when wind farms produce more power than the transmission lines can carry; therefore, some or all the wind turbines on a farm have to be shut down.

In the McCamey area of West Texas and also in an area containing large numbers of wind farms, from Abilene to Snyder, curtailment of output from wind farms was a problem. As part of electric restructuring in Texas in 2005, the Public Utility Commission was placed in charge of Competitive Renewable Energy Zones (CREZs) [45]. One of the primary objectives of CREZ was to bring wind power from West Texas and the Panhandle to the load centers in the ERCOT system. The new lines for ERCOT have a capacity of 18.5 GW. This represents about 11 GW of wind capacity to be added to the ERCOT system (9 GW when CREZ was adopted). Construction of the high voltage transmission lines (345 kV) started in 2009 and was completed in January, 2014 (Figure 11.4). The progression from planning to the end of construction was about 5 years—much less than the national average because ERCOT is not under FERC regulation. Because of the number of wind farms added in the Panhandle, a second circuit was added to the existing line in 2018. That increased the capacity from 2.4 GW to 3.9 GW. Even with new transmission lines, wind farm development in Texas will still be limited by transmission capacity.

Most of the zones in the Panhandle (major wind region) are not within the jurisdiction of Electric Reliability Council of Texas (ERCOT), but are in the Southwest Power Pool (SPP). The transmission lines between those two can only be connected by DC interties. Wind farms can be connected to either of the two major transmission systems. The SPP is also constructing high-voltage transmission lines in Kansas, Oklahoma, Eastern New Mexico, and the Panhandle of Texas, primarily for wind power (Figure 11.5). The Plains & Eastern Clean Line transmission project will deliver 4,000 megawatts of wind power from the Oklahoma Panhandle region to Arkansas and other markets in the Mid-South and Southeast. The Transwest Express Transmission Project [46] will deliver Wyoming

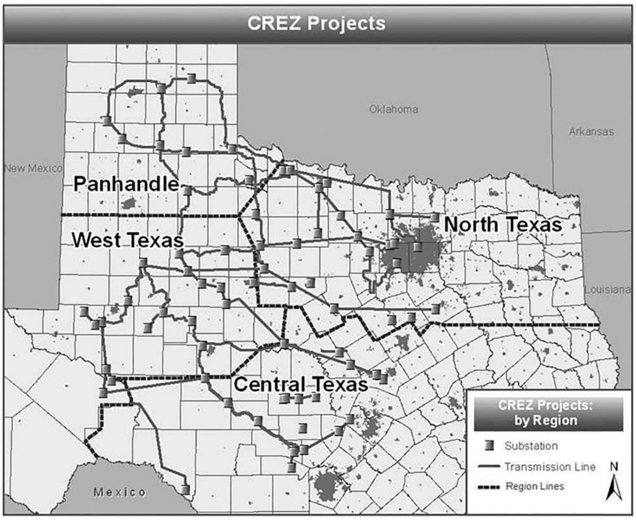


FIGURE 11.4 ERCOT transmission lines for Competitive Renewable Energy Zones (completed January 2014).

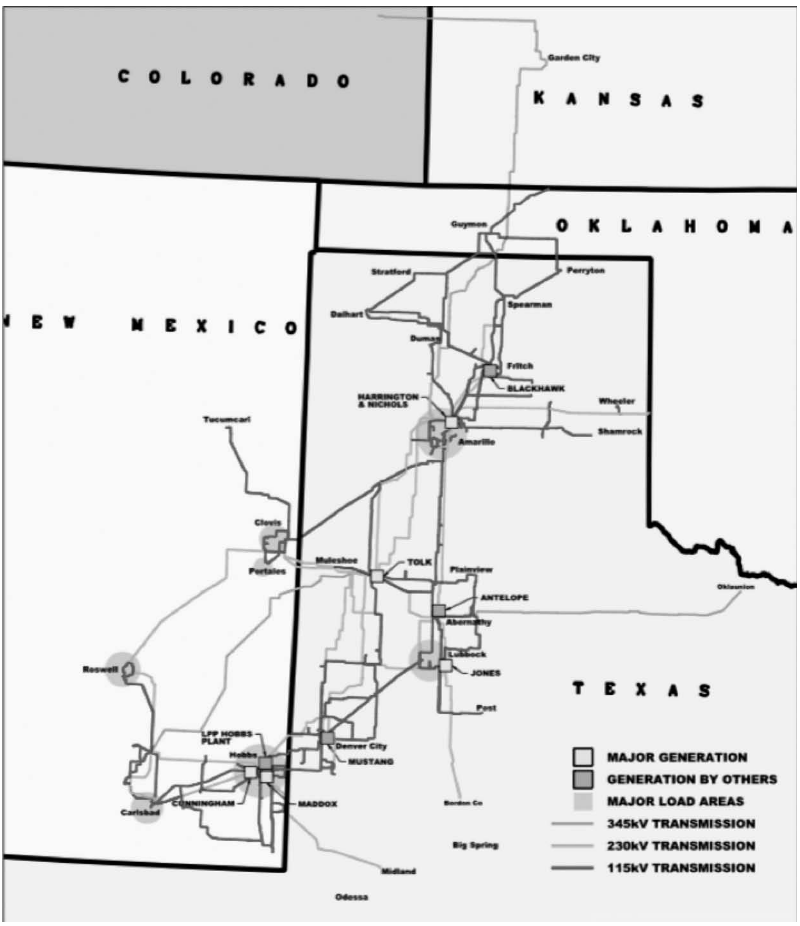


FIGURE 11.5 Southern Public Service (Xcel) transmission lines. Notice the overlap with CREZ lines in the Panhandle (Figure 11.4).

wind energy via a 600 kV high voltage, direct current (HVDC) line to the desert southwest region of the United States. Construction of the 1,170-km (725-mile) line was expected to start in 2014, however, now the timeline is for 2019–2021. The estimated cost is over $3 billion. The Western Grid Group [47] proposed more than 20 major transmission projects around the western United States. Each project has a website detailing size, purpose, and in some cases proposed routes.

Transmission is also a major issue in the EU. Electricity markets are not competitive for four reasons: (1) lack of cross-border transmission links, (2) dominant, integrated power companies, (3) biased grid operators, and (4) low liquidity in wholesale electricity markets. The conclusion is that wind power issues are determined more by economics and regulations than by technical or practical constraints.

China has a few wind farms constructed in locations before adequate transmission capacity was available. China constructed an 800 kV HVDC transmission line to connect the Hami prefecture in eastern Xinjiang with the central city of Zhengzhou (2,210 km). A second 740 kV NVDC line links Xinjiang with the main network of Northwest China (2,180 km). These projects will help transmit electricity from the west—one of the main wind power regions that also has major coal reserves.

PROBLEMS

1. What type of incentives should be devised 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 will 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 types of projects should the U.S. federal government support? (Some examples are R&D, prototype, demonstration, turbine verification, and commercialization.)
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 U.S. states have net energy metering?
12. What is the longest period for net energy billing?
13. What incentives does your state grant for residential size wind systems?
14. Does your electric utility offer green power? If yes, what is it? If no, briefly describe the green power program of Austin Energy in Texas.
15. Go to www.dsireusa.org. How many states have renewable portfolio standards? How many states have rebate programs for purchasing wind systems?
16. What are present market values of renewable energy credits in Texas?
17. Should a pollution tax be imposed on electricity produced by fossil fuels? If yes, how much per metric ton?
18. Calculate the carbon dioxide per year that wind will displace for the world from installed capacity in 2017. Use kilograms per kilowatt-hour from coal power electric plants for comparison. Use a 35% capacity factor for wind plants in estimating annual energy production.
19. Calculate the carbon dioxide per year that wind will displace for the European Union and the United States. Use kilograms per kilowatt-hour from coal power electric plants for comparison. Use a 35% capacity factor for wind plants in estimating annual energy production.

20. What is the estimated cost per kilometer to build 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?
23. What is the status of new high voltage transmission lines for the Great Plains of the United States?
24. What are the values of feed-in tariffs for renewable energy in Canada?
25. Go to EPA, Green Power Partnership [32]. What college and university ranks number one for green power? How much? From what sources?

REFERENCES

1. D. Bain. 1980. An introduction to PURPA, sections 201 and 210. In V. Nelson, Ed., AWEA, Proceedings of Windpower Conference, p. 33.
2. U.S. Federal Energy Regulatory Commission. Order 69. Final rule regarding the implementation of Section 210 of the Public Utility Regulatory Policies Act of 1978. Docket RM79-55.
3. A.J. Cavallo. 1994. High capacity factor wind turbine transmission systems. *Wind Energy* 15, 87.
4. J.E. Bryson. 1980. New directions for utilities. In *AWEA, Proceedings of Windpower Conference*, V. Nelson, Ed., p. 68.
5. Caithness Windfarm Information Forum. Summary of wind turbine accident data to 31st December 2017. www.caithnesswindfarms.co.uk.
6. P. Gipe. 2012. A summary of fatal accidents in wind energy. www.wind-works.org/cms/index.php?id=685.
7. American Wind Energy Association. 2015. Wind energy helps build a more reliable and balanced electricity portfolio. http://awea.files.cms-plus.com/AWEA%20Reliability%20White%20Paper%20-%202-12-15.pdf.
8. B. Parsons et al. 2003. Grid impact of wind power: A summary of recent studies in the United States. www.nrel.gov/docs/fy03osti/34318.pdf.
9. E. Ela, B. Kirby, N. David et al. 2011. Effective ancillary services market design on high wind power penetration systems, NREL/CP-5500-53514. www.nrel.gov/docs/fy12osti/53514.pdf.
10. Distributed Wind Energy. DWEA Permitting & Zoning Resource Center. http://distributedwind.org/zoning-resource-center/.
11. U.S. Fish and Wildlife Service. 2012. Final land-based wind energy guidelines. www.fws.gov/ecological-services/energy-development/wind.html.
12. Stopillwind. http://stopillwind.org.
13. A. Drewitt and R.H.W. Langston. 2006. Assessing the impacts of wind farms on birds. *Ibis* 148, 29.
14. M. Desholm and J. Kahlert. 2005. Avian collision risk at an offshore wind farm. *Biology Letters* 1, 296. www.ncbi.nlm.nih.gov/pmc/articles/PMC1617151/
15. K. C. Sinclair. 2001. Status of avian research at the National Renewable Energy Laboratory. In *AWEA, Proceedings of Windpower Conference,* CD.
16. U.S. DOE, EERE, WINDExchange. Wildlife impacts of wind energy. https://windexchange.energy.gov/projects/wildlife.
17. A. Lue, A. W. Hosmer, and L. Harrison. 1994. Bird deaths prompt rethink on wind farming in Spain. *Windpower Monthly* 10, 14.
18. Geographica. 2003. Photo in *National Geographic*, September.
19. National Wind Coordinating Collaborative. www.nationalwind.org/research/.
20. National Wind Coordinating Collaborative. 2010. Wind turbine interactions with birds, bats, and their habitats. www1.eere.energy.gov/wind/pdfs/birds_and_bats_fact_sheet.pdf. For updated information 2017, https://awwi.org/wp-content/uploads/2017/07/AWWI-Wind-Wildlife-Interactions-Summary-June-2017.pdf
21. American Wind Energy Association. *Wind Energy Siting Handbook*. www.awea.org/Issues/Content.aspx?ItemNumber=5726 (In process of being updated 2018).

22. Wind Turbine Guidelines Advisory Committee. www.fws.gov/habitatconservation/windpower/wind_turbine_advisory_committee.html.
23. M. Costanti, P. Beltrone, and P. Beltrone. 2006. Wind energy guide for county commissioners. www.nrel.gov/docs/fy07osti/40403.pdf.
24. American Society for Testing and Materials, www.astm.org/Standards/E1528.htm.
25. H. Scheer. 1998. *Energy Subsidies: A Basic Perspective*. Paper presented at Second Conference on Financing Renewable Energies, Bonn.
26. IEA. 2016. Energy subsidies. www.iea.org/statistics/resources/energysubsidies/.
27. V. Nelson. 1984. A history of the SWECS Industry in the U.S. *Alternative Sources of Energy*, March/April, 20.
28. L. Flowers and P. J. Dougherty. 2001. Wind powering America. In *AWEA, Proceedings of Windpower Conference*.
29. Database of State Incentives for Renewable Energy (DSIRE). www.dsireusa.org.
30. NREL Voluntary Green Power Procurement. www.nrel.gov/analysis/green-power.html.
31. NREL, E. O'Shaughnessy, et al. 2017. Status and trends in the U.S. voluntary green power market (2016 data). NREL/TP-6A20-70174. www.nrel.gov/docs/fy18osti/70174.pdf.
32. Environmental Protection Agency. Green Power Partnership. www.epa.gov/greenpower.
33. National Renewable Energy Laboratory. Top ten utility green pricing programs. www.nrel.gov/analysis/assets/pdfs/utility-green-power-ranking.pdf.
34. S. Krohn. 2000. Renewables in the EU single market: an economic and policy analysis. In *AWEA, Proceedings of Windpower Conference,* CD.
35. V. Pollard. 2001. Developments in the European policy framework(s) for wind energy. In *AWEA, Proceedings of Windpower Conference,* CD.
36. European Wind Energy Association. 2009. *Wind Energy: A Guide to the Technology, Economics, and Future of Wind Power*. Earthscan: London.
37. M. Ragwits, et al. 2007. Assessment and optimization of renewable energy support schemes in the European electricity market. Final report, Intelligent Energy Europe. https://ec.europa.eu/energy/sites/ener/files/documents/2007_02_optres.pdf.
38. P. Gipe. 2017. Feed laws. Tables only through 2014. www.wind-works.org/cms/index.php?id=86.
39. Clean Energy Wire Factsheet. 2017. B. Wehrmann. High hopes and concerns over onshore wind power auctions. www.cleanenergywire.org/factsheets/high-hopes-and-concerns-over-onshore-wind-power-auctions.
40. *ExternE: Externalities of Energy*. www.externe.info/externe_d7/.
41. Carbon Monitoring for Action. www.carma.org.
42. Energy Information Administration. www.eia.gov/totalenergy/data/browser/?tbl=T12.06#/?f=M&start=200001.
43. EU ETS. https://ec.europa.eu/clima/policies/ets_en.
44. National Renewable Energy Laboratory. Transmission integration. www.nrel.gov/grid/transmission-integration.html.
45. W. Lasher. 2014. The competitive renewable energy zones process. www.energy.gov/sites/prod/files/2014/08/f18/c_lasher_qer_santafe_presentation.pdf.
46. Transwest Express. www.transwestexpress.net.
47. Western Grid Group. Proposed western transmission projects. www.westerngrid.net.

12 Economics

The most critical factors in determining whether installing wind turbines is financially worthwhile 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 a system produces electrical energy for a grid, the price for which the electrical energy can be sold is also critical. Wind farms today are competitive with all new power plants, except for combined-cycle natural gas turbines because the price for natural gas has declined from peak values due to the exploitation of shale formations. Oil prices were around $60/bbl in 2018. As natural gas replaces coal for producing electricity and as electric vehicles increase substantially, some predict a decline in oil demand and that even some oil reserves will be stranded. To increase market penetration of wind systems, the return from the energy generated must exceed all costs in a reasonable time.

All values for electricity produced by wind turbines depend on wind resources and cover a range. Installed weighted average costs for wind farms in the United States declined to $1,200/kW in 2003 and rose to $2,155/kW by 2009. The increase was due primarily to increased cost for steel, cement, and copper; then prices decreased again due to the recession. In 2016 the range was $800–$1,100/kW for wind farms [1].

U.S. DOE goals for wind turbines built for wind farms to produce electricity at $0.03/kWh for class 6 lands (6.7 m/sec annual average at 10 m height) by 2004 and $0.03/kWh for class 4 lands (5.8 m/sec annual average at 10 m height) by 2010 were not met. These values include O&M at $0.005/kWh. However, the cost of electricity from new power plants using fossil fuels also increased, so electricity from wind farms became competitive with Production Tax Credits.

Systems of 1 kW are not cost effective when connected in parallel to a utility grid, even for single residences, but people purchase them for other reasons. Residences connected to a utility grid need 5- to 10-kW systems. Farms, ranches, and businesses need a minimum size of 25 kW (about 10 m diameter) or larger. In general, installed costs for small wind turbines are around $2,500 to $5,000/kW, which translates to a value of electricity produced of $0.15 to 0.30/kWh.

The sizes of wind turbines for residences, farms, ranches, and rural applications depend on the amount and price of electricity from a grid if net metering is available and also the local infrastructure. The kilowatt-hours consumed can be determined from a monthly electric bill or by calling a local utility. To maximize the return on a wind system, most of the energy should be used on-site because it is worth the retail rate. However, net energy billing allows larger systems. A system can be sized to produce all the energy needed within a billing period.

As stated in Chapter 11, economics is intertwined with incentives and penalties, so actual life cycle costs [2] are hard to determine, especially when external factors like pollution control 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 to consider when purchasing a small wind energy system for home, business, farm, or ranch use:

1. Load (power) and energy (calculated by month or day for small systems)
2. Cost of energy from competing energy sources to meet need
3. Initial installed costs (equipment purchase, shipping, installation of foundation, utility connection, labor, and land)
4. Production of energy (wind turbine types and sizes, warranties, vendor reputation and history, reliability, and availability); wind resources including annual and more frequent variations

5. Selling price of energy produced or unit worth of energy; anticipated energy cost changes (escalations) of competing sources
6. Operation and maintenance costs encompassing general operation, ease of service, emergency services and repairs, insurance, infrastructure, availability of trained service personnel
7. Cost of money (fixed and variable interest rates)
8. Inflation (estimated for future years)
9. Legal fees (contract negotiations, land conveyances or leases, easements, and permits)
10. Depreciation (only for business)
11. National and state incentives

12.2 GENERAL COMMENTS

General uncertainties surrounding future energy costs, dependence on imported oil, reduction of pollution and emissions, and availability provided the driving force to develop renewable sources. The prediction of energy cost escalation is a hazardous endeavor because energy cost is driven primarily by oil cost. Oil cost was $15 to 25/bbl in the 1990s. Predictions in the late 1990s were for gradual increases to $30/bbl by the year 2020. However, oil reached the $30 level in 2003, soared to $130 in 2008, and is about $60/bbl in 2018. Price increases have not been and will not be uniform based on time or geography.

At the point when demand exceeds production, the price of oil will increase further. Some experts predicted that the peak of world oil production would occur in this decade; others predict the peak will be from 2020–2040. The most important factors are the estimated total reserves and amounts recoverable. As prices increase, it becomes economic to recover more from existing reservoirs and extract oil from more difficult sources (oil shale, tar sands, polar ice, deep seas).

Every effort should be made to benefit from all national, state, and other incentives for installing wind turbines. The cost of land is a real even for operators that use their own land. This cost is often obscured because it is, in essence, lost income. Wind turbines occupy space and decrease the amount of land available for farming or ranching. Land taken out of production for a wind farm can range from 0.5 to 1.5 hectares (ha) per turbine.

Wind turbine availability is important in determining the quantity of energy produced. For optimum return, the equipment must operate as much of the time as possible, consistent with safety considerations. Performance and failure data should be obtained and used to estimate downtime. Availability for earlier machines was low, but availability is now 95–98%. The distribution of energy throughout the year can affect its value. Energy produced during a time of increased demand on a utility, or when energy is needed at the site is clearly more valuable.

Wind turbines can produce electricity for consumption at or near the site, sell it to a utility, or use it and sell it. The higher the selling price, the more economically feasible a project becomes. Generally, an owner of one or more wind turbines will use some of the energy and sell the excess to a utility. The electricity used on-site displaces electricity at the retail rate. For states that use net energy billing (usually 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 a billing period, it is sold for avoided cost. For locations where retail rate is higher than the avoided cost paid for excess energy fed back to a utility, economic feasibility improves with increasing on-site consumption. The price paid by a utility is negotiated, set by law, or decided by a public regulatory agency.

Example 12.1

A wind turbine produces 2,000 kWh in a month and has 2 meters. One measures energy purchased from a 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.

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 time and parts costs. Until system reliability and durability are better known for long periods, repair costs will be difficult to estimate. It is important for an owner to clearly understand the manufacturer's warranty and the manufacturer should have a good reputation. Estimates should be made of the costs of repairing the most probable failures. Note: Even wind companies that have sold a lot of wind turbines have gone out of business, so service could be a problem in the future. Insurance costs may be complicated by companies that are uncertain about the risks posed by a comparatively new technology. However, the risks are fewer than those associated with operating a car.

Inflation will have its principal impact on expenses incurred over the lifetime of a system. O&M costs, especially for unanticipated repairs, fall into this category. On the other hand, cheaper dollars may be used to repay fixed-rate loans.

12.3 ECONOMIC ANALYSIS

Both simple and complicated economic analyses 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 period up to the lifetime of the system. The time at which earnings equal cost is the payback time. The relatively large initial cost means that the payback time could be several years, and in some cases, earnings may never exceed the costs. Of course, a short payback is preferred, and 5–7 years is acceptable. Longer paybacks should be viewed with caution.

How do you calculate the overall earnings or value of energy? If you had no source of energy for lights, television, and other uses, a cost of \$0.50 to \$1.00/kWh might be acceptable for the benefits received. Many people are willing to pay more for green power because it produces less pollution. Past green power premiums were around \$0.03/kWh for a 100-kWh block but are lower today (see Section 11.6.1.2). A few people want to be completely independent of a 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 between borrowing money for a system and lost interest if an owner or operator has enough money to pay for the system is usually about 3 to 7%. In 2003, and again after 2008, lost interest rates were very low. The easiest payback calculation is cost of the system divided by cost displaced per year, assuming that O&M needs and minimal repairs and will be done by the owner:

$$SP = IC/(AEP \times \$/kWh) \tag{12.1}$$

where SP = simple payback in years, IC = initial cost of installation in dollars, AEP = annual energy production in kilowatt-hours per year, and \$/kWh = price of energy displaced.

Example 12.2

You purchase a 300-kW wind turbine for battery charging. Installed cost = \$900. The unit produces 220 kWh per year at \$0.50/kWh (estimated cost for remote electricity).

$$SP = \$900/(220 \text{ kWh/year} \times 0.50 \text{ \$/kWh})$$

$$SP = 900/110 = 8 \text{ years}$$

The next calculation includes the value of money, borrowed or lost interest, and annual operation and maintenance costs:

$$SP = \frac{IC}{\left(AEP^* \frac{\$}{kWh} - IC^*FCR - AOM\right)} \tag{12.2}$$

where FCR = fixed charge rate per year and AOM = annual operation and maintenance cost in dollars per year.

Example 12.3

You purchase a 3.5-kW wind turbine with inverter to connect to the grid. Installed cost = \$14,000. The unit produces 6,000 kWh per year. You are losing interest at 4% on the installed cost. Retail rate of electricity is \$0.11/kWh. Assume AOM of \$50 per year.

$$SP = 14,000/(6,000 \times 0.11 - 14,000 \times 0.04 - 50) = 14,000/(660 - 560 - 50) = 280 \text{ years}$$

You would think twice before purchasing this system on an economic basis.

The FCR could be the interest paid on a loan or the value of interest that would have been received from money displaced from savings. An average value for a number of years (5) will have to be assumed for cost per kilowatt-hour for displaced electricity because the future costs of electricity from a utility may be difficult to estimate. In general, electric rates do not fluctuate much or increase rapidly. The one change with deregulation is that fuel adjustment cost can change quickly.

Example 12.4

You purchase a 50-kW wind turbine. Installed cost = \$120,000. The unit produces 120,000 kWh per year. AOM = 0.01 × IC = \$1,200 per year. FCR = 0.07. Retail rate of electricity is \$0.11/kWh.

$$SP = 120,000/(120,000 \times 0.11 - 120,000 \times 0.07 - 1,200) = 120,000/(13,200 - 8400 - 1200)$$

$$SP = 33 \text{ years}$$

Equation (12.2) involves several assumptions: The same kilowatt-hours are produced each year, the value of the electricity is constant, and no inflation occurs. More sophisticated analyses would include details such as escalating fuel costs of conventional electricity and depreciation. In general, these factors 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.

$$COE = (IC \times FCR + AOM)/AEP \tag{12.3}$$

TABLE 12.1
Range of Energy Costs for Small Systems (Wind Class 4 to 2)

System, kW	$/kWh
1	0.15–0.25
10	0.12–0.18
50	0.10–0.15
100	0.10–0.15

The COE is one measure of economic feasibility and is compared to the price of electricity from other sources (generally a utility company) or the price for which wind-generated energy can be sold. If you are purchasing a wind turbine to displace electricity on-site, the COE should be compared with a projected 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 sizes of 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 O&M costs.

Example 12.5

You purchase a 50-kW wind turbine. Installed cost = $120,000. The unit produces 120,000 kWh per year. AOM = 0.03 × IC = $1,200 per year. FCR = 0.08. Retail rate of electricity is $0.11/kWh.

$$\text{COE} = (120{,}000 \times 0.08 + 3600)/120{,}000 = \$0.11/\text{kWh}$$

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 the Electric Power Research Institute (EPRI) [3] is similar to Equation (12.3). There are additions for levelized replacement costs (major repairs) and fuel costs for conventional power plants. Because the cost of fuel for wind energy is zero, that term will be left out:

$$\text{COE} = \frac{(\text{IC*FCR}) + \text{LRC} + \text{AOM}}{\text{AEP}} \tag{12.4}$$

where LRC = levelized replacement cost (dollars per year) and AEP = net annual energy production (megawatt hours or kilowatt-hours per year). The COE can be calculated for cost per kilowatt-hour or cost per megawatt hour and the last term could be separate as AOM/AEP, cost per kilowatt-hour, or cost per megawatt hour. 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 to 5% of installed cost.

Example 12.6

The unit is a 1-MW wind turbine. Installed cost = $1,600,000. FCR = 0.08. AEP = 3,000 MWh per year. LRC = $80,000 per year. AOM = $8/MWh = $0.008/kWh.

$$\text{COE} = \frac{(1{,}600{,}000 \times 0.08) + 80{,}000}{3000} + 8 = \$77/\text{MWh} = \$0.077/\text{kWh}$$

That cost of energy must be compared to all expected net income from the wind farm, including incentives, depreciation, and expected rate of return.

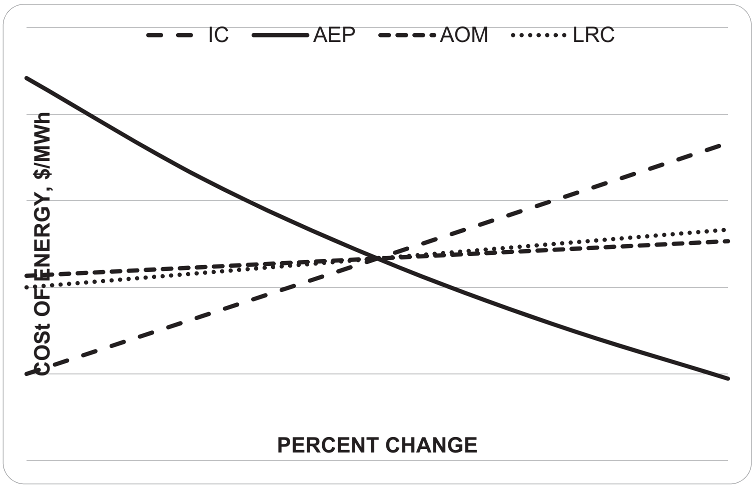


FIGURE 12.1 Sensitivity analysis for cost of energy for wind turbines.

Levelized replacement cost distributes the costs for major overhauls and replacements over the life of a system. For example, storage batteries in a village power system must be replaced every 5 to 7 years. The levelized replacement cost can be calculated with Equation (12.5) below. The result will be an estimate for future replacement costs based on present costs of components:

1. Year in which replacement 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 calculated as

$$PV(n) = PVF(n) \times RC(n) \tag{12.5}$$

where PVF(n) = present value factor for year; n = $(1 + I)^{-n}$; I = discount rate of 0.07; and RC(n) = replacement cost in year n. The levelized replacement cost is the sum of present values multiplied by the capital recovery factor (CRF):

$$LRC = CRF \times \sum_{n=1}^{20} PV(n) \tag{12.6}$$

where CRF = 0.093.

Example 12.7

This spreadsheet can be used to calculate levelized replacement cost (LRC) for a 50-kW turbine.

Component	Years	RC	I	PVF	PV
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			

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 [4] for estimating the value of energy is

$$\frac{f_0}{c} \geq \frac{(1+r)^L \alpha r L}{\left[(1+\alpha)^L\right]\left[(1+r)^L - 1\right]} \tag{12.7}$$

where f_0 = value of energy saved per year (dollars); c = initial installed cost (dollars); L = years to payback; α = fuel inflation rate; and r = interest rate.

Because there is no factor for O&M, the interest rate should be increased by 1 to 2%. Equation (12.7) can be solved by iteration using different values of L to calculate the right side and comparing that to the left side of the equation. As interest rates increase, payback times increase. As fuel inflation factors and electricity costs increase, payback times decrease.

12.4 LIFE CYCLE COSTS

A life cycle cost (LCC) analysis reveals the total cost of a system including all expenses incurred over the life of the system and salvage value, if any [2,5,6]. Two reasons to conduct an LCC analysis are to (1) compare different power options and (2) determine the most cost-effective design. The competing options to small renewable energy systems are batteries or small diesel generators. For these applications, the main concerns are the initial cost of the system, the infrastructure to operate and maintain the system, and the price people pay for the energy. However, even if small renewable systems are the only options, LCC analysis can be helpful for comparing costs of various designs and determining whether a hybrid system would be a cost-effective option. An LCC analysis allows a designer to study the effects of different components with different reliabilities and lifetimes. For instance, a less expensive battery may be expected to last 4 years, while a more expensive battery may last 7 years. Which is the best buy? This type of question can be answered with an LCC analysis:

$$LCC = IC + M_{PV} + E_{PV} + R_{PV} - S_{PV} \tag{12.8}$$

where LCC = life cycle cost, IC = initial cost of installation, M_{PV} = sum of all yearly O&M costs, E_{PV} = energy cost (total 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), usually 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 but replacement costs for components must be calculated. Present worth factors are given in tables or can be calculated. Life cycle costs are the best bases for purchasing decisions and show that many renewable energy systems are economical.

The financial evaluation can be done yearly to determine cash flow, break-even point, and payback time. A cash flow analysis will be different in every 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 by graphing data. Bergey Windpower has a spreadsheet that can be downloaded on its website for calculating cash flow analysis (http://bergey.com/technical).

Example 12.8

The example is a 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 per year, energy production = 50,000 kWh per 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 analysis should be done on a spreadsheet.

Year	0–1	2	3	4	5	6	7	8	9	10
Down payment	7,000									
Principle 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	500
Insurance	50	50	50	50	50	60	60	60	60	60
Property tax	70	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	630
Value energy used	3,000	3,090	3,183	3,278	3,377	3,478	3,582	3,690	3,800	3,914
Value energy sold	500	515	530	546	563	580	597	615	633	652
Rebate	4,000									
Income	7,500	3,605	3,713	3,825	3,939	4,057	4,179	4,305	4,434	4,567
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 year 8. There are a number of assumptions about the future in the analysis. A more detailed analysis would include inflation and increases in O&M costs as equipment ages.

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 business expenses. The economic utilization factor is calculated from the ratio of the costs of electricity used at a site to the costs of the electricity sold to the utility.

The RETScreen tool [7] consists of standardized and integrated renewable energy project analysis software that can be used to evaluate energy production, life cycle costs, and greenhouse gas emission reductions for several 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 [8] includes economic analysis.

The cost of energy for wind, PV, and solar thermal has decreased dramatically since 1980 (Figure 12.2). The variability from \$3 to \$10/MWh is due primarily to the value of the renewable resource and the installed costs. In 2017, corporations in 10 different countries signed power purchase agreements (PPA) for 5.4 GW of renewable energy, much of it being wind power.

The weighted average cost for PPAs for wind in the United States was around \$20/MWh (2016 data for nine projects) and the median bid for a 100-MW project in Colorado in 2017 was \$18.10/MWh. These are cheaper than gas-fired generation at \$40/MWh and much cheaper than nuclear at \$100/MWh. However, other factors need to be considered; gas should have a carbon cost added to the generation cost, volatility of price of gas, and shorter term contract and wind needs the added cost of managing variability.

In Europe, auctions in 2017 for wind energy ranged from €43–57/MWh compared to gas-fired generation at \$60/MWh. Power purchase agreements around other parts of the world are even lower; India, \$37.8/MWh; Dubai, \$29.9/MWh; Mexico, (\$22/MWh); and Chile, \$29.1/MWh. Of course, offshore wind is higher, around double. Wind Europe has offshore wind at €100/MWR by 2020 and

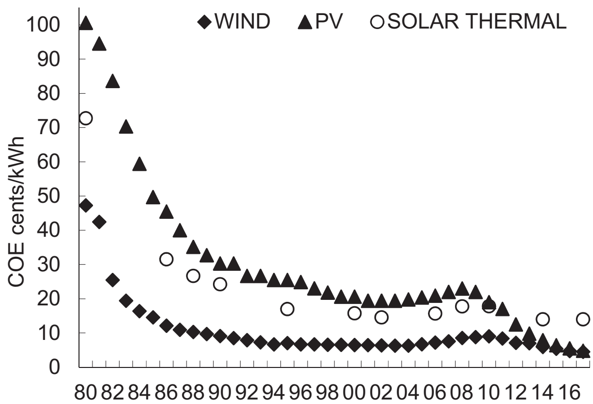


FIGURE 12.2 Cost of energy for generation of electricity; wind, photovoltaic, and solar thermal energy (2017 dollars).

€70 to €85/MWh by 2025. The International Renewable Energy Agency [9] has a renewable cost database (15,000 utility scale projects and 5,600 PPAs) plus interactive map and costs (LCOE and installed costs) [10].

An economic cash flow model, cost of renewable energy spreadsheet tool (CREST), and a simplified levelized cost of energy calculator are available from NREL [11]. CREST is a suite of four analytic tools, for solar (photovoltaic and solar thermal), wind, geothermal, anaerobic digestion, and fuel cell.

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 that 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:

$$PW = \frac{(\text{cost total for year S}) - (\text{financial benefit total for year S})}{(1+d)^M} \tag{12.9}$$

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 over 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 a bank or lost opportunity cost) is appropriate. Possibly the rate of return on a given investment perceived as desirable 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:

$$\text{annualized cost} = \frac{PWd(1+d)^P}{(1+d)^P - 1} \tag{12.10}$$

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 step 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 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 sources of energy.

RETFinance is an Internet-based cost of electricity model 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 considering the effects of inflation. A number of sites on the Web show inflation calculations from past years to the present [11]. Of course, the amount of inflation in the future is a guess, but most people assume the number will be positive.

12.6 EXTERNALITIES

Externalities now play a role in integrated resource planning (IRP) as future costs for pollution, carbon dioxide, and other factors are added to 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 assigned by legislation and regulation (public utility commissions).

As always, both sides will litigate. 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 other entities. It focused its protest on values assigned to CO_2 emissions based on an acknowledged lack of reliable science proving that CO_2 emissions are harmful to society. In Europe, different values assigned to CO_2 emissions make wind energy more cost competitive.

Wind turbines have three main beneficial externalities; (1) local sources of energy, (2) no requirement for water to aid generation, and (3) no emissions of greenhouse gases. In Texas, fossil fuel power plants use 1,670 L/MWh [12] of water per year, so the 22.6 GW of wind power in Texas (2017) will save about 11×10^7 m^3 of water per year. An average of 700 kg of CO_2/MWh is emitted from coal and natural gas power plants. The 22.6 GW of wind in Texas will reduce CO_2 emissions by around 47×10^6 metric tons per year. The present value for CO_2 trading in Europe is around $16/metric ton.

12.7 WIND PROJECT DEVELOPMENT

The three most important considerations for the development of wind farms are (1) land with good to excellent wind resources, (2) contract to sell produced electricity, and (3) access to transmission lines (proximity and carrying capacity). The American Wind Energy Association [13,14] has information on project development. Some wind manufacturers publish information about project development on their websites. *Wind Energy Engineering* has a chapter on planning and execution of wind projects [15]. The project development list covers many areas but it is based on economics because the final decision to proceed is based on economics. Much of the information came from Disgen [16].

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)
- Term: 20 years, with option to terminate early
- Installation bonus: $2,000/MW plus security deposit

- Royalty: 4%, years 1 through 10; 6%, years 11 through 20; minimum annual royalty projected income stream
- Wind turbines: 48 Vestas V47 660 kW
- RECs: Royalty paid if any value realized
- Removal bond: Mutual agreement
- Hunting: Company indemnified
- University audits: Independent outside auditor
- Meter calibration: Every 3 years
- Curtailment: Shared by all landowners

A wind farm landowner may receive one or more offers, and the lease terms (Table 12.2) will differ by region, wind resources, and access to transmission. Some landowners are forming associations for dealing with wind farm developers. In general, a landowner in the United States has three options for payment of electricity generated by a wind farm: (1) percent royalty on net production; (2) per turbine payment of $4,000 to 6,000 per MW; (3) larger value of (1) or (2) for each year.

If a landowner signs a lease and a wind farm is constructed, there is no guarantee that a wind turbine will be placed on that land, so the only payment received would be for roads and/or transmission lines. Some developers guarantee at least one wind turbine for each landowner and some farmer associations have provisions for sharing payments across the association. In the United States, wind turbines can be installed on land currently under the Conservation Reserve Program (CRP), but penalties or reimbursements may be decided by the CRP district.

Other considerations for the landowner are who certifies the energy meter and how often. The landowner should share future revenue from pollution credits. In countries where national or state governments control the land, the questions concern present occupants. In addition to determining who receives payments (once or annually), the amount to be paid for land removed from previous use must be settled.

The development of a project will take 1.5 to 3 years; the construction phase will take 6 to 12 months, but total development time from land selection to commissioning may take up to 6 years (Table 12.3). Problems of economics, financing, and access to adequate transmission can extend the time beyond 6 years. Wind farms can be installed much faster than transmission lines can be built.

12.7.1 Costs

The weighted average installed costs [17] in 2016 for onshore wind farms were $1,245/kW in China, $1,121/kW in India, $1,994/kW in Brazil, $1,800 in Europe, and 1,775/kW in North America.

TABLE 12.2
Representative Lease Terms for a Wind Farm

Resource	1–3 year
Flat fee or	$10,000
$/acre/year	$1–$4
Contract	30 year
Option	2 (10 year)
Construction, road, etc.	$3–$4/m
or flat fee	$4,000/MW
Income/year	
Royalty and/or	4%–6%
per turbine (minimum)	$4,000–$6000/MW
Escalation	0.5% every 5 year

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 6–12 months
Install anemometers, collect and analyze data 12–24+ months	Turbine purchase agreement 12–24 months	Commission 1–2 months
◄————————	Developer (36–72 months)	————————►
◄————	Turbine supplier (12–24 months)	————►

Offshore cost in 2016 for Europe was $4,487/kW. O&M costs for onshore wind farms range from $0.01 to 0.025/kWh and for offshore installations range from $0.027 to $0.048 because of the difficulties of the environment. The levelized cost of energy at good wind sites was $0.06 to 0.14/kWh.

The installed costs [18] for wind farms in the United States (Figure 12.3) increased from around $1.2 million/MW in 2004 to $1.7 to 2.2 million in 2010. The fairly wide range of installed costs depends somewhat on project size and region. Prices started to increase after 2004 because of the increases in the prices of steel, copper, and cement. Then, due to the recession and larger turbines with better economics, costs decreased. In general, 30 MW is required to achieve economies of scale, primarily for installation. For example, the cost of a crane to install a single 3-MW wind turbine is not economical.

The world largest offshore wind farm, the London Array (630 MW, commissioned in spring 2013), cost an estimated $4.4 million per MW. The installed cost for offshore wind farms in Europe is around two to three times the cost of wind farms on land. However, because the offshore winds are better and land costs are high, offshore wind farms are economical in Europe.

A comparison of the estimated components of the cost of energy formula shows, as expected, that capital cost is the major component and the primary capital cost of a project is for wind turbines (Table 12.4). For offshore wind farms, the wind turbine is around 40 to 50% of the installed costs.

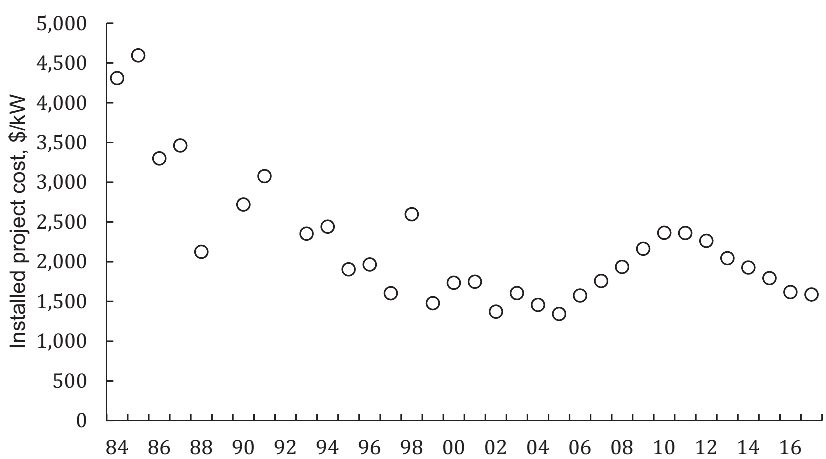


FIGURE 12.3 Weighted average installed costs for wind projects in the United States. Data from over 900 projects, 2016 dollars. (2016 Wind Technologies Market Report.)

TABLE 12.4
Wind Farm Installation Component Costs (%)

Component	%
Turbine	74–82
Foundation	2–5
Electric	2–7
Connection to the grid	3–7
Finance	1–5
Land	1–3
Roads	1–5
Consultants	1–3

12.7.2 Benefits

Wind farms represent rural economic development. The primary benefit to landowners is long-term stable income (no fluctuations typical of commodity prices). 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) and the site could include 10 to 30 landowners. Around 1 to 3% of the land will be removed from production, primarily for roads. The return from a wind farm on land removed from previous use is around $10,000 to 16,000/ha/year—a far greater return per hectare than farming or ranching. In contrast to oil and gas leases, the return on a wind farm is lower, but it presents the big advantage of a non-depletable resource.

Rural economic development involves construction and then operation. Construction will create 100 to 200 jobs for 4 to 8 months (about one man year per megawatt). The administration, operation, and maintenance of wind farms require 6 to 10 people per 100 MW. The long-term economic impacts at county level across the Great Plains of the United States [19] was estimated at approximately $11,000 per megawatt for annual earnings from 2000 through 2008. This shows why state legislatures and local entities promote wind power and also promote area manufacturing of turbines and components.

The Colorado Green Wind Power Project near Lamar is an example. Construction started in summer, 2003. The 162-MW project consists of 108 GE wind turbines (1.5 MW) on a lease of 4,450 ha from 14 landowners. The footprint from the wind farm is about 2% of the land. Construction created 200 to 300 jobs and operation after completion involved about 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 Sales of Electricity

The crunch number for a wind farm project is the sale price of electricity generated. For some older contracts in Texas, the sale price was below $25/MWh for 15 years. The only way this could happen was utilizing the production tax credit, accelerated depreciation, tax abatements, and renewable energy credits (RECs). For wind farms installed today in the United States, the production tax credit is still the main driver. Sale contracts were higher through 2005–2012, but declined from 2015–2018. Some wind farms sell electricity in the wholesale and merchant markets. One selling price is the mandatory avoided cost. The minimum value that should be paid is the fuel adjustment cost of the utility.

The levelized COE is estimated for a 50-MW wind farm in the Panhandle of Texas with class 4 winds. The wind turbines are rated at 1 MW and sited on 70-m towers. The installed cost (2017 dollars) is around $1,000/kW, and from Example 12.6, the COE is $48/MWh. A production tax

credit (PTC) of $24/MWh plus other factors such as accelerated depreciation assist in the return. Therefore, the wind farm developer would need to obtain around $24/MWh. The value to the landowners can be estimated as:

$$\text{AEP} = 50 \times 3 \times 10^6 \ \text{kWh/year} = 1.5 \times 10^8 \ \text{kWh/year}$$

The $24/MWh (landowners will not receive PTC) generates $3.6 million per year and at 4% royalty, the landowners receive $140,000/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 is $7,000/ha/year. This is much more than a farmer or rancher would earn from crops and livestock.

The wind farm will also pay property taxes. However, in many cases, they try to obtain tax abatements for some period based on economic development. Instead, the wind farm will pay some amount in lieu of taxes, primarily for schools.

Quarterly data on megawatt hours generated, income, and rates paid to wind farms can be obtained from the Federal Energy Regulatory Commission (www.ferc.gov/docs-filing/eqr.asp). However the reports cover all types of electricity generation of electricity so a user must know the reporting name of a wind farm to access specific data. 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 determined from the rate (power purchase agreement at fixed rate, power purchase agreement with peak and off-peak values). For market sales, the database shows high and low values plus averages. As an example, for 2011, the Wildorado Wind Ranch received $18.1 million for 644 GWh from an average power purchase agreement of $28.12/MWh. Because the farm has an installed capacity of 161 MW, the capacity factor for the year was 45.7%.

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 Alaska, the average price was $0.38/kWh for a village electric cooperative powered by diesel gensets. In 2017 the cost of village electricity was from $0.40–0.50/kWh. Note that a significant amount of wind has been added to village systems, which has reduced costs. The expense breakdown is as follows:

	2004%	2008%	2015%
Fuel	46	77	48
Operation and maintenance	21	9	6
Renewal and replacement	19	8	21
Customer account expense			11
General and administration	14	6	14
Total	100	100	

Three 100-kW wind turbines produce around 675,000 kWh/year as part of a wind–diesel plant at Toksook Bay, Alaska. The turbines displace 196,000 L of diesel fuel per year. If the bulk price of diesel is $1.50/L or even more, the annual savings are $300,000 per year. If the installed cost for the wind turbines was around $1.5 million, the simple payback would be 5 years. In 2017, bid price for bulk diesel in remote Alaska was around $1.90/L.

At St. Paul Island, Alaska, the installed cost was $905,000 (1999 dollars) for a wind–diesel system that provided power to an industrial complex (no grid). The high-penetration, no-storage system consisted of one 225-kW wind turbine 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 dollars). Since

then, two more turbines (225 kW) have been added to support economic development and generate enough power for residential consumption.

For villages in Nunavik, Canada served by Hydro Quebec, diesel fuel represented 54% of the operation costs. In some remote communities in Canada, the cost of electricity is over $1.00/kWh. In the Maldives Islands, diesel cost ranged from $1.10 to 1.22/L, so at a conversion rate of 3.65 kWh/L, the fuel cost for producing electricity was $0.33 kWh. On small islands that have little infrastructure, diesel fuel is delivered in barrels.

On Ascension Island, the simple payback was estimated at 7 years for the addition of two 900-kW wind turbines in a high-penetration system. This saves an additional 2.4 million L of fuel per year. For diesel fuel at $1.50/L, the savings would be $3,600,000/year and the simple payback would be around 3 years. Most wind–diesel system results are not so dramatic. High-penetration systems should also save on diesel maintenance, because the diesel gensets will not operate as many hours but more on and off switching could increase O&M costs.

Two wind turbines (225 kW) were installed on Thursday Island between Australia and Papua New Guinea. They produced around 1,700 MWh per year and saved around 434,000 L of diesel fuel annually so the payback time is estimated at 7 years.

Costs for renewable village power systems vary widely as shown below.

Company	Size (kW)	Wind (kW)	PV (kW)	Battery (kW)	Inverter (kW)	Energy (kW/year)	Cost
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 systems consist of components from various suppliers and manufacturers and are located in remote areas. The best example is China's SDDX project (2002–2005) consisting 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. The total investment was 4.7×10^9 Yuan (about $570 million), or an average of $4,370/kW [20, Chapter 6].

The cost was $178,000 for one village hybrid system (Figure 12.4) in a remote region of China (2003 dollars) for all systems including power generation and mini grid transmission lines. The configuration is two 10-kW wind turbines, 4-kW PV power, 30 kVA diesel generation, 1,000 Ah battery bank, and a 38 kVa DC–AC inverter. At 54 kW, the installed cost was $3,300/kW—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 energy supplied by the diesel generator, cost of diesel fuel, levelized replacement costs, and O&M costs. A known major cost is battery bank replacement every 5 to 7 years.

Small hybrid systems that can be set up as modular units are available. Most manufacturers do not supply prices on their websites. Shipping and installation to remote locations will increase the cost, sometimes to double the cost of the energy components. Energy cost can be estimated from the initial cost and projected energy production.

For village power, the source choices are wind, PV, or hybrid wind–PV. A life cycle cost analysis for a hybrid system can determine the ratio of wind to PV energy. The advantages of PV are the lack of moving mechanical parts and placement 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%; the solar capacity factor 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. Installed costs are lower for wind power than for PV, so the reason for choosing wind power is obvious. That is also the reason that hybrid systems generate more from wind than PV power—five times or more. Since PV prices have dropped dramatically they will become a bigger part of hybrid systems.

FIGURE 12.4 Hybrid (wind–PV–diesel) renewable village power system for Subashi, Xinjiang Province, China. (Photo courtesy of Charlie Dou.)

12.9 SUMMARY

Wind farms are the cheapest renewable energy sources for generating electricity, although PV is becoming more competitive. The cost of energy (COE) from wind turbines decreased from over \$0.50/kWh in the 1970s to less than \$0.05/kWh. In 2000, NREL projected the COE through 2020 (Figure 12.5). The projections for 2005 and later were too low, primarily because of the increased costs of materials and oil as the COE for wind farms rose to \$0.07 to 0.12/kWh in 2011. The earlier numbers in Figure 12.5 represent cost of energy for a class 6 wind resource. Starting in 1995, the change was made to class 5 and class 4 winds. Now with the present day costs, wind farms are being built in class 3 regimes.

Wind is cheaper than other renewable sources of energy for producing electricity (Figure 12.6), and is competitive with new fossil fuel plants (except combined-cycle natural gas turbines at \$3/mcf). Also, the numbers are averages for a range. The range for wind energy depends primarily on wind resources and installed costs. The wind farm business is much like the oil and gas business, except it is much easier to prospect for wind and the resource is non-depletable. As externalities are added to fossil fuel costs, wind energy becomes the most economical method of generating electricity. Of course, wind cannot provide all the electricity needed because of its variability. If an

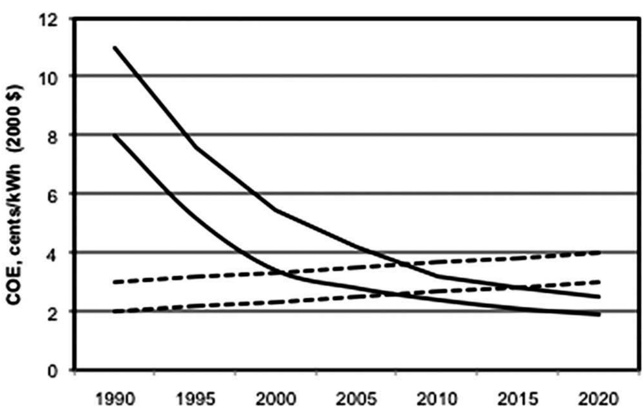


FIGURE 12.5 Cost of electricity from wind turbines to 2002 and projected future costs. Solid lines for high and medium wind regimes, dashed lines, bulk power generation. Values from NREL graph.

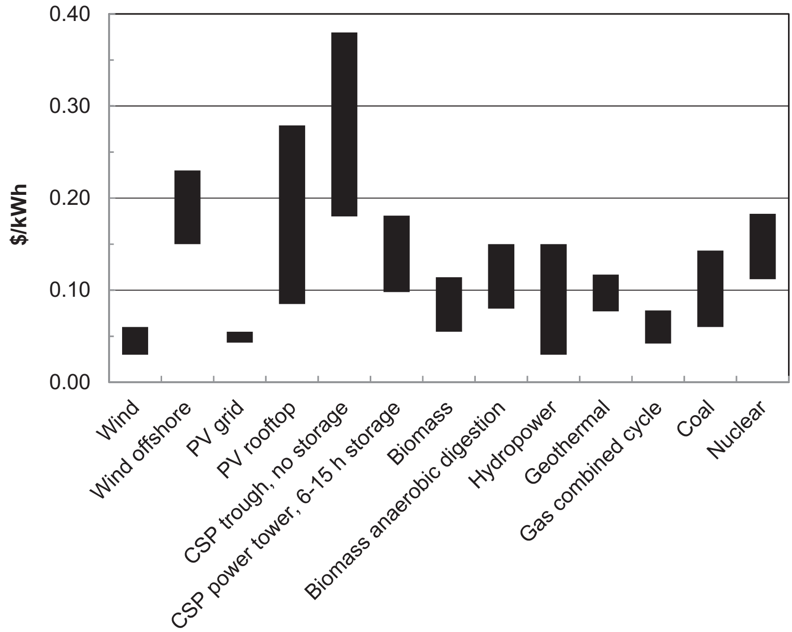


FIGURE 12.6 Levelized cost of energy (2018).

effective and economical storage system becomes available, the markets for all types of new power plants will change.

Economic considerations, legal requirements, and voluntary acceptance will lead to more use of renewable energy. Traditional energy sources have the advantage that fuel costs are not taxed but renewable energy incurs no fuel costs. The issue for renewable energy is high initial cost. Most consumers would rather pay for fuel as they use it. In 2017, small (10-kW) wind turbines were not generally cost-competitive with electricity from grids. However, if life cycle costs are used or if rebates are available, wind turbines are competitive in some locations.

Green pricing is now available from many utilities. At the beginning, the premium was around \$0.03/kWh for a block of 100 kWh per month; however, rate premiums continue to drop. In the United States, 2016 voluntary green power sales were 95.5×10^6 MWh, with 6.3 million participants.

The capacity of existing transmission lines and the curtailment of wind farms are major problems. Another issue is the distance of wind resources from major loads. New transmission lines have been built and others are being considered. The questions arising from deregulation are decisions about who will finance construction and who will overcome 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 assigned by legislation and regulation and litigation may have to decide which parties will pay external costs.

New wind farms in 2017 had power purchase agreements of \$20/MWh, a very competitive number, however past PPAs had values \$30–80/MWh. There are also merchant or market sellers that, in the past, received more income than PPAs, from \$10 to 20/MWh more. However there is a problem with large wind capacity, especially when there is more total generation capacity on the grid than demand. That means curtailment or negative price at times of low demand on the grid for MWh delivered. Some negative price can be offset by the production tax credit (remember 10-year limit).

The market rate is based on 5-minute intervals and has large volatility, high price for high demand and negative price for low demand. For example, a wind farm in the Panhandle of Texas commissioned in 2001 had a fixed rate for 15 years and now is selling at the market rate. For the fourth quarter of 2017, maximum was \$218/MWh and minimum was a negative \$132/MWh with

an average of $13.3/MWh on production of 27,200 MWh. That return is low and probably only covers payments to landowners and O&M. So, the wind farm owner has the following options: do not perform repairs and only cover ordinary O&M, decommission, or repower. The American Windmill Museum shuts down their 660-kW wind turbine at night because of the negative price of electricity.

Another major driving force for renewable energy is economic development and job creation at local or state levels. Renewable energy is produced locally; it does not have to be shipped from another state or country.

12.10 FUTURE DEVELOPMENTS

Predictions about the future are always risky and generally wrong about specifics, but some trends are fairly clear. For example, a prediction of the price of oil at $200/bbl by 2020 was questionable and is now obviously way off unless there is a major war in the Middle East. Here are our observations about the future of wind energy made in 2008.

1. A distributed wind market very similar to the present farm implement business will develop. This prediction has not been realized as there has not been the price reduction for small wind compared to megawatt wind turbines. A farmer, rancher, or agribusiness owner will obtain a bank loan for a wind turbine of 25 to 1,000 kW. He will expect a payback of 5 to 7 years and the system will make money for him for the next 15 years. One great advantage of earnings from wind-generated energy, the value of energy displaced (retail rates), and the avoided cost for electricity is that unlike other agriculture commodities, the benefits will not fluctuate.
2. Major transmission lines will be built from the windy U.S. Plains areas to load centers. This prediction has been realized and other lines are under consideration. Lines will also be built in other countries that install large wind projects to produce electricity. Wind energy has become an economic competitive source of electricity.
3. The United States will implement carbon dioxide trading similar to the system of trading in NOX and SOX. Who knows when carbon tax or trading will be realized for the United States, even though it is obvious it is needed to combat global warming. The La Venta II wind farm (83 MW) in Oaxaca, Mexico, displaces 205,380 tons of carbon dioxide annually. 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 will increase by $0.03 to 0.04/kWh if the avoided CO_2 is worth $30/ton.
4. Cooperative wind plants of one to ten units will become common. Because of economies of scale, groups of farmers will form cooperatives to buy larger wind turbines. This has been realized through distributed wind.
5. Our low estimate for global wind capacity for large turbines was 600 GW by 2020 and 1,000 GW by 2030, based on an average linear increase of 40 GW per year. At the end of 2012, world installation was 282 GW and at end of 2017, world installation was 536 GW, so that low estimate will be reached. Another estimate is 1,400 GW by 2030 based on goals for the United States, China, and Europe. Past global and national forecasts for wind capacity were always underestimated, but the past exponential (2016) growth rates of 28% per year (1995 through 2012) will decrease (11% for 2017) and at some point change to linear growth or less.

Figure 1.15 shows that exponential growth. The Global Wind Energy Council forecasts (2016) 792 GW by 2020 (a reduction from previous prediction of 832 GW), and 1,776 GW by 2030. The International Energy Agency predictions have always been low, 415 GW by 2020 and 572 GW by 2030. The United States has a goal of 20% of electricity from wind by 2030 [21], which would

require a capacity of 304 GW. China has goals of 200 GW by 2020 and 400 GW by 2030. Europe [22] has goals of 180 GW by 2020 and 300 GW by 2030.

As stated in Chapter 2, the world faces a tremendous energy problem and a number of organizations have sounded the warning and suggested solutions [23–25]. The first priorities are conservation and energy efficiency, followed by the increased use of renewable energy. Wind has now become part of national energy policies, which is reflected in the large wind capacity across the world.

PROBLEMS

1. What are the two most important influences on the cost of energy?
2. Calculate the simple payback for a 1-kW wind turbine (stand alone with battery) on a 20-m tower. The turbine produces 2,000 kWh per year. Estimated installed cost $8,000. Assume O&M and FCR = 0.
3. Calculate the cost of energy according to Equation (12.3) for a 400-W wind turbine. Installed cost of $2,000 includes 10-m tower and battery. Annual energy production is 400 kWh. Assume FCR and AOM = 0.
4. Calculate the cost of energy according to Equation (12.3) for a 10-kW wind turbine (grid connected) on a 30-m tower in a good wind regime. Installed cost = $60,000. Estimate the AOM and FCR. You can use a simple method to estimate annual kilowatt-hours.
5. Calculate the cost of energy from Equation (12.4) for a 50-kW wind turbine that produces 120,000 kWh per year. The installed cost is $200,000; fixed charge rate is 6%; O&M represents 1% of installed cost, and levelized replacement cost is $4,000 per year.
6. Estimate the years to payback using Equation (12.7). IC = $150,000, r = 8%, AEP = 120,000 at $0.09/kWh. Assume a fuel escalation rate of 4%. This problem must be done numerically. Assume L, calculate, and then modify L in terms of your answer and calculate again.
7. Explain life cycle costs for a renewable energy system.
8. In 2017, the COE for wind was around $40–55/MWh. What is the estimated COE for electricity generation (large plants) for photovoltaic, solar thermal, biomass, and geothermal energy?
9. The estimated cost of energy from a wind farm is around $0.05/kWh (2017). Make a comparison to proposed new nuclear power plants. What is the COE (retail rate) for the newest nuclear plants installed in the United States? (Do not calculate, instead, use an estimate from any source.)
10. What are today's values for fuel inflation, discount rate, and interest rate? What is your estimate for 5 years into the future?
11. A 100-MW wind farm (100 turbines, 1 MW) is installed in a class 4 wind regime. The production is around 3,000 MWh per turbine annually. The utility company pays about $30/MWh for the electricity produced. Estimate the yearly income from the wind farm. If the landowners receive 4% royalties, how much do they receive per year?
12. For the previous problem, assume installed costs are $1,200/kW, FCR = 6%, capacity factor = 35%, and AOM = 0.01/kWh. Calculate the COE using Equation (12.4). You will need to estimate the levelized replacement costs or calculate LRC using Equations (12.5) through 12.7. Compare your answer to the $0.03/kWh estimated price the wind farm receives. How can the wind farm make money?
13. The wind farm boom in Texas led to the installation of more than 10,000 MW from 2005 to 2012. Why? Explain in terms of economics.
14. From 2014–2017, Texas continued to lead the nation in new installations. Why?
15. What is the price of oil (dollars per barrel) today? Estimate the prices of oil for 2030. Compare the estimate to the U.S. Energy Information Administration projections for the same year.

16. Estimate the price for oil (dollars per barrel) if the costs for the U.S. military to keep the oil flowing from the Middle East were added.
17. Why were wind turbines installed primarily in California from 1981 through 1985? Discuss in terms of economics.
18. How much should the U.S. government fund for conservation and efficiency, renewable energy, and wind energy contain? Compare your answer to the fiscal year 2017 budget for the same items. What did the budget allocate for fossil fuels and nuclear energy (nuclear fusion counts)? See the Links section at the end of the chapter.
19. For students from countries outside the United States: At what dollar level should your national government fund renewable (wind) energy? What should it fund for fossil fuel and nuclear energy? Compare your results to the national budget for the current fiscal year or the latest year for which information is available.
20. Estimate the cost of energy for a hybrid system. 10-kW wind, 1-kW PV. Installed costs estimated at $100,000. AEP around 20,000 kWh/year. You will have to estimate FCR and O&M.
21. Estimate the cost of energy 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 per day, FCR = 0.03, and 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 of 65,000 kWh, FCR of 0.03, and AOM of $0.01/kWh. Calculate the cost of energy. How does the cost compare to the present rate you pay 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). This only covers data up to 2nd quarter 2013. Use Llano Estacado Wind (White Deer, installed capacity = 80 MW) or another wind farm. If you use another wind farm you will need to obtain data on MW and installed costs.

24. What is the rate of the power purchase agreement?
25. Installed cost was $1 million/MW or $80 million. For 2011, what was the income generated? Assume that 2011 was an average year. What is the time of simple payback?
26. For Problem 25, consider an 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 2011.
28. Find a wind farm in the United States that sells electricity at the market rate. State quarter, what are the high, low, and average rates (dollars per megawatt hour)?
29. What is the world installed wind capacity? What is your estimate for 2030?
30. What is the goal for your country for wind power for 2030?
31. Go to Lazard's levelized cost of energy for latest values (see Links). State year. What is the LCOE for wind? For utility scale solar? For rooftop solar?
32. What is the cost to the government for wind installed in 2017 (7 GW) in the United States? PTC is $0.024/kWh for 10 years. Assume capacity factor of 35%.

LINKS

Wind Europe. Economics. https://windeurope.org/policy/topics/economics/.

National Renewable Energy Laboratory. Energy analysis. www.nrel.gov/analysis/.

National Renewable Energy Laboratory. Image gallery. http://images.nrel.gov (photos of wind turbines and projects: small systems, grid connections, village power, and hybrid systems).

U.S. Department of Energy. EERE. Budget & Performance. www.energy.gov/budget-performance.

Lazard's Levelized Cost of Energy Analysis. www.lazard.com/perspective/levelized-cost-of-energy-2017/.

Open Energy Information. Transparent Cost Database. Very informative, has information on generation (LCOE, overnight capital cost, fixed operating cost, variable operating cost, capacity factor) fuels, and vehicles. https://openei.org/apps/TCDB/.

REFERENCES

1. R. Wiser and Bolinger et al. 2016. Wind technologies market report. DOE, EERE. www.energy.gov/sites/prod/files/2017/10/f37/2016_Wind_Technologies_Market_Report_101317.pdf.
2. R.J. Brown and R.R. Yanuck. 1980. *Life Cycle Costing: A Practical Guide for Energy Managers*. Fairmont Press: Atlanta.
3. J.M. Cohen, et al. 1989. A methodology for computing wind turbine cost of electricity using utility economic assumptions. In *AWEA, Proceedings of Windpower Conference,* CD.
4. H.C. Wolfe, Ed. 1975. Efficient use of energy. In *Proceedings of American Institute of Physics Conference*.
5. W.R. Briggs. 1980. SWECS cost of energy based on life cycle costing. Technical Report RFP-33120/3533/80/13, UC-60. Wind Energy Research Center, NREL.
6. J.M. Sherman, M.S. Gresham, and D.L. Ferguson. 1982. Wind systems life cycle cost analysis. RFP-3448, UC-60. Wind Energy Research Center, NREL.
7. RETScreen International. Clean energy project analysis tools. www.retscreen.net.
8. Hybrid2, Wind Energy Center, University of Massachusetts. www.umass.edu/windenergy/research/software.
9. IRENA. 2016. www.irena.org/en/costs.
10. National Renewable Energy Laboratory. CREST Cost of Energy Models. https://financere.nrel.gov/finance/content/crest-cost-energy-models.
11. U.S. Department of Labor. Inflation calculator. www.westegg.com/inflation/; Consumer price indices. http://data.bls.gov/cgi-bin/cpicalc.pl.
12. P. Torcellini, N. Long, and R. Judkoff. 2003. Consumptive water use for U.S. power production. NREL/TP-550-33905. www.nrel.gov/docs/fy04osti/33905.pdf.
13. American Wind Energy Association. Ten steps to developing a wind farm. http://cusp.umn.edu/WE_Readings/Lec%202_3%20Ten%20Steps%20to%20Developing%20a%20Wind%20Farm.pdf.
14. American Wind Energy Association. 2008. W*ind Energy Siting Handbook*. AWEA: Washington, DC. www.awea.org/siting-handbook.
15. P. Jain. 2011. *Wind Energy Engineering*. McGraw-Hill: New York.
16. DISGEN. www.disgenonline.com.
17. International Renewable Energy Agency. 2017. Renewable power generation costs in 2017. www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf.
18. R. Wiser and M. Bolinger. 2016. Wind technologies market report. www.energy.gov/eere/wind/downloads/2016-wind-technologies-market-report.
19. U.S. Department of Energy. The impact of wind development on county-level income and employment: review of methods and an empirical analysis. www.nrel.gov/docs/fy12osti/54226.pdf.
20. C. Dou, Ed. 2008. Capacity building for rapid commercialization of renewable energy in China. CPR/97/G31, UNDP/GEF, Beijing, PR China.
21. U.S. Department of Energy. 2008. Twenty percent wind energy by 2030. www1.eere.energy.gov/wind/pdfs/41869.pdf.
22. European Wind Energy Technology Platform. 2006. Wind energy: A vision for Europe in 2030. www.windplatform.eu/fileadmin/ewetp_docs/Structure/061003Vision_final.pdf.
23. L.R. Brown. 2009. *Plan B 4.0: Mobilizing to Save Civilization*. W.W. Norton: New York.
24. L.R. Brown. 2011. *World on the Edge*. W.W. Norton: New York.
25. R.E. Smalley. 2003. Nanotechnology, energy and people. www.americanenergyindependence.com/energychallenge.aspx.

Index

Z