

# Wind Energy Information

*Guide*

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**MASTER**



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Washington, DC 20585

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## How to Use this Book

This book is divided into nine chapters. Chapters 1-8 provide background and annotated references on wind energy research, development, and commercialization. Chapter 9 lists additional sources of printed information and relevant organizations. Four indices provide alphabetical access to authors, organizations, computer models and design tools, and subjects. A list of abbreviations and acronyms is also included.

The publisher or sponsoring organization listed in the bibliographic citation is often the primary distributor of the document. Documents produced by the federal government are distributed to the public through the Government Printing Office (GPO) and the National Technical Information Service (NTIS). The appropriate stock number or order number is included in the citation. Older NTIS documents do not have an order number; the report number, without the slashes and hyphens, is used instead (for example, LBL 12200). Requests for government documents, including those of the U.S. Department of Energy (DOE) or DOE contractors, can be sent to

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Phone: (202) 512-1800

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Springfield, VA 22161  
Phone: (703) 487-4650  
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U.S. Department of Energy  
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P.O. Box 62  
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E-mail: [reports@adonis.osti.gov](mailto:reports@adonis.osti.gov)

American Society of Mechanical Engineers reports and publications listed in this guide may be obtained, for a fee, from

American Society of Mechanical Engineers  
345 East 47th Street  
New York, NY 10017  
Phone: (800) 843-2763  
Fax: (201) 882-1717  
E-mail: [infocentral@asme.org](mailto:infocentral@asme.org)

American Wind Energy Association publications may be obtained from

American Wind Energy Association  
122 C Street, NW 4th Floor  
Washington, DC 20001  
Phone: (202) 383-2500  
Fax: (202) 383-2505  
E-mail: [7395895@mcimail.com](mailto:7395895@mcimail.com)

Electric Power Research Institute reports can be obtained from

Electric Power Research Institute  
Distribution Center  
3412 Hillview Avenue  
Palo Alto, CA 94304  
Phone: (510) 934-4212

National Renewable Energy Laboratory reports can be obtained from

National Renewable Energy Laboratory  
Document Distribution Service  
1617 Cole Boulevard  
Golden, CO 80401  
Phone: (303) 275-4363  
E-mail: sally\_evans@nrel.gov

Information on International Energy Agency reports and publications listed in this guide may be obtained from

International Energy Agency  
(Agence Internationale de l'Energie)  
2, rue Andre Pascal  
F-75775 Paris Cedex 16  
France  
Phone: +33 1 4524 8200  
Fax: +33 1 4524 9988

Libraries offer the most expedient method for locating the majority of documents cited in this guide, including government reports and other relevant materials. The documents can be borrowed through public, academic, and special libraries with which the reader is affiliated. Most libraries also offer an interlibrary loan (ILL) service to patrons. Through the ILL cooperative arrangement, a library can borrow documents or obtain photocopies of items not in its collection. Charges for acquiring some materials might be collected from the requester.

Often, the best way to access databases is also through libraries. Libraries that subscribe to a computer search service, such as DIALOG or BRS, can perform database searches for patrons. Commercial search services have standard charges for on-line search time and printed results.

In addition to local libraries, several information centers provide assistance specifically for inquiries concerning energy. The Energy Efficiency and Renewable Energy Clearinghouse (EREC), affiliated with DOE, provides information on the full spectrum of renewable energy and energy conservation technologies, including wind energy. Formerly the Conservation and Renewable Energy Inquiry and Referral Service (CAREIRS) and the National Appropriate Technology Assistance Service (NATAS), the combined service maintains contact with a nationwide network of public and private organizations that specialize in highly technical or regionally specific information.

Energy Efficiency and Renewable Energy Clearinghouse  
P.O. Box 3048  
Merrifield, VA 22116  
Phone: (800) 363-3732  
Fax: (703) 893-0400  
BBS: (800) 273-2955  
TDD: (800) 273-2957  
E-mail: energyinfo@delphi.com

Wind energy information is also available from the Energy Efficiency and Renewable Energy Network (EREN), a single point of access to computer bulletin boards, on-line catalogs, manufacturer and vendor lists, and Internet servers. Please direct inquiries about EREN to the Energy Efficiency and Renewable Energy Clearinghouse.

URL: <http://www.eren.doe.gov>  
Phone: (800) 363-3732

The National Wind Technology Center is the U.S. Department of Energy's primary wind energy research facility. The center maintains an electronic web site which includes information about wind energy research, recent publications, and an on-line publication order form. The web site is available through the World Wide Web.

National Wind Technology Center  
National Renewable Energy Laboratory  
1617 Cole Boulevard  
Golden, CO 80401  
Phone: (303) 384-6909  
Fax: (303) 384-6999  
URL: <http://nwtc.nrel.gov>

The National Energy Information Center (NEIC) is the branch of the Energy Information Administration (EIA) in charge of answering inquiries and disseminating information. EIA is the information arm of DOE; it collects and analyzes data on many aspects of energy. NEIC answers questions on production, consumption, prices, trends, and resource availability. It can also provide references to other sources of energy information.

National Energy Information Center  
1000 Independence Avenue, SW  
Forrestal Building, 1F-048  
Washington, DC 20585  
Phone: (202) 586-8800  
Fax: (202) 586-0747  
E-mail: [infoctr@eia.doe.gov](mailto:infoctr@eia.doe.gov)

The National Climatic Data Center is the national collection center and custodian of the U.S. weather records. It is also the repository for the Wind Energy Resource Information System (see Databases section in Chapter 9). Principal areas of research interest are climate, including temperature, pressure, precipitation, and wind; meteorology; solar radiation; and other atmospheric phenomena.

National Climatic Data Center  
151 Patton Avenue, Room 120  
Asheville, NC 28801-5001  
Phone: (704) 271-4800  
Fax: (704) 271-4876  
E-mail: [orders@ncdc.noaa.gov](mailto:orders@ncdc.noaa.gov)

Finally, state energy offices can be good sources of information. Check the index of state agencies and departments in your state to find relevant programs.

# Chapter 1

## Introduction

### Potential of Wind Power

In the United States, the power in the wind could produce more than one and one-half times the electricity consumed by the entire country in 1990. Wind machines are already supplying economically competitive electricity throughout the world. In the United States alone, wind turbines produce more than 3.5 billion kilowatt-hours (kWh) of electricity each year—enough electricity for a city the size of San Francisco. And wind power capacity in the United States and around the world is continuing to increase as utilities, consumers, and society realize the benefits of wind power.



*There is great potential for wind energy to meet the world's energy needs.*

National Renewable Energy Laboratory. (1996). *International Energy Agency Wind Energy Annual Report 1995*. NREL/SP-440-20860. Golden, CO: National Renewable Energy Laboratory.

This annual report reviews the progress in the Agreement for Cooperation in the Research and Development of Wind Turbine Systems, operated under the auspices of the International Energy Agency. The agreement concerns national programs for research, development, and deployment of wind energy systems.

Gipe, P. (1995). *Wind Energy Comes of Age*. New York, NY: John Wiley & Sons, Inc. 536 pp.

The current status of wind energy technology and its potential are covered.

Brower, M.S.; Tennis, M.W.; Denzler, E.W.; Kaplan, M.M. (1993). *Powering the Midwest: Renewable Electricity for the Economy and the Environment*. Cambridge, MA: Union of Concerned Scientists; 188 pp.

This book contains chapters on wind and biomass energy, distributed power generation, utility integration, the case for renewable energy, and policies that enhance the use of renewable energy sources. It also contains wind resource maps of the Midwest.

Cavallo, A.J.; Hock, S.M.; Smith, D.R. (1993). "Wind Energy: Technology and Economics." Chapter 3 in *Renewable Energy: Sources for Fuels and Electricity*. Edited by T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams. Washington, DC: Island Press; pp. 121-156.

The development of modern wind turbines, turbine technology research, and the economics of wind-generated electricity are discussed.

Van Wijk, A.J.M.; Coelingh, J.P. (1993). *Wind Power Potential in the Organization of Economic Cooperation and Development (OECD) Countries*. 93091. Utrecht, The Netherlands: Utrecht University; 35 pp.

Wind energy technology status, the potential for large-scale electricity production, and the economics of wind energy for OECD countries are reviewed.

Dodge, D.M. (June 1993). "Wind Power Rising." *The World & I.* Washington, DC: The Washington Times Corporation; pp. 187-193.

By extracting the kinetic energy in the wind, wind turbines generate electrical or mechanical power. In the past, mechanical wind machines were widely used for specific tasks such as pumping water or grinding grain. Today, the power in the wind can be used to generate electricity that can be used for any task that electrical devices can perform.

Demand for the economic and social benefits electricity provides continues to grow worldwide. Wind turbines can meet that demand while providing a number of benefits: a free and widely available fuel source; no air, soil, or water pollution; and continually improving technology. Each year wind turbines become more attractive sources of electric power.

Because wind turbines use energy from the wind to generate electricity, the fuel is free. The wind energy resource is also abundant and largely available for exploitation around the world. Almost every region of the United States has areas with good wind energy potential. Some states, such as those that lie on the Great Plains stretching from Texas to North Dakota, could generate electricity from wind that far exceeds their current electric power demand. Many parts of the developed and developing world have wind energy resources to meet growing needs for clean, inexpensive electricity.

As environmental regulations continue to transform the planning and operation of electric utilities, wind power is becoming increasingly attractive. Using wind turbines to generate electricity contributes no net carbon dioxide (CO<sub>2</sub>) or other greenhouse gases to the atmosphere and produces no pollutants of soil or water. In fact, wind-generated electricity kept more than 2.5 million tons of CO<sub>2</sub> and 15,000 tons of other pollutants out of the air in 1994. The U.S. Department of Energy (DOE), utilities, and independent power producers are installing cost-shared wind power plants to further reduce greenhouse gas emissions.

Finally, wind turbine hardware and management experience are available in the marketplace. Technology is improving, and the experience to operate power plants is growing. Wind power plants have shown themselves to be reliable and durable. And the operation and maintenance costs of wind power plants are predictable. The maturity of the technology is most convincingly demonstrated by the fact that utilities are buying wind turbines for their own generation facilities.

In addition, the commercial success of wind power plants in California has sparked an interest in wind from utilities across the nation. In 1990, in cooperation with the Electric Power Research Institute (EPRI) and DOE, a number of utilities formed the Utility Wind Interest Group (UWIG) to assist members with the integration of wind power into their networks. UWIG's cooperative activities include publishing periodic reports and brochures on wind power that are aimed at utility management. The group also sponsors regional seminars to highlight trends in wind power development. UWIG

This article reviews recent promising developments to optimize the ancient windmill, making wind energy competitive with other energy sources, even coal.

Lamarre, L. (December 1992). "Building Interest in Wind." *EPRI Journal*. Palo Alto, CA: Electric Power Research Institute; 12 pp.

This article describes how EPRI and DOE are collaborating on a new program to accelerate the commercialization of advanced wind turbine technologies.

Hock, S.M.; Thresher, R.W.; Williams, T. (1992). "The Future of Utility-Scale Wind Power." Chapter 9 in *Advances in Solar Energy: An Annual Review of Research and Development*. Edited by K.W. Boer. Vol. 7. Boulder, CO: American Solar Energy Society; pp. 309-371.

This chapter discusses the technological advances necessary to make wind-generated electricity cost competitive, including accurate characterization of wind inflow to turbines at power plant sites, an understanding of unsteady aerodynamics, fatigue-resistant machines, and accurate computer models of turbine operations.

California Energy Commission. (1992). *1992 Energy Technology Status Report*. P500-92-007E. Sacramento, CA: California Energy Commission; 82 pp.

This report includes technology evaluations for more than 230 electrical generation and end-use technologies. The status of new and existing technologies is evaluated.

American Wind Energy Association. (1992). *Wind Energy for Sustainable Development*. Washington, DC: American Wind Energy Association; 22 pp.

Wind energy can supply the energy needs of a utility, community, or individual home. The book includes discussions of wind energy economics, environmental impacts and basic turbine operating principles, as well as a list of organizations that offer assistance to those interested in using wind energy.

*The Potential of Renewable Energy, An Interlaboratory White Paper; Appendix F.* (March 1990). Prepared for the Office of Policy, Planning and Analysis, U.S. Department of Energy, in support of the National Energy Strategy. SERI/TP-260-3674. Golden, CO: National Renewable Energy Laboratory; 11 pp. (NTIS no. DE90000322).

This white paper analyzes the extent to which renewable energy resources, including wind, can contribute to diversifying the energy supply of the United States. This paper was an important part of developing the National Energy Strategy in 1991.

Swisher, R. (American Wind Energy Association); Ancona, D.F. (U.S. Department of Energy); and Edworthy, J. (Canadian Wind Energy Association). (September 1990).

provides crucial information to state regulatory agencies, legislative programs, and budget planning processes across the nation.

The companies manufacturing and selling wind turbines and wind turbine components form a substantial and growing industry in the United States. The trade association representing this industry, the American Wind Energy Association, estimates that the 1,700 MW of installed wind capacity in the United States will more than double in the next three to four years. This dramatic growth reflects the industry's faith in new technology that is now being deployed in many countries around the world. The existence of this industry and the consensus standards it has developed is another indicator that the technology for generating electricity with wind power has come of age.

## The U.S. Department of Energy Wind Program

The mission of the DOE Wind Energy Program is to assist utilities and industry in developing advanced wind turbine technology that will be an economically competitive energy source. In addition, the program works with industry and utilities to develop new markets and applications for wind systems.

The DOE Wind Turbine Development Programs support the U.S. wind industry's efforts to improve the technology, lower the cost of wind turbines, and accelerate the commercialization of products. DOE also supports development of new products combining the best of existing designs with the most promising new technology available. Finally, DOE is helping to develop next-generation, utility-grade wind turbines for the year 2000 and beyond.

Since its founding, DOE has funded and directed research to speed the adoption of wind energy to generate electricity. The DOE field offices and national laboratories implement the program's technical activities, including administering subcontracts with utilities, industry, and universities. The agreements with utilities and industry are designed to further the rapid commercialization of wind energy systems, whereas university subcontracts help build the wind energy technology base.

The National Renewable Energy Laboratory (NREL) (formerly the Solar Energy Research Institute), located in Golden, Colorado, is the primary national laboratory for DOE's Wind Energy Program. NREL manages the National Wind Technology Center, a full-service test center available to industry for research and development (R&D) of commercial and prototype wind systems and components. In addition, NREL scientists conduct research in structures, fatigue testing, wind resource assessment and characterization, aerodynamics, advanced components, and systems.

NREL also supports experts studying atmospheric physics relating to wind turbines, and develops tools for wind resource assessments and

"Wind Energy Developments in the Americas." *European Community Wind Energy Conference and Exhibition; September 10-14, 1990; Madrid, Spain.* Bedford, England: H.S. Stephens & Associates; pp. 43-48.

This paper highlights the key activities and programs of Western Hemisphere countries including Argentina, Canada, Costa Rica, Colombia, Mexico, and several Caribbean countries.

Cadogan, J.B., Parsons, B., Cohen, J.M., Johnson, B.L. (1996). *Characterization of Wind Technology Progress.* NREL/TP-440-21467. Golden, CO: National Renewable Energy Laboratory. 10 pp. (NTIS no. DE96007954).

The federal wind energy program periodically re-evaluates its characterization of wind technology and revisits wind research and development cost and performance goals. This is part of a larger DOE effort to establish a consistent data base of technology progress information for its major programs.

Link, H., Laxson, A., Smith, B., Goldman, P. (1995). *The U.S. Department of Energy Wind Turbine Development Program.* NREL/TP-441-7390. Golden, CO: National Renewable Energy Laboratory. 7 pp. (NTIS no. DE95000292).

This paper describes the details of DOE's approach to enhancing the technology and market acceptance of wind turbine generators.

*Wind Energy Program Overview, Fiscal Year 1994.* (March 1995). DOE/GO-10095-071. Golden, CO: National Renewable Energy Laboratory. (NTIS no. DE95000288).

As in the program overviews for previous years, this report features the research, development, and industrial accomplishments of the fiscal year. It is a guide to the U.S. Department of Energy's Wind Energy Program.

*Wind Energy Program Overview, Fiscal Year 1993.* (April 1994). DOE/CH10093-279. Golden, CO: National Renewable Energy Laboratory. (NTIS no. DE94000285).

Laxson, A.S.; Dodge, D.M.; Flowers, L.T.; Loose, R.; Goldman, P. (1993). *An Overview of DOE's Wind Turbine Development Programs.* NREL/TP-441-5761. Golden, CO: National Renewable Energy Laboratory; 8 pp.

site evaluations. NREL works directly with industry, utilities, and wind power plant operators for cooperative research and to determine wind energy resource potential. Until 1994, this work was managed by the Pacific Northwest Laboratory.

Sandia National Laboratories, located in Albuquerque, New Mexico, conducts supporting research in computer modeling, structural dynamics, fatigue testing, reliability, aerodynamics, controls, and materials. Sandia works closely with NREL in aerodynamics, structures, and fatigue testing and in solving problems applicable to a broad range of wind turbine technologies. In addition, Sandia has performed specialized work developing technology for vertical-axis wind turbines.

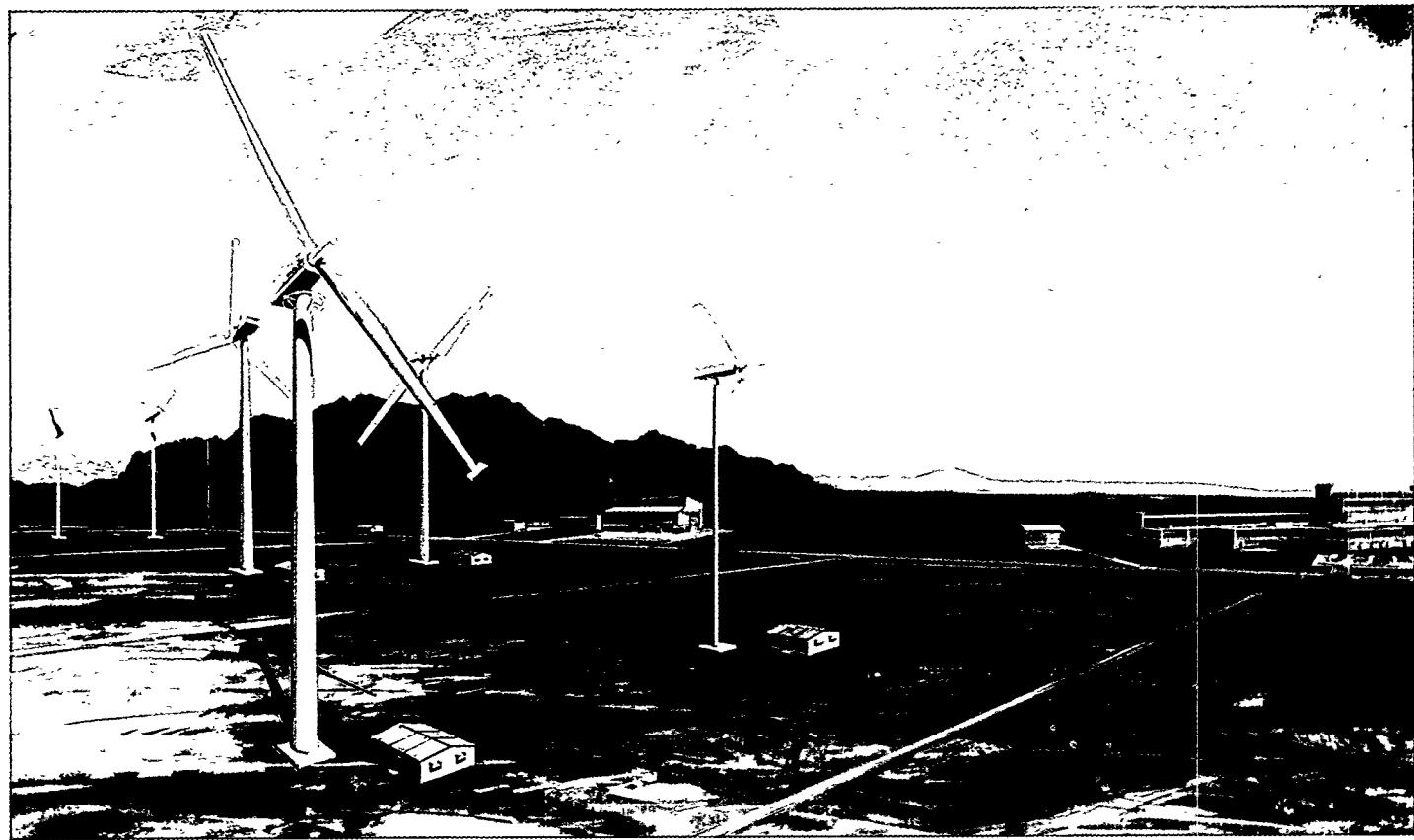
Until 1988, the NASA Lewis Research Center managed the large horizontal-axis wind turbine research and development program for DOE. The program was completed after the development of three generations of machines. The first-generation machines demonstrated that large wind turbines could operate continuously in a utility network. The second-generation, 2.5-MW prototype machines underwent extensive testing at Goldendale, Washington, where a cluster of three machines generated more than 16 million kWh for

Dodge, D.M.; Bollmeier, W.S., II. (March 1992). *Cooperative Field Test Program for Wind Systems*. NREL/TP-253-4252. Golden, CO: National Renewable Energy Laboratory; 38 pp. (NTIS no. DE92001209).

This report summarizes technical results from the Cooperative Field Test Program and the Cooperative Research Program, which assembled joint industry-government research teams to exercise and validate analytical codes and to formulate and validate solutions to specific technical problems. Addressed are a dynamic response test, precipitation effects, a micrositing study, wake studies, fatigue tests, wind/diesel tests, and water-pumping tests.

Butterfield, C.P.; Musial, W.P.; Scott, G.N.; Simms, D.A. (1992). *NREL Combined Experiment Final Report—Phase II* (draft). NREL/TP-442-4807. Golden, CO: National Renewable Energy Laboratory; 32 pp. (plus appendices).

This study explores how the performance of an airfoil in a wind tunnel differs from that on an operating wind turbine. Results are derived from aerodynamic pressure measurements, wind turbine load measurements, and flow visualization studies.



*The National Wind Technology Center offers state-of-the-art test equipment and data collection systems to the industry. Manufacturers can test concepts and materials under special arrangements that ensure confidentiality to protect proprietary innovations.*

the Northwest power grid. The third-generation machine, the 3200-kW MOD-5B, built under a cost-sharing program with the Boeing Aerospace Company and Hawaiian Electric Renewable Systems, Inc., features an advanced variable-speed generator, new aerodynamic systems and controls, and other extensive technology improvements. The research program for multi-megawatt systems concluded with the sale of the MOD-5B to Hawaiian Electric Renewable Systems in January 1988. Makani Uwila Power Company (now owned by New World Power) operates the turbine.

Since 1976, the Agriculture Research Service of the U.S. Department of Agriculture has been conducting field experiments to identify, develop, and test applications of wind power in agriculture.

Additional studies have been conducted on economics and load requirements for wind machines.

Improving wind turbine performance hinges on an understanding of the complex aerodynamic interactions between the wind and a wind turbine blade. To identify these fundamental interactions, DOE researchers designed the Combined Experiment in 1988. This test bed consists of a 20-kW wind turbine instrumented to measure pressure along the blades. Work continues with this turbine in unsteady aerodynamic experiments using constant-chord twisted blades with the NREL S809 airfoils. (See Chapter 4 for a discussion of airfoils.)

To help U.S. industry meet stiff international competition, the DOE Wind Energy Program launched the Advanced Wind Turbine Program in 1991. Under cost-shared contracts, manufacturers incorporated incremental refinements into existing designs. In addition, the program is funding work to develop next-generation technology for the 21st century.

Another DOE program, the Value Engineered Turbine project, supports wind power plant operators in their efforts to refine turbine designs. These turbine operators work, based on wind turbine operating experience, to improve the performance and reliability of commercial turbines. The goal is for the United States to manufacture wind turbines with known and well-documented records of performance, cost, and reliability to take advantage of near-term market opportunities.

The primary market for wind turbine products developed under DOE's programs is the utility industry. Utility acceptance of wind-generated electricity will increase as the performance and reliability of new products are demonstrated. Therefore, DOE has entered into a collaborative program with EPRI to verify the performance of wind turbines for utilities.

The EPRI/DOE Utility Wind Turbine Verification Project will deploy and evaluate commercial prototype wind turbines in typical utility operating environments. This joint project provides a bridge between technology development programs and the commercial availability of utility-grade wind turbines. The EPRI/DOE collaborative venture is



*This 3.2-megawatt wind turbine, operating in Hawaii, was built under the U.S. Department of Energy Large Wind Turbine Development Program.*

Butterfield, C.P.; Musial, W.P.; Simms, D.A. (1992). *Combined Experiment Phase I: Final Report.*

NREL/TP-257-4655. Golden, CO: National Renewable Energy Laboratory; 222 pp. (NTIS no. DE99300012/XAB).

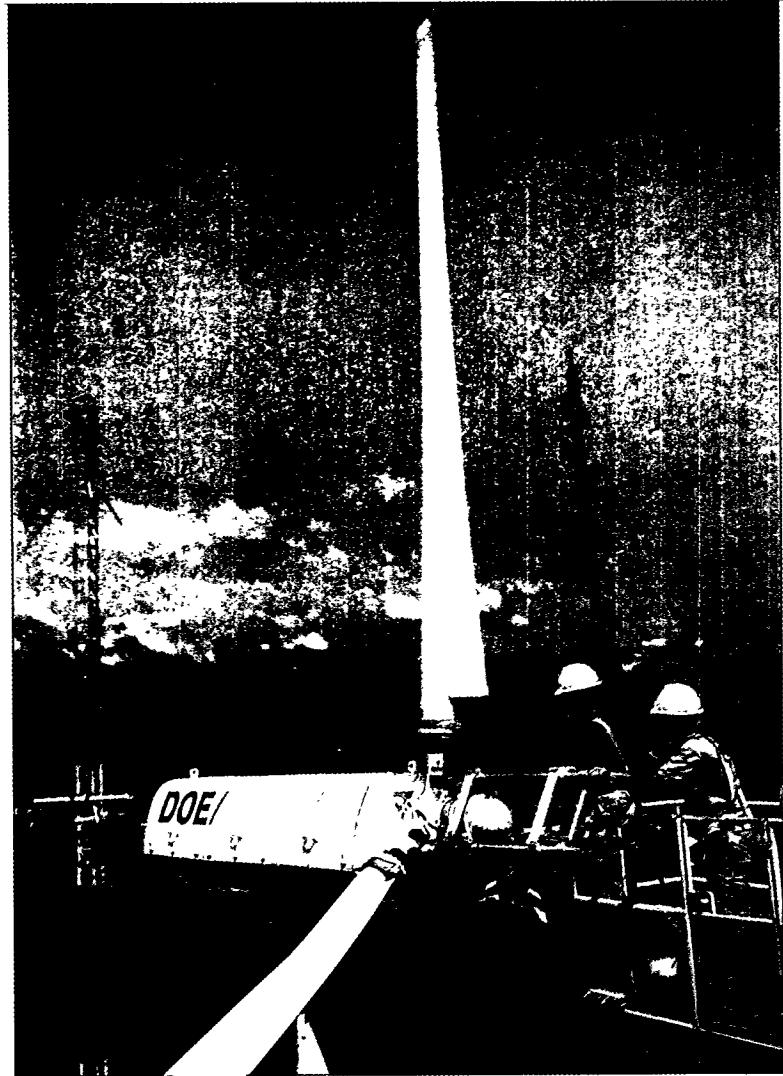
This report describes the instrumentation and results of the Combined Experiment, a project to better understand aerodynamic response of wind turbines. Researchers assembled a basic 20-kW wind turbine from a prototype. They used this machine as a test bed for the Combined Experiment measurements.

*A Government-Industry Partnership Experience: The Cooperative Field Test Program in Wind Research.* (May 1991). 6 pp. Available from American Wind Energy Association, Washington, DC.

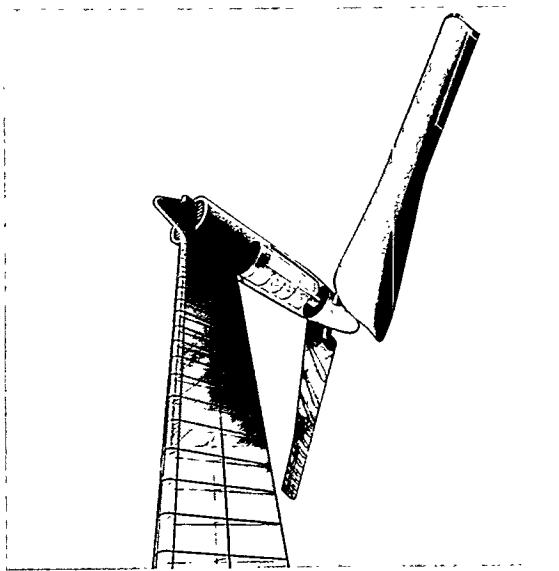
This brochure outlines the projects cost-shared under the Cooperative Field Test Program.

designed to hasten wind power's use and the realization of its benefits.

The next generation of turbines will be larger and produce significantly more energy than the turbines of the 1980s. Because they are more economical at lower wind speeds, these turbines will use a greater portion of the nation's vast wind resource.



*This machine, assembled during the Combined Experiment Program, serves as a test bed for sophisticated measurements to correlate wind forces to the performance of wind turbines.*



*To encourage innovation in wind turbine design, the U.S. Department of Energy shares the cost with industry to develop subsystems as well as complete turbines. Advanced wind turbines will include the most successful approaches to components and systems design.*

# History of Wind Energy

Since early recorded history, people have been harnessing the energy of the wind. Wind energy propelled boats along the Nile River as early as 5000 B.C. By 200 B.C., simple windmills in China were pumping water, while vertical-axis windmills with woven reed sails were grinding grain in Persia and the Middle East.

New ways of using the energy of the wind eventually spread around the world. By the 11th century, people in the Middle East were using windmills extensively for food production; returning merchants and crusaders carried this idea to Europe. The Dutch refined the windmill and adapted it for draining lakes and marshes in the Rhine River Delta. When settlers took this technology to the New World in the late 19th century, they began using windmills to pump water for farms and ranches, and later, to generate electricity for homes and industry.

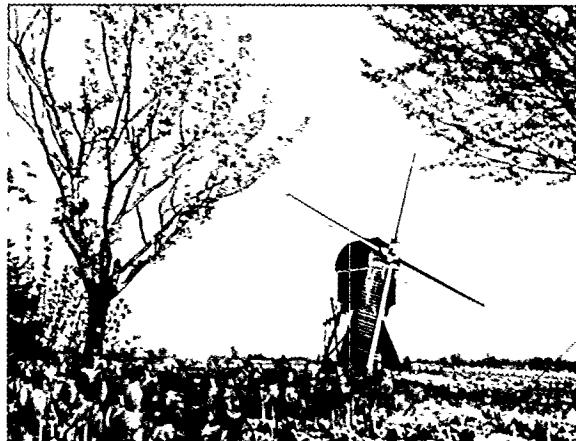
Industrialization, first in Europe and later in America, led to a gradual decline in the use of windmills. The steam engine replaced European water-pumping windmills. In the 1930s, the Rural Electrification Administration's programs brought inexpensive electric power to most rural areas in the United States.

However, industrialization also sparked the development of larger windmills to generate electricity. Commonly called wind turbines, these machines appeared in Denmark as early as 1890. In the 1940s the largest wind turbine of the time began operating on a Vermont hilltop known as Grandpa's Knob. This turbine, rated at 1.25 MW in winds of about 30 mph, fed electric power to the local utility network for several months during World War II.

The popularity of windmills has always fluctuated with the price of fossil fuels. When fuel prices fell after World War II, interest in wind turbines waned. But when the price of oil skyrocketed in the 1970s, so did worldwide interest in wind turbine generators.

The wind turbine technology R&D that followed the oil embargoes of the 1970s refined old ideas and introduced new ways of converting wind energy into useful power. Many of these approaches have been demonstrated in "wind farms" or wind power plants—groups of turbines that feed electricity into the utility grid—in the United States and Europe.

Today, the lessons learned from more than a decade of operating wind power plants, along with continuing R&D, have made wind-generated electricity very close in cost to the power from conventional utility generation in some locations.



Shepherd, D.G. (Cornell University). (December 1990). *Historical Development of the Windmill*. (DOE/NASA-5266-2). Washington, DC: U.S. Department of Energy; 45 pp. (NTIS no. DE91006447/XAB).

This report describes key stages in the technical development of windmills into modern wind turbines.

Ancona, D.F. (1989). "Power Generation, Wind, Ocean." *Wilk's Encyclopedia of Architecture: Design, Engineering, and Construction*. Vol. 4. New York, NY: John Wiley & Sons; pp. 32-39.

This chapter reviews both historical and modern wind turbine designs.

Baker, T.L. (1985). *A Field Guide to American Windmills*. Norman, OK: University of Oklahoma Press; 516 pp.

This guide includes a general history of turbine-wheel mills and illustrations of the 112 models.

Johnson, G.L. (1985). *Wind Energy Systems*. New York, NY: Prentice Hall.

A general reference on various types of wind energy conversion systems.

Koepll, G.W. (1982). *Putnam's Power From the Wind*. 2nd edition. New York, NY: Van Nostrand Reinhold Company, Inc.; 470 pp.

This edition updates Palmer Cosslett Putnam's original book, *Power from the Wind*, which described the Smith-Putnam wind turbine project that took place from 1934 to 1945. The original text is followed by a new section that summarizes large wind turbine technology and development between 1945 and 1980.

Golding, E.W. (1976). *The Generation of Electricity by Wind Power*. New York, NY: John Wiley & Sons; 332 pp.

This book describes research and development performed in Great Britain and other countries. Topics include wind characteristics, wind machines, and the economic use of wind power.

Torrey, V. (1976). *Wind Catchers: American Windmills of Yesterday and Tomorrow*. Brattleboro, VT: The Stephen Greene Press; 226 pp.

*Wind Catchers* presents a broad, historical summary tracing wind energy from its beginnings to its use in the United States.

## How Wind Machines Capture Energy from the Wind

Wind energy is the kinetic energy of large masses of air moving over the earth. Because the sun heats the earth's surface and atmosphere unevenly, thermal differences drive air masses around the planet. The earth's rotation also contributes to powerful air currents.

A wind energy conversion system (WECS) converts this kinetic energy into mechanical energy and electric energy using airfoils, a drivetrain, and a generator. The conversion process begins as air flows over a blade, called an airfoil, that has features of an airplane wing or propeller. Air passes more rapidly over the longer (upper side) of the blade, creating lower pressure above the airfoil than beneath it. The pressure difference results in a force known as aerodynamic lift, which rotates the blade about a central hub and shaft. The blades of a wind machine can rotate around a horizontal or a vertical axis (see illustration). This rotational energy can operate a mechanical device, such as a water pump, or can turn a generator to produce electricity.

Although wind energy conversion is relatively simple in concept, turbine design can be quite complex. For example, the amount of power a wind turbine produces is reduced by drag forces that result from air flow over the blades. This makes lift-to-drag ratio one of the prime considerations in blade design. The number of blades also affects performance; one-bladed rotors minimize energy loss from drag forces, but two- and three-bladed rotors are considered the best trade-off for stability, aerodynamic performance, and cost.

Wind speed is basic to a wind turbine's productivity. Because the amount of power available in the wind is proportional to the cube of the wind speed, relatively small changes in wind speed result in relatively large changes in power. Because the power in the wind varies from place to place, accurately predicting the wind speed is an important consideration in choosing a productive site for a machine. For example, if the wind speed at a site is 20% higher than expected, the turbine may produce 73% more power. If the wind speed at a site is 20% lower than expected, the turbine will produce about half the power anticipated.

The power available is proportional to the area of the circle swept by the blades, or rotor. As blade length increases, more power can be generated, yet rotor size is limited by factors such as material and joint strength, weight, and cost. In the past, wind turbines with blades from about 1 meter (m) (3 feet [ft]) to 15 m (49 ft) were the norm because of lower installed costs and ease of maintenance. However, with today's improved technology, wind power plant

Spera, D.A. (May 1994). *Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering*. No. 100368. Fairfield, NJ: American Society of Mechanical Engineers; 700 pp.

This collection of articles compiled by the American Society of Mechanical Engineers provides an advanced look at all aspects of the modern wind turbine including airfoils, rotor wakes, acoustics, system configuration, and fatigue design.

Nelson, V.; Gilmore, E.H.; Starcher, K. (1994). *Introduction to Wind Energy*. 93-3. Canyon, TX: Alternative Energy Institute; 28 pp.

This book provides a comprehensive look at wind energy and its development from the earliest windmills to modern-day, utility-scale machines. The wind resource, wind generators, and economics are discussed.

*Introduction to Small Wind Systems*. (1993). Washington, DC: American Wind Energy Association; 22 pp.

This booklet answers many basic questions about small wind systems, including how they operate.

Gipe, P. (1993). *Wind Power for Home & Business*. Post Mills, VT: Chelsea Green Publishing Company; 413 pp.

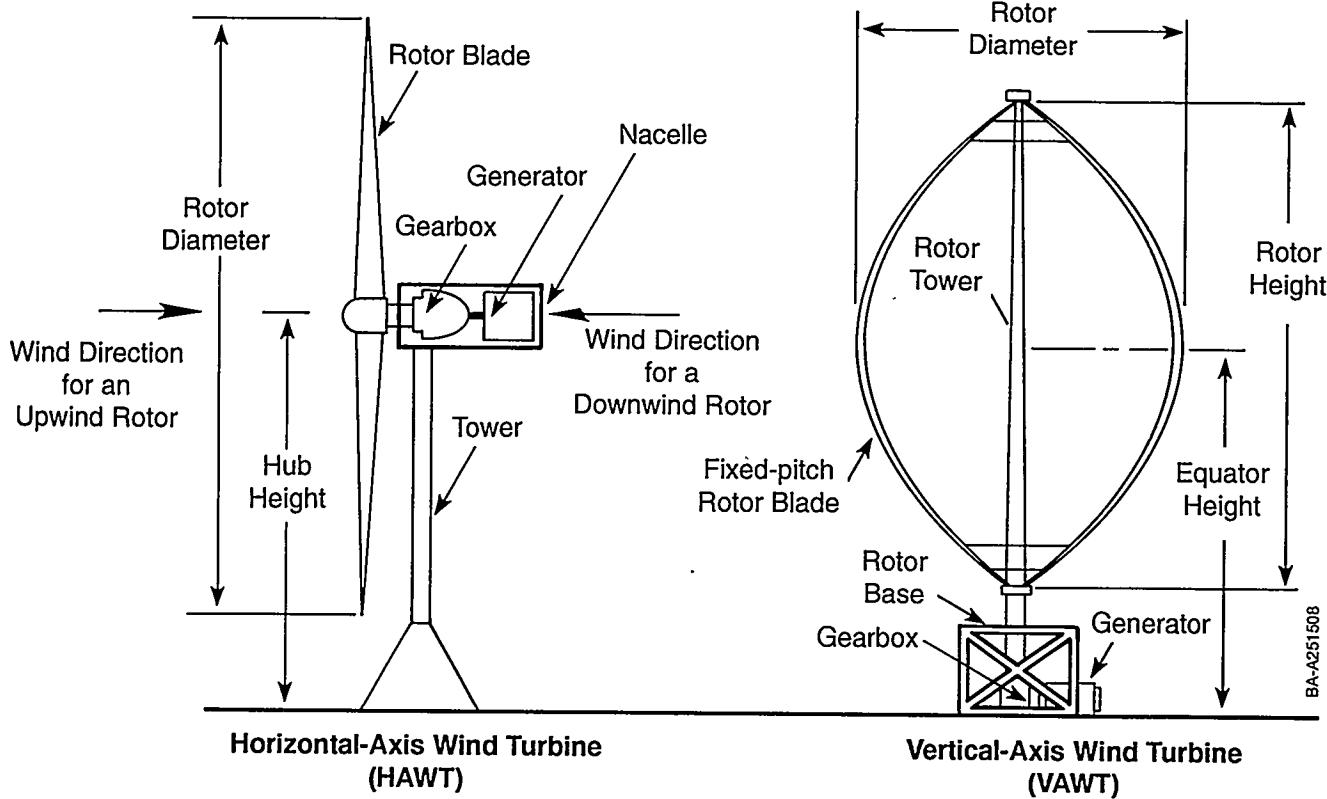
A reference on many aspects of post-1970s wind energy machines, this book contains tables to guide estimation of annual electricity production from any size wind turbine for various wind conditions. Also included are wind resource maps of all 50 states and a list of manufacturers of wind machines.

Dodge, D.M.; Thresher, R.W. (1989). "Wind Technology Today." *Advances in Solar Energy, An Annual Review of Research and Development*. Vol. 5. New York, NY: Plenum Press.

This chapter describes the status of wind turbine technology and the U.S. DOE program to support industry's efforts to improve the technology.

Eggleston, D.M.; Stoddard, F.S. (1987). *Wind Turbine Engineering Design*. New York, NY: Van Nostrand Reinhold Company, Inc.; 352 pp.

This textbook of wind turbine engineering design includes technical facts, recommended procedures, and a guide to the most useful handbooks and references. Part I discusses basic methods for



*Both horizontal- and vertical-axis wind turbines generate electricity in wind power plants.*

operators are using machines with blades of as much as 30 m (98 ft) in length to generate more electricity per machine.

The power expected by design from a wind turbine is often expressed as its rated power. Rated power is the power the machine is designed to produce at a selected wind speed, called its rated wind speed. Rated wind speed is selected for optimal operation of all the wind turbine components. Winds greater than the rated speed result in shedding excess power to maintain rated power. Consistently high loads can wear out (fatigue) components and lead to reliability problems.

To keep loads within design tolerances, most wind turbines include features to slow or stop the rotor in high winds. These braking systems can include aerodynamic features such as blades with pitchable (twistable) tips, or ailerons (movable flaps along the blade trailing edge), to slow or stop blade rotation before damage can occur. Other strategies involve turning the machine away from the wind with motors or applying a mechanical or electronic brake somewhere along the drivetrain.

The system efficiency of a wind turbine is determined by the combined efficiencies of the rotor, drivetrain, and generator. The theoretical maximum aerodynamic efficiency (Betz limit) is 59% of the total power in the wind. Today's best machines can convert

modeling rotor aerodynamics, details of rotor design, digital programs for wind turbine design and analysis, performance, economics, and siting. Part II discusses structural dynamics, including system engineering models, blade motions, blade and hub loads, instabilities, and load specification. Part III, on system engineering, includes discussions of fatigue, electric generators, and control systems.

Moretti, P.M; Divone, L.V. (June 1986). "Modern Windmills." *Scientific American* (254:6); pp. 110-118.

This overview of windmill technology emphasizes the production of electricity by modern wind machines.

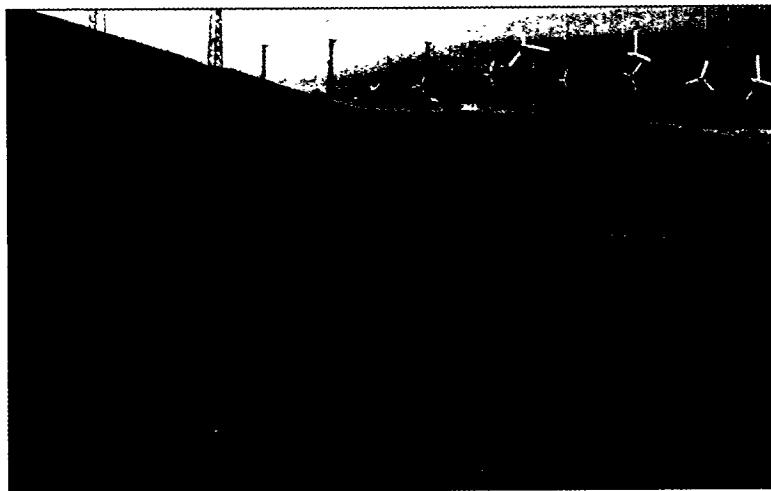
Le Gourieres, D. (1982). *Wind Power Plants, Theory and Design*. New York, NY: Pergamon Press.

Park, J. (1981). *The Wind Power Book*. Palo Alto, CA: Cheshire Books; 253 pp.

This book provides the potential user of a small-scale wind system with information about design and construction. Appendices contain detailed charts, tables, and diagrams.

Eldridge, F.R. (1980). *Wind Machines*. 2nd edition. New York, NY: Van Nostrand Reinhold Company, Inc.; 214 pp.

about 40% of the wind's energy to mechanical energy. After passing through the drivetrain and generator, the overall efficiency of conversion to electricity is about 35%.



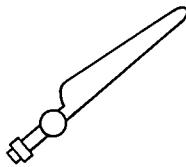
*Wind turbine generators at a wind power plant operate on the same ranch as does a classic water-pumping windmill in Altamont Pass, California.*

This book surveys the history, taxonomy, and potential of various types and sizes of wind machines. Information on possible applications, siting problems, performance characteristics, and systems designs is also provided.

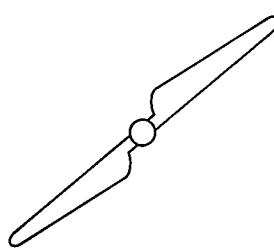
Park, J.; Schwind, D. (September 1978). *Wind Power for Farms, Houses, and Small Industry*. RFP-2841/1270/78/4. Mountain View, CA: Nielsen Engineering and Research, Inc.; 229 pp.

This report describes basic wind turbines, energy conversion, wind behavior, site selection, power and energy requirements, components of a WECS, selecting a WECS, system economics, and legal aspects of using small turbines.

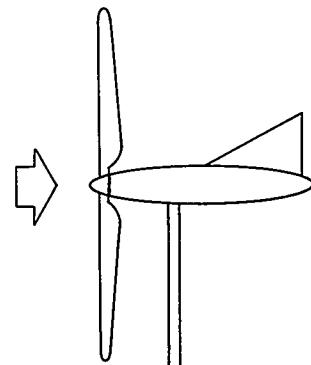
### Wind Machine Taxonomy



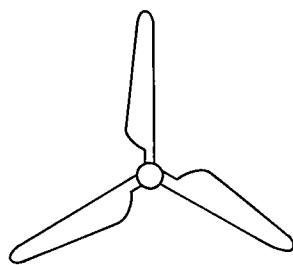
Single-bladed



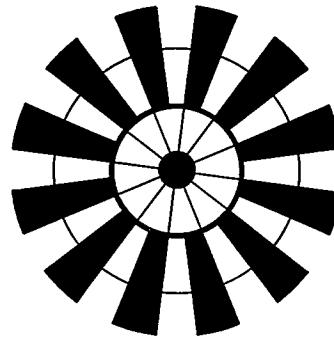
Double-bladed



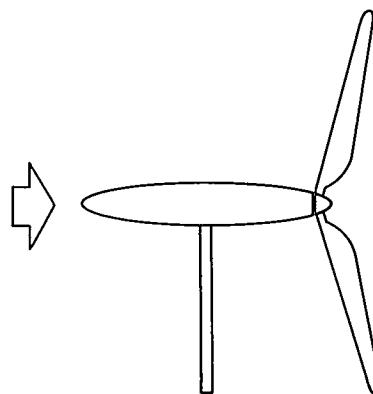
Upwind



Three-bladed



U.S. Farm Windmill  
Multi-bladed



Downwind

EA-A251509

# Chapter 2

## Economics of Using Wind Energy

### The Falling Cost of Wind Energy

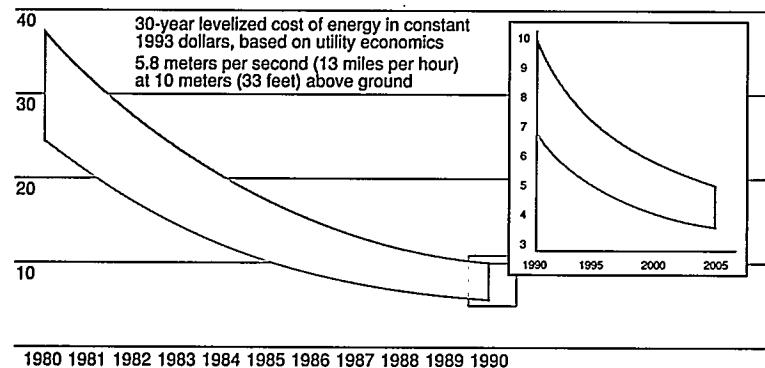
Potential users of wind energy systems compare the cost of energy from wind turbines with the cost of electricity from conventional sources. The cost of energy from wind systems depends on three parameters: installed purchase price, annual energy capture, and operation and maintenance (O&M) costs. All three of these parameters have improved, thereby lowering the cost of energy from wind turbines to ranges that are competitive with costs of conventional electrical generation.

The installed purchase price of the wind energy system is the initial capital cost to the owner or project developer. This price includes all costs entailed in the design, materials, manufacture, and installation of the wind system. The purchase price of wind turbine generators has fallen from more than \$1,800 per rated kilowatt (kW) in 1984 to between \$800 and \$1,000 per rated kW in 1994. Lower purchase prices for wind turbines ultimately lower the cost of energy from wind.

The annual energy capture depends on the quality of the wind turbine's design and construction, as well as on the wind resource. Improvements in wind turbine design and construction techniques have increased the efficiency and reliability of operation. In addition, more than a decade of wind power plant construction, operation, and research experience has improved turbine siting and increased productivity. As a result, annual energy produced per installed kW of capacity increased from less than 400 kilowatt-hours (kWh) per kW in 1984 to more than 1800 kWh per kW in 1994. Finally, wind turbine operators have benefitted from more than a decade of experience with wind turbine operation and maintenance.

#### The Cost of Electricity from Wind Turbines

Amounts in cents/kWh



Milligan, M.R.; Miller, A.H.; Chapman, F. (May 1995). *Estimating the Economic Value of Wind Forecasting to Utilities*. NREL/TP-441-7803. Golden, CO: National Renewable Energy Laboratory; 10 pp. (NTIS no. DE95009203).

The authors examine the economics of an accurate wind forecast, and provide a range of estimates calculated by a production cost model and real utility data. An accurate forecast can affect, and benefit, resource scheduling.

Milligan, M.R.; Miller, A.H. (July 1993). *The Value of Windpower: An Investigation Using a Qualified Production Cost Model*. NREL/TP-441-5730. Golden, CO: National Renewable Energy Laboratory; 10 pp. (NTIS no. DE93010043).

This paper applies the Environmental Defense Fund's Electric Utility Financial & Production Cost Model (Elfin) as a tool to determine the value of wind energy to specific utilities. By using two wind-speed distributions, two different wind turbines, and two different utilities, the authors calculate how much the turbines need to cost to have positive value for the utilities.

*Economic Lessons From a Decade of Experience*. (1993). Produced under the auspices of the Utility Wind Interest Group; published by the Electric Power Research Institute; 4 pp. Available from the National Renewable Energy Laboratory, order no. UWIG 1.

This pamphlet reviews trends in costs and productivity of wind energy systems during the previous decade.

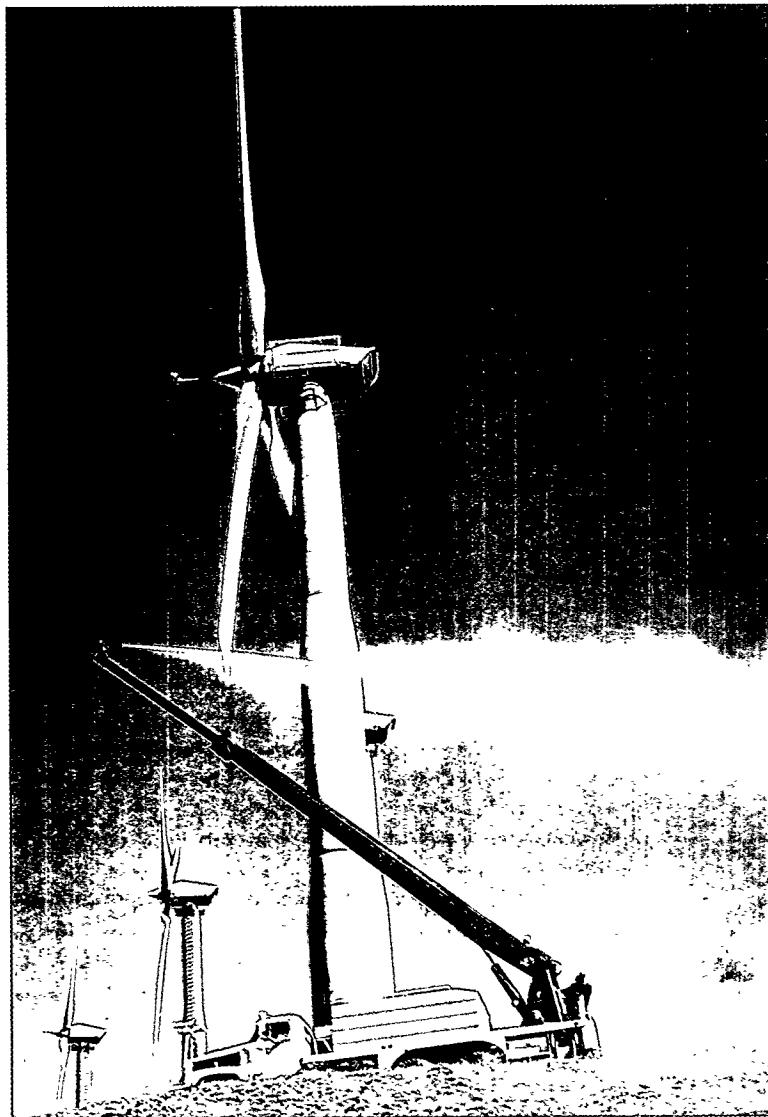
Swift, A.; Thresher, R.W.; Hock, S.M. (National Renewable Energy Laboratory). (1992). "Advanced Wind Turbine Performance and Cost Projections: A Configuration Study." *Windpower '92 Conference; October 19-23, 1992; Seattle, Washington*. Washington, DC: American Wind Energy Association; pp. 431-447.

This paper examines the projected performance and cost for the next generation of utility-scale wind turbines using a survey of experienced designers and evaluators of wind turbine technology.

Karas, K.C. (1992). "Wind Energy: What Does it Really Cost?" *Windpower '92 Conference; October 19-23, 1992; Seattle, Washington*. Arlington, VA: American Wind Energy Association; pp. 157-166. Also NREL/TP-441-5245. Golden, CO: National Renewable Energy Laboratory; 10 pp. (NTIS no. DE93000044).

Specialized companies often manage O&M activities, particularly at large wind power sites. Maintenance programs at large wind power plants have taken advantage of economies of scale to lower O&M costs dramatically. In addition, improvements in design have greatly decreased the number of unscheduled maintenance events. O&M costs have fallen from more than 3¢ per kWh in 1984 to about 1¢ per kWh in 1994.

As a result of these developments, the cost of energy for new wind power plants fell from about 13.4¢/kWh in 1984 to about 5.4¢/kWh in 1994 (cost of energy estimated using the EPRI TAG™ [Electric Power Research Institute Technical Assessment Guide] method referenced in this document). The U.S. Department of Energy expects costs to fall to less than 5¢/kWh, well within the competitive range of conventional forms of power production.



*More than a decade of experience operating wind power plants has taught the industry and utilities how to effectively manage this type of electric generating facility.*

This paper explains that initial economic assumptions—cost of financing, hub height, wind regime, and computational conventions such as levelization—greatly influence the results. These assumptions must be clearly specified in any cost-of-energy estimate.

Van der Horst, M., et al. (March 1992). *SOMES Version 3.0 Technical Reference Manual*. NWS-92010-2. The Netherlands: Rijksuniversiteit Utrecht. Available from Department of Science, Technology and Society, Faculty of Chemistry, University of Utrecht, P.O. Box 80093, 3508 TB Utrecht (The Netherlands); 68 pp.

This report describes the Simulation and Optimization Model for Renewable Energy Systems (SOMES version 3.0). Another report available from this source, *SOMES 3.0 User's Manual*, describes user interface and the output generated. The SOMES computer model calculates the economically optimum configuration for renewable energy systems, taking into account local conditions and the required reliability of electricity supply. It evaluates the performance of an electrical energy system consisting of renewable sources (wind turbine or photovoltaic generator), a storage system (batteries), and a backup system (a diesel generator or an electricity grid).

Dodd, H.M.; Hock, S.M.; Thresher, R.W. (1990). "The Sensitivity of Wind Technology Utilization to Cost and Market Parameters." *Windpower '90 Conference; September 25, 1990; Washington, DC*. Arlington, VA: American Wind Energy Association. Also SERI/TP-257-3986. Golden, CO: National Renewable Energy Laboratory; 6 pp. (NTIS no. DE91002122).

Cost curves for wind technology evolution are presented and used with wind resource estimates and energy market projections to estimate the penetration of wind power into the market. This penetration depends on key cost parameters and underlying modeling assumptions, which are evaluated.

*Recommended Practices for Wind Turbine Testing: 2. Estimation of Cost of Energy from Wind Energy Conversion Systems; 1. Edition 1983.* (1983). Edited by J. Nitteberg, A.A. deBoer, and P.B. Simpson. 23 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems. (NTIS no. DE84901132).

This document describes the recommended procedure for estimating energy costs from wind energy conversion systems (WECS). It provides a standard methodology for comparing the costs of energy produced by commercially available WECS.

Capital Cost	\$775/kW
System Rating	300 kW
Net Annual Energy	628 kWh/yr
<b>Total Installed Cost</b>	<b>\$232,500</b>
O&M Fixed Cost	\$8.20/kW
O&M Variable Cost	1¢/kWh
<b>Total O&amp;M Cost</b>	<b>1.4¢/kWh</b>
Plant Life	30 yr
Fixed Charge Rate	10.9%
Capacity Factor	24%
Wind Speed at 10 m	13.0 mph
Wind Speed at 37-m hub ht	15.6 mph
<b>Levelized Cost of Energy (Constant 1994 \$)</b>	<b>5.4¢/kWh</b>

Cost-of-energy method presented in Cohen et al. 1992.

## Economics of Wind Energy for Utilities

Wind power plants have several characteristics that make them economically attractive to utilities and their ratepayers. One of these features is predictable annual operating costs. Because wind turbines consume no fuel, most of the costs of wind generation are known in advance, when the systems are installed. Wind power plants aren't subject to the risks of fuel price fluctuations as are plants fired by fossil fuels. Wind power's lack of fuel costs can help utilities to stabilize the rates they charge consumers for electricity.

Another advantage wind plants offer is modularity. Wind plants' minimum economic size is small compared to that of conventional generation technologies. The unit cost per kilowatt of capacity is relatively insensitive to plant size. Time required to approve and build projects is short. Short lead-time requirements and modularity offer planning flexibility and reduce cost forecasting and regulatory risks associated with conventional generation. Other advantages of wind turbine modularity are greater flexibility in operating and maintaining units and an improved ability to match acquisitions to load growth.

In addition, wind power plants bring environmental benefits to utilities. Wind generators have no significant airborne emissions, use no water, have no radiation hazards, and are compatible with other land uses such as farming or ranching. Wind generation, a clean source of energy, can help a utility reduce its net emissions on a per kilowatt-hour basis. This reduction can, in turn, become a source of sulfur dioxide emission allowances created under the Clean Air Act Amendments of 1990. By reducing emissions and creating emission allowances to offset older, fossil-fuel-fired plant emissions, wind power can help a utility improve its overall environmental performance. (See Chapter 6 for further discussion of environmental issues.)

*TAG™ Technical Assessment Guide; Volume 1: Electricity Supply—1993 (Revision 7).* (June 1993). Technology and Fuels Assessment Department, Electric Power Research Institute. TR-102276-V1R7. Palo Alto, CA: Electric Power Research Institute.

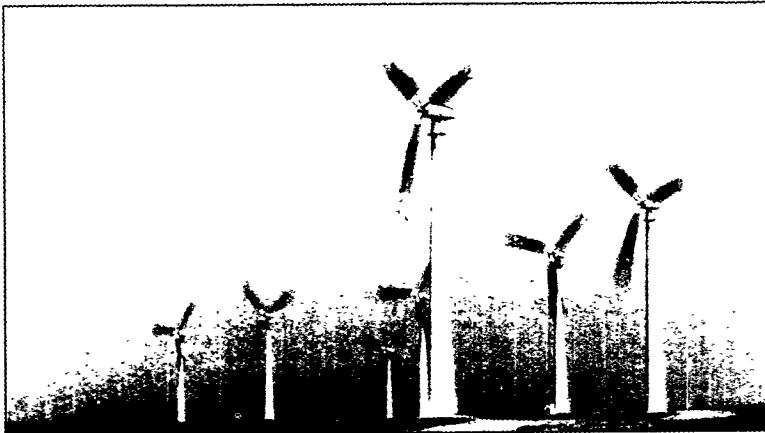
This version provides up-to-date information for preliminary resource planning in the electric utility industry. It discusses conventional and advanced power generation technologies and presents cost and power performance data, economic factors, and fuel price scenarios. The report also includes economic evaluation methodologies for regulated and unregulated power producers.

Quinlan, P.; Bourg, J.; Poff, K. (NEOS Corporation). (1993). "Wind Power's Role in Utility Integrated Resource Planning." *Windpower '93 Conference; July 12–16, 1993; San Francisco, CA.* Washington, DC: American Wind Energy Association; pp. 97–104.

This paper describes the integrated resource planning (IRP) process that is becoming more prevalent in utilities across the United States and conducts a sample evaluation of wind power under IRP.

Cadogan, J.B.; George, K.E.; Schweizer, T.C.; Cohen, J.M. (1992). "The Risks of Conventional Utility Supply Sources and the Rewards of Renewable Energy." *Windpower '92 Conference; October 19–23, 1992; Seattle, WA.* Washington, DC: American Wind Energy Association; pp. 101–112.

The paper compares the investment decision of a utility considering a gas-fired combined-cycle plant to that for a hybrid wind gas turbine plant. An improved approach to quantifying wind energy's benefits—modularity, relatively quick siting and installation, no fuel escalation or environmental risk—is presented.



Wind power plants, like this one in the Midwest, generate electricity for utility customers.

Utilities interested in the potential benefits from wind energy determine the value of wind energy to their systems through resource planning. The use of wind power poses a variety of planning challenges for utilities, primarily because wind is highly variable and cannot be controlled. The wind resource, like solar radiation, is said to be "intermittent" because it varies during each day, with the weather, and with the seasons of the year.

Studies to determine the benefits of wind-powered generation for utilities use economic methods familiar to utilities in combination with the growing database generated by operating wind power plants. Determining the impact of intermittent technologies on electric utilities involves three basic steps: (1) estimating performance, (2) determining the correlation between the time profile of energy produced by the wind system and the time profile of the utility electric power requirements, and (3) calculating the resulting change in the utility's production costs. Other considerations affecting utilities' use of wind power include terrain and availability of land to the utility; the economic and technical constraints on wind machine size, rated capacity, and capacity factors; project economics; and regulatory issues.

In utility wind power plant applications, the time profiles of power produced from the wind plant and the utility's load determine the extent to which a wind plant can displace conventional generation. Because intermittent solar electric technologies generally have higher capital costs per kW of capacity but lower operating costs per kWh than conventional units, a utility would seek to minimize operating costs by using power from the wind plant whenever it was available.

Various methods are used to determine the potential value of a wind system for a particular utility. In general, the WECS value is the amount a utility can afford to pay for a wind turbine based on its performance and the fuel cost savings if the wind system is installed. Because WECS provide intermittent power, they must be treated carefully in utility planning models. Therefore, the economic assessment often first analyzes a base case (without a WECS) and then an alternative case that includes wind turbines.

Cohen, J.M.; Schweizer, T.C. (Science Applications International Corporation); Hock, S.M. (National Renewable Energy Laboratory); Cadogan, J.B. (U.S. Department of Energy). (1992). *A Methodology for Computing Wind Turbine Cost of Electricity Using Utility Economic Assumptions (revised)*. Golden, CO: National Renewable Energy Laboratory.

The cost of electricity is one measure of the overall economic status of wind turbines. This paper describes a method that considers initial cost, operation and maintenance costs, and annual energy production. Consistent use of this method over time will provide comparable information on the economic status of wind-generated electricity.

Bergey, K.H. (Bergey Windpower Company, Inc.). (1991). "Windfarm Strategies: The Economies of Scale Revisited." *Windpower '91 Conference; September 24-27, Palm Springs, California*. Washington, DC: American Wind Energy Association; pp. 72-81.

This paper analyzes wind power plant cost of energy, considering costs of various sizes of turbines, optimal turbine densities, and energy capture. The author concludes that intermediate-size turbines (rotor diameters of 100 ft to 200 ft) may be less cost effective than either smaller or much larger units.

Hock, S.M.; Thresher, R.W. (National Renewable Energy Laboratory); Cohen, J.M. (Science Applications International Corporation). (1990). "Performance and Cost Projections for Advanced Wind Turbines." *American Society of Mechanical Engineers, Winter Annual Meeting; November 25, 1990; Dallas, Texas*. Also SERI/TP-257-3795. Golden, CO: Solar Energy Research Institute; 7 pp. (NTIS no. DE90000370).

Power electronics that allow variable-speed operation and a stall-controlled rotor can increase energy capture at least 40% without incurring appreciably increased costs. Turbines with an annual average hub-height wind speed of 6.8 meters per second (mps) to 8.5 mps are estimated to have an electricity cost of 3-6¢/kWh.

Merrill, O.; Schweizer, T.C.; Chernoff, H.; Conopask, H.; Knowles, R.; Nagle, R. (Science Applications International Corporation). (August 1985). *Early Market Potential for Utility Applications of Wind Turbines*. EPRI-AP-4077. Palo Alto, CA: Electric Power Research Institute; 200 pp.

This report concludes that if installed prices for reliable turbines decline to \$1,100/kW (1980 dollars), cumulative nationwide market potential will exceed 21,000 MW by the year 2000. This figure does not represent a forecast of development levels but rather the potential market under reasonable expectations of electric demand, coal prices, oil prices, and related factors.

Flaim, T.; Hock, S.M. (May 1984). *Wind Energy Systems for Electric Utilities: A Synthesis of Value Studies*. SERI/TR-211-2318. Golden, CO: Solar Energy Research

Economic assessments of intermittent, grid-connected solar electric technologies help provide an understanding of what these intermittent technologies must cost to compete with conventional technologies. The studies also assess the effects of incentives, such as tax credits, on project economics. Some studies present results in the formats, such as value analyses, used by utility analysts.

Institute; 112 pp.

This report normalizes and interprets the results from eight value analysis studies that estimate the value of WECS to utilities.

Sullivan, R.L.; Flaim, T.; Percival, D. (March 1982). *WECS Value Analysis: A Comparative Assessment of Four Methods*. SERI/TR-211-1563. Golden, CO: Solar Energy Research Institute; 51 pp.

This report compares four methods developed for conducting economic assessments of WECS in utility applications. The methods, developed by the Solar Energy Research Institute, the Aerospace Corporation, and the JBF Scientific Corporation, were applied to two case-study utilities. Results were compared for each step in the analysis, including WECS performance, load modification, production cost, capacity displacement, and break-even cost.

Percival, D.; Harper, J. (January 1982). *Electric Utility Value Determination for Wind Energy. Vol. I, A Methodology*. SERI/TR-732-604R-V.1, 94 pp. (NTIS no. DE82010771). *Vol. II, A User's Guide*. SERI/TR-732-604R-V.2, 121 pp. (NTIS no. DE82010926). Golden, CO: Solar Energy Research Institute; 2 Vols.

This report describes a method, contained in Solar Energy Research Institute computer models, that electric utilities can use with their own planning models to determine the value of wind energy systems.

## Economics of Wind Energy for Small Applications

Wind generators rated less than 50 kW can be used with or without utility-supplied electric power. Homeowners or businesses that are not connected to utility power can operate one or more small wind turbines in conjunction with batteries, diesel generators, or other solar electric systems to supply their needs for electricity. In some areas, homeowners or small commercial enterprises may opt to use electricity from a wind generator in addition to electricity available from the grid. In this situation, when the wind is blowing, power is used on site, with any extra flowing into the utility distribution system. Under the Public Utility Regulatory Policies Act, electric utilities must buy electricity from such small power producers as long as they meet safety and power quality requirements. (See Chapter 7.)

Grid-connected wind generators do pose some technical issues for the utility and the owner. One key issue is the safety of utility personnel. For example, if the utility shuts down power to a line for repair, the line must not be accepting power from the wind turbine, or workers could be injured. In addition, a large number of widely distributed generation sources subject to rapid power-output fluctuations may pose operational problems for the utility.

Moyle, R.A.; Chernoff, H.; Schweizer, T.C.; Patton, J.B. (November 1982). *Assessment of Distributed Solar Power Systems: Issues and Impacts*. EPRI AP-2636. Palo Alto, CA: Electric Power Research Institute; 184 pp.

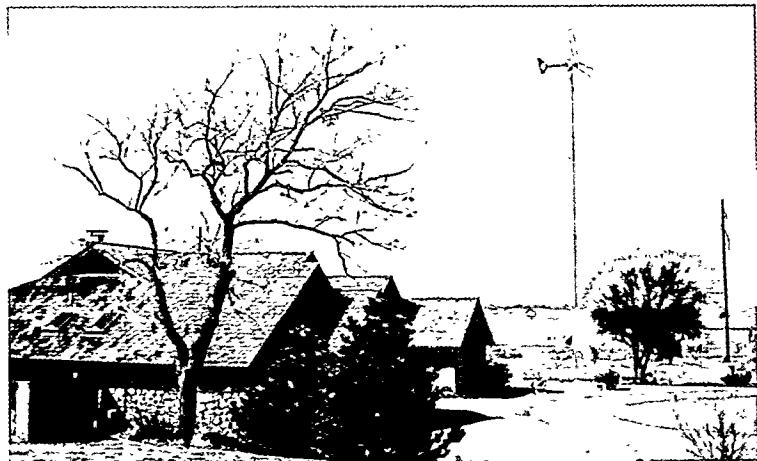
Some of the technical and economic impacts of dispersed solar power systems are discussed. Among the economic issues are user purchase criteria, structure and installation costs, marketing and product distribution costs, and interconnect costs. In addition, the report describes the development of an interactive computer program that calculates allowable system and generation equipment prices.

Britt, J.F.; Davey, H.L.; McCarroll, D.A.; Wysocki, K.J. (December 1981). *Small Wind Turbine Production Evaluation and Cost Analysis*. SERI/TR-09049-1. Golden, CO: Solar Energy Research Institute; 2 Vols.

This study determined the suitability for manufacture of a specific 10-kW horizontal-axis wind turbine design. It also analyzed production at three different manufacturing rates and generated a cost analysis of the production processes.

Today's power-conditioning and controller units make grid-connected systems easier to use. The controller automatically shuts down the wind turbine if utility power goes off, preventing wind-generated electricity from flowing into the "dead" line. In addition, power-conditioning units make wind-generated electricity match the electricity flowing in the grid, a basic requirement for selling power to the utility.

To select the appropriate small wind system for a particular application, the user must determine power needs (otherwise known as load requirements) and estimate the wind system's power output at the selected site. This process of matching user requirements with the machine's capabilities is often referred to as sizing.



*Homeowners, ranchers, and small businesses can use wind-generated electricity.*

*Evaluating Residential Wind System Economics.* (1994). Washington, DC: American Wind Energy Association; 20 pp.

This booklet guides the reader through the evaluation and selection of a small wind system. Topics include determining cost of energy, cost of loans, and cost over the life of the wind system. A worksheet is included.

Wyatt, A. (Research Triangle Institute). (1992). *Wind Electric Pumping Systems: Sizing and Cost Estimation.* Washington, DC: American Wind Energy Association; 39 pp.

This document presents step-by-step procedures for sizing and estimating the costs of an electric water-pumping system. Sections address estimating water-pumping requirements, assessing the wind resource, selecting components, predicting output, and preparing bid specifications. (Also available in Spanish.)

Moment, R.L. (February 1983). *Performance and Size Estimating for Wind Systems.* RFP-3586. Golden, CO: Rockwell International Corporation; 69 pp. (NTIS no. DE84006980).

This report explains how to estimate wind energy system performance given rated wind speed and annual energy production in common wind regimes (10–18 miles per hour) for rotor diameters ranging from 10 to 40 feet.

JBF Scientific Corporation (June 1981). *Small Wind Systems Application Analysis.* RFP-3147/2. Golden, CO: Rockwell International Corporation; 217 pp. (NTIS no. DE82003748).

This study estimates the potential market for small (less than 100-kW) WECS for farms, homes, feed grinders, rural electric cooperatives, and remote communities.

Stafford, R.W.; Greeb, F.J.; Smith, M.F.; Des Chenes, C.; Weaver, N.L. (January 1981). *Economic Analysis of Wind-Powered Farmhouse and Farm Building Heating Systems; Final Report.* DOE/SEA-3408-20691/81/1. Washington, DC: U.S. Department of Energy; 360 pp. Available from NTIS.

This study evaluates the break-even value of wind energy for selected farmhouses and farm buildings, focusing on the effects of thermal storage on the use of WECS production and value.

Garling, W.S.; Haufer, M.R.; Merchang-Geuder, L; Welch, M. (March 1980). *Economic Analysis of Wind-Powered Refrigeration Cooling/Water Heating Systems in Food Processing.* DOE/SEA-1109-20401/81. Washington, DC: Department of Energy; 150 pp. Available from NTIS.

This study analyzes the economics of wind power in refrigeration, cooling, and water-heating systems in plants that process meat and poultry, dairy, fruits and vegetables, and aquatic organisms.

# Chapter 3

## Wind Energy Resource

### Extent and Location of the Wind Resource

The wind resource in the United States is vast. There is sufficient wind potential in the continental United States to produce more than 4.4 trillion kilowatt-hours (kWh) of electricity each year, according to studies performed at Pacific Northwest Laboratory (PNL) in 1994. This is more than one and one-half times the 2.7 trillion kWh of electricity consumed in the United States in 1990. The wind resource is more than adequate to supply cost-effective electricity using wind turbine generators.

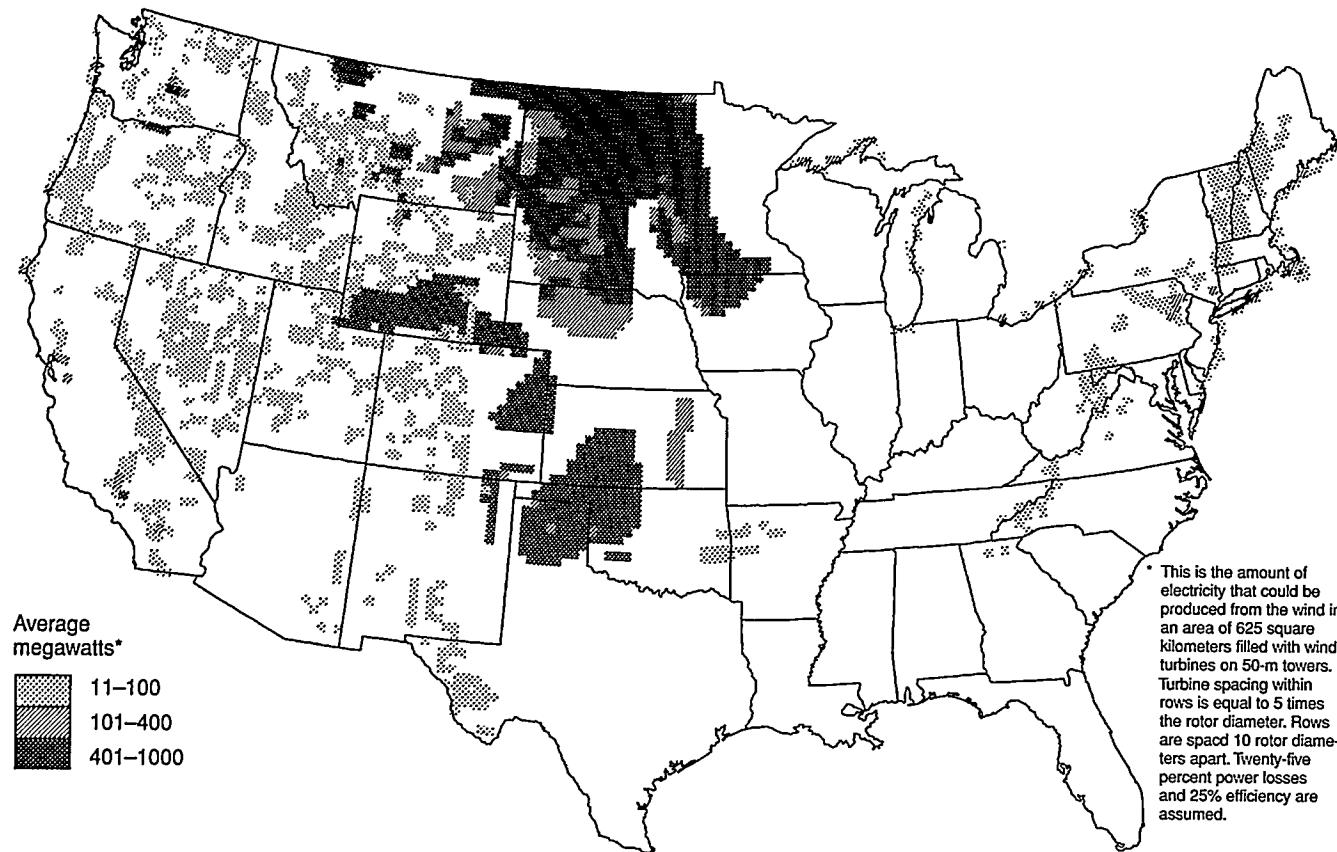
The single most important factor for design and performance of wind turbine generator installations is average wind speed. Knowing the wind speed probability distribution helps designers select the best

Pacific Northwest Laboratory. (1994). *Shaded Relief Elevation Maps for Wind Prospectors*. Washington, DC: American Wind Energy Association.

These computer-generated shaded relief maps are a useful prospecting tool when used with the state wind density maps in the Wind Energy Resource Atlas. Each map covers one degree of latitude and longitude on a letter-sized sheet of paper.

Elliott, D.L.; Schwartz, M.N. (September 1993). *Wind Energy Potential in the United States*. PNL-SA-23109. Richland, WA: Pacific Northwest Laboratory; 10 pp. (NTIS no. DE94001667).

**The U.S. Wind Resource**



turbine and assess the power performance of a machine with previously specified operating characteristics. Seasonal and diurnal, or daily, wind speed variations are especially important for load matching—correlating peak power demand with peak energy production. Gustiness of the wind affects the power output of a given machine design. And because wind speed increases with height above the ground, designers must trade off increased output power on tall towers against the added cost of taller towers.

The U.S. Department of Energy (DOE) sponsors programs to measure, understand, analyze, and explain meteorology as it relates to wind energy systems. Until 1994, PNL, operated for DOE by Battelle Pacific Northwest Laboratory, was responsible for atmospheric research in support of the DOE Wind Energy Program. Since 1994, research about the wind energy resource has been performed at the National Renewable Energy Laboratory.

In 1980, DOE supported work to develop a valuable tool for locating good wind resource areas. Researchers at PNL compiled twelve atlases covering the United States and its territories. The atlases depict regional and statewide wind resources in graphic, tabular, and narrative form. Surface wind data used to compile the atlases were obtained from a number of sources, with the National Climatic Data Center (NCDC) providing the greatest amount of data.

The NCDC collects and archives the data recorded by the National Weather Service and its predecessor agencies along with the weather services of the Air Force and Navy, the Federal Aviation Administration, the Coast Guard, and cooperative observers.

Detailed site-specific data used in developing the wind atlases was compiled in the Wind Energy Resource Information System (WERIS). Wind data was extracted from the full climatic records of the NCDC through 1978. This compiled information on the wind resource was turned over to the NCDC in Asheville, North Carolina. Summaries from WERIS and data from major U.S. weather stations are available from the NCDC for the cost of reproduction. The data base used to produce the regional wind energy assessments is available from the NCDC. Check under Associations in Chapter 9 for more information about data available from the NCDC and the American Wind Energy Association.

In an effort to improve information about the wind resource, DOE is compiling the wind data collected by NCDC since 1978. Although the wind resource has not changed since 1978, there are several reasons a new compilation of wind data should prove useful. First, there are many more data collection stations now, and some are in areas of interest to wind developers. Second, the equipment used to collect wind data takes more readings in the same time period, is more reliable, and is more automated than pre-1980 equipment. Third, more stations are following standards developed by the wind industry for wind data collection, making the data more comparable from one location to another.

This report estimates that more than one and a half times the current electricity consumption of the United States could be generated by wind power on the land area available for wind energy development. The estimates are based on published wind resource data and exclude windy lands that are not suitable for development due to environmental or land-use conflicts.

Schwartz, M.N.; Elliott, D.L.; Gower, G.L. (1992). "Gridded State Maps of Wind Electric Potential." *Windpower '92, October 19-23; Seattle, Washington.* Washington, DC: American Wind Energy Association; pp. 50-58.

This paper presents revised data on the wind-electric potential and available windy land calculated in 1991. Actual data on the distribution of environmental exclusion areas where wind energy development would be prohibited are incorporated into a new gridded data base and used to generate maps for the 48 contiguous states.

*America Takes Stock of a Vast Energy Resource.* (1992). Produced under the auspices of the Utility Wind Interest Group; published by the Electric Power Research Institute; 10 pp. Available from the National Renewable Energy Laboratory, Golden, CO, order no. UWIG 3.

This pamphlet summarizes recent resource assessments and presents basic information on the potential of wind energy development for the United States.

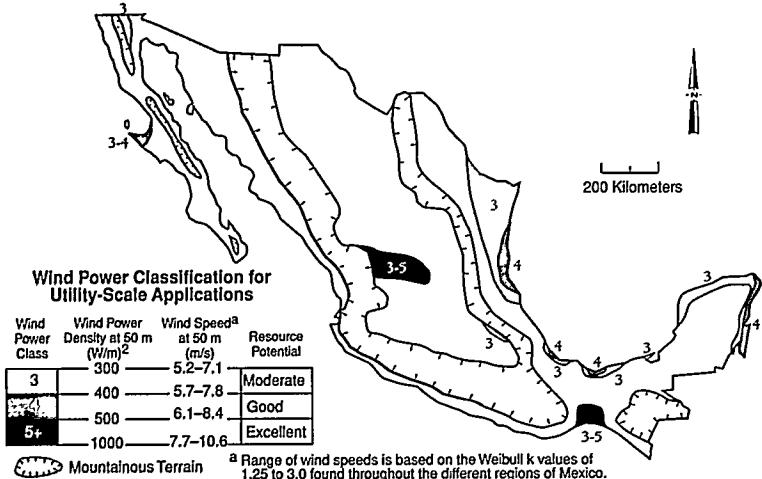
Elliott, D.L.; Gower, G.L.; Wendell, L.L. (August 1991). *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States.* PNL-7789. Richland, WA: Pacific Northwest Laboratory; 92 pp. (NTIS no. DE91018887).

This report estimates the land areas with various levels of wind energy resource and resultant wind energy potential in the contiguous United States. The estimates exclude some windy lands as a result of environmental and land-use considerations. Even with these exclusions, the amount of wind resource is surprisingly high.

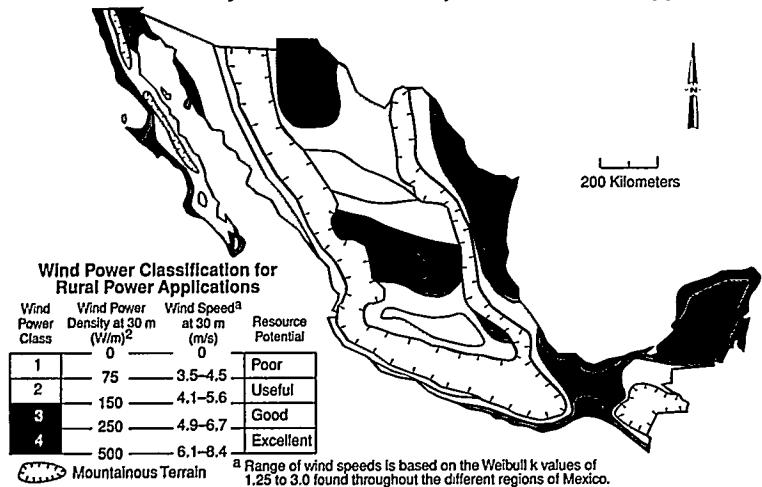
Troen, I.; Petersen, E.L. (1989). *European Wind Atlas.* Roskilde, Denmark: Risø National Laboratory; 655 pp. This report, sponsored by the Commission of the European Communities Directorate-General for Science, Research and Development, identifies and documents large regions with good promise for widespread exploitation of the wind resource. A computer program that can be used with the atlas allows calculation of wind energy potential and can guide developers in siting turbines in complex terrain.

Elliott, D.L. (October 1987). *Caribbean and Central America Wind Energy Assessment.* PNL-SA-15102. Richland, WA: Pacific Northwest Laboratory.

## Mexico—Preliminary Wind Resource Map for Utility-Scale Applications



## Mexico—Preliminary Wind Resource Map for Rural Power Applications



Researchers are compiling data from other countries to help the industry locate foreign markets. The top map shows areas suitable for utility power plant development. The bottom map indicates where hybrid power or stand-alone wind systems could be used to generate electricity.

This paper provides an overview of the Caribbean and Central America wind resource assessment and the data and techniques used in producing the assessment. It includes maps for 35 areas.

Elliott, D.L.; Holladay, C.G.; Barchet, W.R.; Foote, H.P.; Sandusky, W.F. (March 1987). *Wind Energy Resource Atlas of the United States*. DOE/CH10093-4. Richland, WA: Pacific Northwest Laboratory; 210 pp. (NTIS no. DE86004442).

This atlas estimates the wind energy resource for each state in the United States and in its territories, and indicates general areas of high wind. Chapter 2 presents national maps of the annual and seasonal average wind resource, certainty rating, and area distribution. Chapter 3 presents regional summaries of the wind resource estimates. Appendices provide information on synthesis of the regional assessments, the Wind Energy Resource Information System, annual and seasonal mean wind speed and power summaries for selected stations, evaluation of new site data for verifying or updating the wind resource estimates, and annual and seasonal mean wind speed and power summaries for 35 candidate wind turbine sites.

*California Wind Atlas*. (April 1985). Sacramento, CA: California Energy Commission; 210 pp. Available from California Energy Commission, Publication Unit, 1516 Ninth Street, MS-15, Sacramento, CA 95814.

This atlas summarizes wind data since 1930. Tables summarize wind station locations; mean hourly, monthly, and annual wind speeds; peak wind gusts; mean wind power; year-to-year and vertical wind variations; and wind resources that can be developed. Maps locate wind measurement sites, wind resource potential, and the electric transmission system.

Elliott, D.L. (1981). "Worldwide Wind Energy Resource Distribution Estimates." *Meteorological Aspects of the Utilization of Wind as an Energy Source*. Technical Note 175. Geneva, Switzerland: World Meteorological Organization.

This chapter includes maps of the wind resource showing its worldwide variations.

Changery, M.J. (December 1978). *National Wind Data Index*. HCO/T1041-01. Asheville, NC: National Climatic Data Center; 245 pp.

This index is a guide to locations in the United States for which original wind data, in any form, have been archived at the National Climatic Data Center.

Changery, M.J.; Hodge, W.T.; Ramsdell, J.V. (September 1977). *Index—Summarized Wind Data*. BNWL-2220 WIND 11. Richland, WA: Pacific Northwest Laboratory; 151 pp.

## Wind Prospecting and Siting

Developers need to find sites with sufficient wind to make wind-generated electricity competitive with other sources of generation. The site-screening process they use is sometimes referred to as wind prospecting. The process of placing the turbines within a specific piece of land is called siting.

Finding the best location for wind turbines involves three levels of analysis. First, a large region of land is screened for potential development using existing wind data and other indicators. Next, the wind resource within a defined area is characterized through meteorological monitoring. Finally, field measurements or models, or both, are used to locate the optimum position for turbines at a particular site.

A careful examination of the countryside can sometimes reveal where strong, prevailing winds have left their mark. For example, trees and plants can be greatly deformed (flagged) in a consistent way by the wind. In arid areas, where few plants are found, eolian landforms such as sand dunes, playas, and scour features can be another indicator of an area's wind conditions.

Certain topographical features are conducive to strong winds. Long, sloping valleys parallel to prevailing winds can channel and amplify wind in their troughs. High plains, exposed ridge crests, mountain summits, and exposed coastal sites often have the higher wind speeds associated with high elevations.



A tree flagged by high prevailing winds.

This index provides a description of all wind summaries then available at the National Climatic Data Center.

*Understanding Your Wind Resource.* (1994). Washington, DC: American Wind Energy Association; 12 pp.

This brochure briefly explains the wind resource and how it affects wind turbine production.

*Recommended Practice for the Siting of Wind Energy Conversion Systems.* (1993). AWEA Standard: AWEA 8.2-1993. Washington, DC: American Wind Energy Association; 24 pp.

This document provides guidelines for proper siting programs including large-scale land assessments and site-specific applications. The standard addresses siting topics such as meteorological measurements at candidate sites, instrumentation, and wind flow modelling.

McCarthy, E.F. (KENETECH/U.S. Windpower, Inc.); Meroney, R.N.; Neff, D.E. (Colorado State University). (1993). "Elevation and Vegetation Considerations on Wind Power Availability." *Windpower '93 Conference; July 12-16, 1993; San Francisco, California.* Washington DC: American Wind Energy Association; p. 213.

Forested hills and ridges pose significant technical and environmental issues for siting wind turbines. This paper reports the results of wind tunnel measurements and hilltop wind speed profiles examined as a function of surface roughness.

Wendell, L.L.; Gower, G.L.; Birn, M.B. (July 1993). "Applicability of Digital Terrain Analyses to Wind Energy Prospecting and Siting." *Windpower '93 Conference; July 12-16, 1993; San Francisco, California.* Washington DC: American Wind Energy Association.

This document presents an overview of the nature of wind and the methods of assessing the wind energy potential of a given site.

Council, C. (Western Area Power Administration); Quinlan, P.; Garrick, J. (NEOS Corporation). (1991). "Overview of Western Area Power Administration's Wind Prospecting Program." *Windpower '91 Conference; September 24-27; Palm Springs, California.* Washington, DC: American Wind Energy Association; pp. 219-225.

This paper describes the largest wind prospecting effort in the United States to date. Site data characteristics, quality assurance methods, and results of the program are included.

Elliott, D.L. (September 1991). "Status of Wake and Array Loss Research." *Windpower '91 Conference; September 24-27; Palm Springs, CA.* Washington, DC: American Wind Energy Association.

Wind prospectors can also use physical and numerical modeling to point the way to good areas. Numerical models estimate the effects of terrain on air flow. Numerical models also can interpolate wind data from locations where wind observations exist to locations where there are no data. In physical modeling, researchers simulate the wind flow over terrain by placing a scaled representation of the terrain in a wind tunnel and measuring the resulting currents and eddies.

Some of the reports and atlases listed here show general areas of a state with good wind potential. But on-site measurement is always needed to detail a prospective wind power plant site's wind energy potential. In addition to wind speed, prospectors must also evaluate related environmental factors such as temperature and precipitation to find suitable sites for wind power plants. Further, because of topographical features, high winds may blow in areas that don't show up on national maps.

Researchers have developed handbooks that help determine the best locations for wind turbines, a process known as siting. Siting handbooks are based on studies of the effects of wind characteristics on wind machine performance. After a potential wind power development site is located, siting handbooks provide techniques to evaluate a particular site's wind resource and to select and place the wind machine to best take advantage of the resource. An optimum site meets the following criteria:

- High average annual wind speed
- Acceptable daily, seasonal, and annual variations of the wind
- Acceptable extreme winds and turbulence levels
- Acceptable levels of other environmental factors that affect structural integrity and system lifetime, such as icing or salt spray.

The shaded relief maps available from the American Wind Energy Association provide site-specific wind speed information and useful information about terrain.

For wind energy to have a significant effect on U.S. electric power production, wind turbines have to be grouped in wind power plants, also called arrays. Because wind turbines create wakes of low-energy air behind them, wake interference is a significant factor in the design of these arrays. Close spacing of wind turbines can result in some machines operating in the wakes of other units, causing possible detrimental effects on power output and structural integrity. Considerable attention has been given to wake interference problems, as described in the recent studies listed here.

A good scientific understanding of wind turbine wakes is necessary for the formulation of analytical tools. These tools are used to place turbines within an array to maximize wind power plant annual energy

Single-turbine wake characteristics are generally described well by existing theoretical models. Wind turbine array wake effects for small arrays with two to four rows of turbines have been measured. But little has been published on wake effects within large arrays. The few measurements taken suggest that wake deficits downwind of large arrays are substantially larger and extend farther downwind than expected.

Lissaman, P.B.S; Lindberg, D.T. (AeroVironment, Inc.); Armstrong, J.B. (SeaWest Industries, Inc.) (1990). "Development of the Advanced AV-Lissaman Wind Turbine Array Interference Model." *Proceedings of the European Community Wind Energy Conference*. Bedford, England: H.S. Stephens and Associates; pp. 163-165.

This paper describes a new proprietary numerical model, improving on the 1977 and 1982 versions, that can be used in array design applications in complex terrain. The model was developed under the U.S. Small Business Innovative Research (SBIR) program.

Barnard, J.C. (June 1990). *An Evaluation of Three Models Designed for Siting Wind Turbines in Areas of Complex Terrain*. PNL-7357. Richland, WA: Pacific Northwest Laboratory; 50 pp. (NTIS no. DE90013625).

The three models evaluated all performed poorly and exhibited wind speed prediction errors of about 25%. Using six wind input stations greatly improved model simulations, underscoring the necessity for wind data at more than one point for some modeling situations.

Nierenberg, R. (Altamont Energy Corporation). (1990). *Wake Deficit Measurements on the Jess and Souza Ranches, Altamont Pass*. SERI/STR-257-3455. Golden, CO: Solar Energy Research Institute.

In this part of DOE's Cooperative Field Test Program, Altamont Energy Corporation measured wake effects on power production of 65-kilowatt machines at two different wind power plants. The report includes wind power plant maps detailing the wake effects measured in the tests.

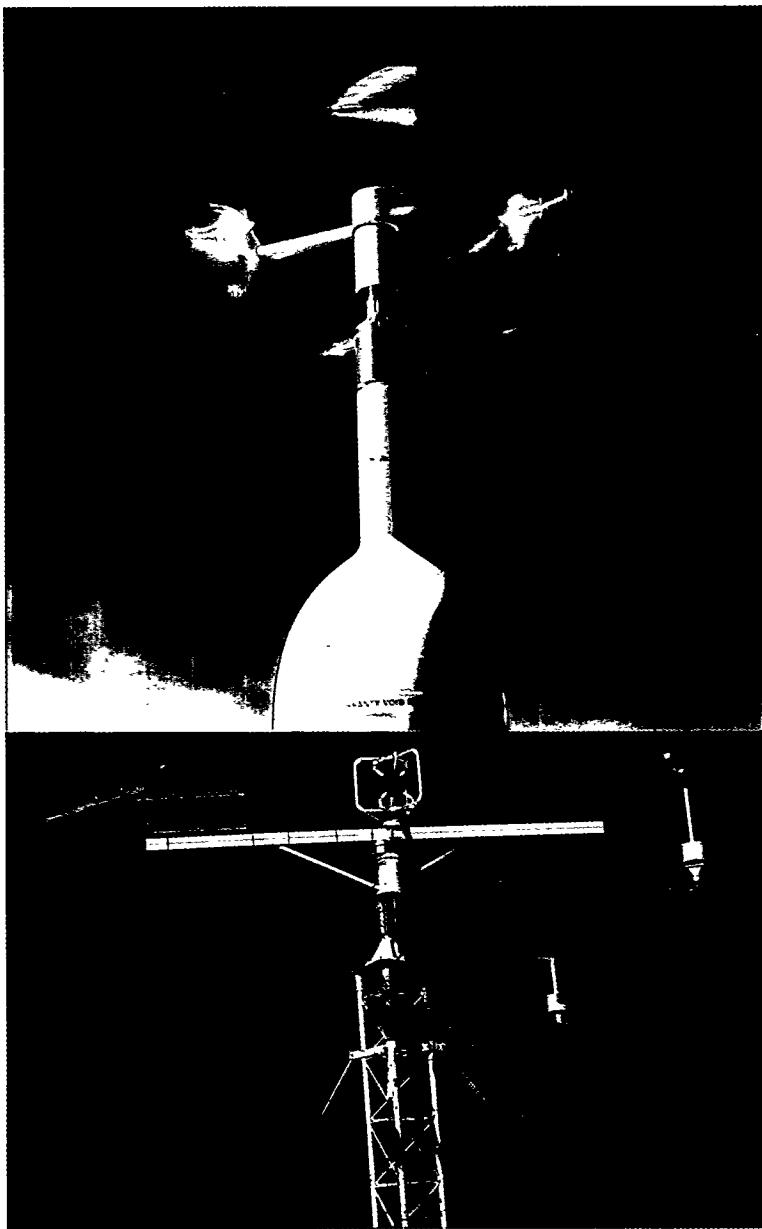
Connell, J.R.; Morris, V.R. (1990). "Turbulent Wind at the Equatorial Segment of an Operating Darrieus Wind Turbine Blade." *Ninth ASME Wind Energy Symposium*. SED-Vol. 9. New York, NY: American Society of Mechanical Engineers.

This paper reports the theory, measurement approach, and data collected at an operating vertical-axis wind turbine.

Elliott, D.L.; Barnard, J.C. (1990). "Effects of Trees on Wind Flow Variability and Turbulence." *Journal of Solar Energy Engineering*. Vol. 112, November 1990. New York, NY: American Society of Mechanical Engineers.

This paper describes a field experiment at Goodnoe Hills, Washington, to examine the effects of trees on wind flow variability and turbulence. Wind data

capture and reduce fatigue damage caused by the wake velocity deficiency and high turbulence.



*With a special data-filtering technique developed under the U.S. Department of Energy Wind Energy Program, the inexpensive cup anemometer (top) can supply measurements almost as useful as those made with a sonic anemometer (bottom).*

collected at nine towers across the site revealed that surface roughness changes in the upwind fetch caused pronounced variations in the wind flow over the site.

Elliott, D.L.; Cadogan, J.B. (1990). "Effects of Wind Shear and Turbulence on Wind Turbine Power Curves." *European Community Wind Energy Conference and Exhibition; September 10-14, 1990; Madrid, Spain.* Bedford, England: H.S. Stephens & Associates.

During an analysis of power curves for three 2.5-megawatt wind turbines, the authors discovered the importance of turbulence and wind shear on power curve measurements.

Wade, J.E.; Baker, R.W.; Walker, S.N. (Oregon State University). (February 1990). *Wind Forecasting for Utility Operations.* DOE/BP/63406-9. Washington, DC: U.S. Department of Energy; 62 pp. (NTIS no. DE90009466).

This report examines two wind-forecasting problems: Forecasting wind energy output and forecasting extremely strong (potentially damaging) winds. Studies have shown that wind forecasts must be accurate to within 2 mph. This report concludes that current methods result in a forecasting error of about 3 mph.

Veenhuizen, S.D.; McCoy, T.J.; Lin, J.T.; Rumbaugh, J.H. (1989). "Modeling Wind Turbine Array Wake Effects." *Proceedings of Windpower '89.* Washington, DC: American Wind Energy Association; pp. 7-13.

This paper describes work performed under an SBIR contract to develop a numerical model to design wind turbine arrays in complex terrain.

Nierenberg, R. (Altamont Energy Corporation). (1989). *Free-Flow Variability on the Jess and Souza Ranches, Altamont Pass.* SERI/STR-217-3404. Golden, CO: Solar Energy Research Institute.

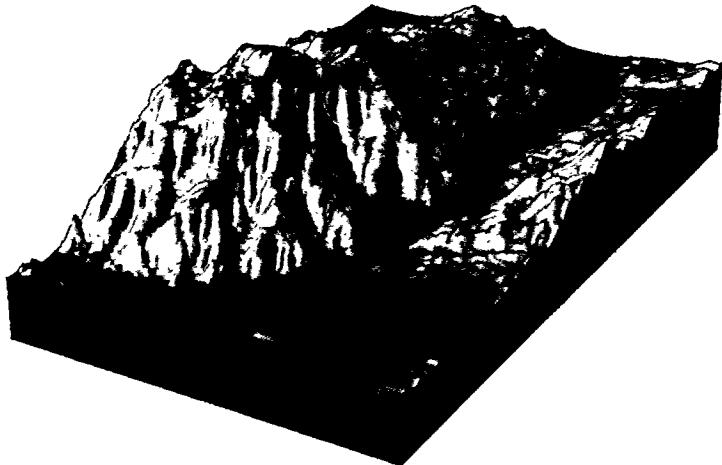
This report presents the findings of field tests conducted under the DOE Cooperative Field Test Program. Wind data were collected at two wind farms. To obtain a high spatial density of wind speed measurements, every other wind turbine in both arrays was instrumented. Measurements were taken with the wind turbines shut down to determine variation in flow caused by interaction with terrain.

Elliott, D.L.; Buck, J.W.; Barnard, J.C. (April 1988). *An Examination of Wake Effects and Power Production for a Group of Large Wind Turbines.* PNL-6528. Richland, WA: Pacific Northwest Laboratory; 58 pp. (NTIS no. DE88009906).

Data from a group of three MOD-2 wind turbines and two meteorological towers at Goodnoe Hills were analyzed to evaluate turbine power output and wake effects and the atmospheric factors influencing them.



New techniques are being developed each year for recording, analyzing, and communicating the extent and location of the wind resource. This shaded relief map combines terrain features with the grids from the Wind Energy Atlas.



This terrain map of San Gorgonio Pass, near Palm Springs, California, illustrates the kind of computer analysis available to developers for site assessments.

Walker, S.N. (Pacific Wind Energy). (1988). *Local Wind Measurements for Micrositing*. SERI/STR-217-3320. Golden, CO: Solar Energy Research Institute.

This work conducted under the DOE Cooperative Field Test Program collected detailed wind measurements across sites considered appropriate for wind farms. The measurements confirmed general observations about the sites and demonstrated the high degree of wind speed variability that can exist across a single wind farm.

Simon, R.L. (Fayette Manufacturing Corporation). (April 1988). *Wake Effects in a Fayette 85-IIS Wind Turbine Array*. SERI/STR-217-3186A. Golden, CO: Solar Energy Research Institute; 75 pp.

In this research conducted under the DOE Cooperative Field Test Program, a group of 35 turbines was investigated to quantify array wake effects (losses in energy production because of operating downwind from other turbines) and the factors influencing them.

Liu, H.-T. (FloWind Corporation). (1988). *Field Investigation of a Wake Structure Downwind of a VAWT in a Wind Farm Array*. SERI/STR-217-3370. Golden, CO: Solar Energy Research Institute.

This report presents work conducted under the DOE Cooperative Field Test Program. More than 150 hours of measurements were made of wake configurations to evaluate row effects, single (or "primary") turbine effects, and "side turbine" effects.

Barnard, J.C.; Wegley, H.L. (January 1987). *A Preliminary Evaluation of the Performance of Wind Tunnel and Numerical Modeling Simulations of the Wind*. PNL-6105. Richland, WA: Pacific Northwest Laboratory; 20 pp. (NTIS no. DE87004634).

This report analyzes physical and numerical model simulations of wind flow over complex terrain at Altamont Pass, California.

*Standard Procedures for Meteorological Measurements at a Potential Wind Turbine Site*. (1986). AWEA Standard: AWEA 8.1-1986. Alexandria, VA: American Wind Energy Association; 18 pp.

This document provides procedures and methods for obtaining meteorological measurements. It presents standards for meteorological measurement systems as well as the installation, operation, and calibration of equipment. Appendices contain guidelines for sampling strategies, data processing, and site evaluation.

Pennell, W.T. (January 1983). *Siting Guidelines for Utility Application of Wind Turbines*. EPRI-AP-2795. Palo Alto, CA: Electric Power Research Institute; 266 pp.

This report presents guidelines for identifying viable sites for wind turbines. Topics include predicting



wind turbine performance at potential sites, analyzing wind turbine economics, estimating installation and maintenance costs, and more.

Wade, J.E.; Maule, P.A.; Bodvarsson, G.; Rosenfeld, C.L.; Woolley, S.G.; McClenahan, M.R. (February 1983). *Remote Sensing for Wind Power Potential, A Prospector's Handbook*. DOE/ET 20316-81-1. Richland, WA: Pacific Northwest Laboratory; 308 pp.

This report combines several techniques into a method for quickly pinpointing promising wind power sites. Emphasis is on the use of remote-sensing, imagery-based information such as satellite imagery, high-altitude aerial photos, maps, and low-level aerial photos.

Wade, J.E.; Hewson, E.W. (October 1981). *A Guide to Biological Wind Prospecting*. DOE/ET/20316-80-2. Corvallis, OR: Oregon State University; 112 pp.

The growth form of trees and shrubs is affected by the wind. This book provides guidelines for determining prevailing wind direction and estimating average annual wind speed at a site by studying the vegetation.

Frost, W.; Shieh, C.F. (December 1981). *Guidelines for Siting WECS Relative to Small-Scale Terrain Features*. DOE/ET/20242-78/1. Tullahoma, TN: FWG Associates, Inc.; 196 pp.

*Meteorological Aspects of the Utilization of Wind as an Energy Source*. (1981). Technical Note 175. Geneva, Switzerland: World Meteorological Organization; 180 pp.

The report includes information on atmospheric circulation systems; wind energy technology; and wind energy meteorology. Appendices provide detailed information on turbulence and the atmospheric boundary layer, wind measurement instruments, computation of power output, and nomenclature.

Hiester, T.R.; Pennell, W.T. (January 1981). *The Meteorological Aspects of Siting Large Wind Turbines*. PNL-2522. Richland, WA: Pacific Northwest Laboratory; 512 pp.

This report addresses the meteorological aspects of site selection and machine design and wind energy economic evaluation related to meteorological siting concerns.

Wegley, H.L.; Orgill, M.M.; Drake, R.L. (March 1980). *A Siting Handbook for Small Wind Energy Systems*. PNL-2521 Rev. 1. Richland, WA: Pacific Northwest Laboratory; 132 pp.

This is a guide for individuals wishing to install small wind systems with rated capacity below 100 kW. The following topics are covered: siting in flat terrain, siting in nonflat terrain, methods of site analysis, wind measurements, and environmental hazards for WECS operations.

Corotis, R.B. (May 1980). *Application of Statistical Techniques to Wind Characteristics at Potential Wind Energy Conversion Sites*. DOE/ET/20283-2. Evanston, IL: Northwestern University; 122 pp.

*Proceedings of the Conference and Workshop on Wind Energy Characteristics and Wind Energy Siting; June 19-21, 1979; Portland, Oregon.* (1979). PNL-3214. Richland, WA: Pacific Northwest Laboratory; 471 pp.

Marrs, R.W.; Gaylord, D.R. (April 1979). *A Guide to the Interpretation of Windflow Characteristics from Eolian Landforms*. RLO-2343-79/2. Laramie, WY: University of Wyoming; 39 pp.

Frost, W.; Long, B.H.; Turner, R.E. (December 1978). *Engineering Handbook on the Atmospheric Environmental Guidelines for Use in Wind Turbine Generator Development*. NASA-TP-1359. Huntsville, AL: National Aeronautics and Space Administration, Marshall Space Flight Center; 372 pp.

This report presents design criteria relative to wind speed, wind shear, turbulence, wind direction, ice and snow loading, and other climatological factors. Each chapter provides a range of recommended design values for a general purpose wind turbine generator. Following these summarized values are detailed computational procedures and working data that allow designers to establish their own design values. The design criteria are presented in an engineering format that can be used directly in wind turbine design computations.

# Chapter 4

## Wind Turbine Design, Development, and Testing

### General Design and Engineering Practices

Modern wind turbine design uses the principles of materials science, structural dynamics, finite element analysis, turbulence theory, and aerodynamic engineering to develop machines that, given a certain set of site conditions, convert energy at the lowest possible cost per kilowatt-hour. Researchers are continually gaining a better understanding of the principles of wind machine operation. These principles are then used to optimize a wind energy conversion system design.

Several major challenges are involved in advancing the understanding of wind turbine dynamics. First, wind turbines operate under environmental conditions that can be severe, unpredictable, and poorly defined. Moreover, the basic physical processes involved in generating electricity from the wind are characterized by complex, dynamic interactions. Accurate modeling of these processes will require major advances in analytical capability. Finally, the response of a wind turbine to its operating environment will depend on its particular design characteristics. Therefore, wind turbine dynamics research must address a wide variety of machine sizes and configurations.

Current research activities featured in the following sections include atmospheric fluid dynamics (inflow and turbulence characterization), aerodynamics, and structural dynamics, all of which will improve



Wind power plants provide important data for improving wind turbine design.

Spera, D.A. (May 1994). *Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering*. No. 100368. Fairfield, NJ: American Society of Mechanical Engineers; 700 pp.

This collection of articles compiled by the American Society of Mechanical Engineers provides an advanced look at all aspects of the modern wind turbine including airfoils, rotor wakes, acoustics, system configuration, and fatigue design.

Glanz, J. (August 1992). "High-Tech Windmills' Future Burns Bright." *R&D Magazine*. Des Plaines, IL: Cahners Publishing Company.

This article discusses the design challenges for engineers working to improve wind turbine performance and costs.

Araj, K.J.; Fisher, T.A.; Kronenburg, J.C. (National Research Council, Washington, DC). (1991). *Assessment of Research Needs for Wind Turbine Rotor Materials Technology*. DOE/AL/58181-T1. Washington, DC: U.S. Department of Energy; 108 pp. (NTIS no. DE92018563).

This report presents a simplified description of the relationship between the power in the wind and the power flow through the turbine drivetrain. The author describes the characteristics of the wind environment that impact both the short- and long-term structural integrity of wind turbines. The need for improved materials properties, manufacturing processes, and control systems is defined.

*Design Criteria Recommended Practices: Wind Energy Conversion Systems*. (1988). AWEA Standard: AWEA 3.1-1988. Arlington, VA: American Wind Energy Association; 25 pp.

This document describes the criteria used to design wind energy conversion systems. It includes general design criteria, system design considerations, component design criteria, and mechanical, structural, and electrical attachment conditions.

Eggleston, D.M.; Stoddard, F.S. (1987). *Wind Turbine Engineering Design*. New York, NY: Van Nostrand Reinhold Company, Inc.; 352 pp.

Part I of this book discusses the aerodynamics of wind turbine design: modeling rotor aerodynamics, sizing of rotors, wind turbine design and analysis,

researchers' understanding of the basic physical processes created by a wind turbine's interaction with its environment.

To explore the effects of machine size and configuration, field tests are conducted with a wide variety of machines, including U.S. Department of Energy (DOE) experimental turbines and existing commercial machines in wind power plant installations. Researchers also conduct wind tunnel tests and theoretical analyses. The purpose of these research activities is to provide the necessary data for the development and validation of models, which will serve as design tools for industry to develop more cost-effective wind machines.

## Inflow and Turbulence Characterization

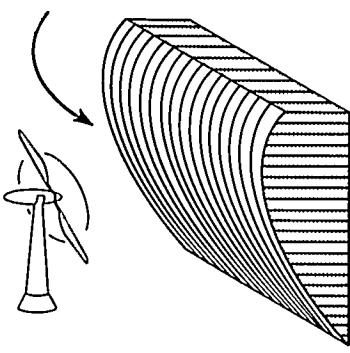
One of the major challenges to developing cost-effective wind turbines has been building turbines that can withstand the structural loads imposed by unsteady (turbulent) wind flowing to the rotor (inflow). By 1989, many commercial wind turbines that had been operating a number of years exhibited fatigue to structural components.

To improve designs for turbulence, atmospheric fluid dynamics research is continuously refining models of the wind. These models will provide a better understanding of turbulence and atmospheric flow across complex terrain. However, developing and verifying these models requires accurate measurement of turbulent winds. Turbulence, which results from the interaction of uneven terrain and vegetation with variable atmospheric conditions and wind velocities, has proven difficult to measure.

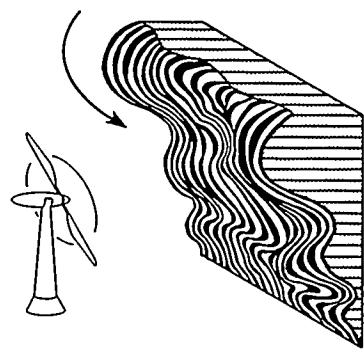
With industry input, DOE created a measurement system consisting of two towers, five anemometers, and a data acquisition system. The systems, installed at utilities across the country, measure the severity and frequency of violent turbulence. This information allows turbine designers to come up with more durable turbines for extreme conditions.

### Wind Inflow Models

Uniform Wind Shear



Unsteady Wind



Steady Wind Model

and performance, economics, and siting. Part II discusses the structural dynamics of wind turbines: system engineering, blade equations of motion, blade motions, instabilities, and load specification. Part III discusses fatigue, electrical generators, and control systems.

Miller, A.H.; Dugundji, J.; Martinez-Sanchez, M.; Gohard, J.; Chung, S.; Wendell, J. (Massachusetts Institute of Technology). (September 1978). *Wind Energy Conversion, Volume 1: Methods for Design Analysis of Horizontal-Axis Wind Turbines*. COO-4131-Tq (Vol. I). Washington, DC: U.S. Department of Energy; 253 pp.

Wendell, L.L.; Barnard, J.C.; Morris, V.R. (1993). "New Parameters for Characterizing Turbulence at a Potential Wind Site." *Windpower '93 Conference; July 12-16, 1993; San Francisco, California*. Washington, DC: American Wind Energy Association; pp. 234-243.

This project produced a database of three-component wind turbulence at four strategic locations over a rotor disk in different types of complex terrain. This paper discusses a comparison of Turbulence Intensity, Turbulence Engulfing Test, and Turbulence Fluctuating Shear parameters.

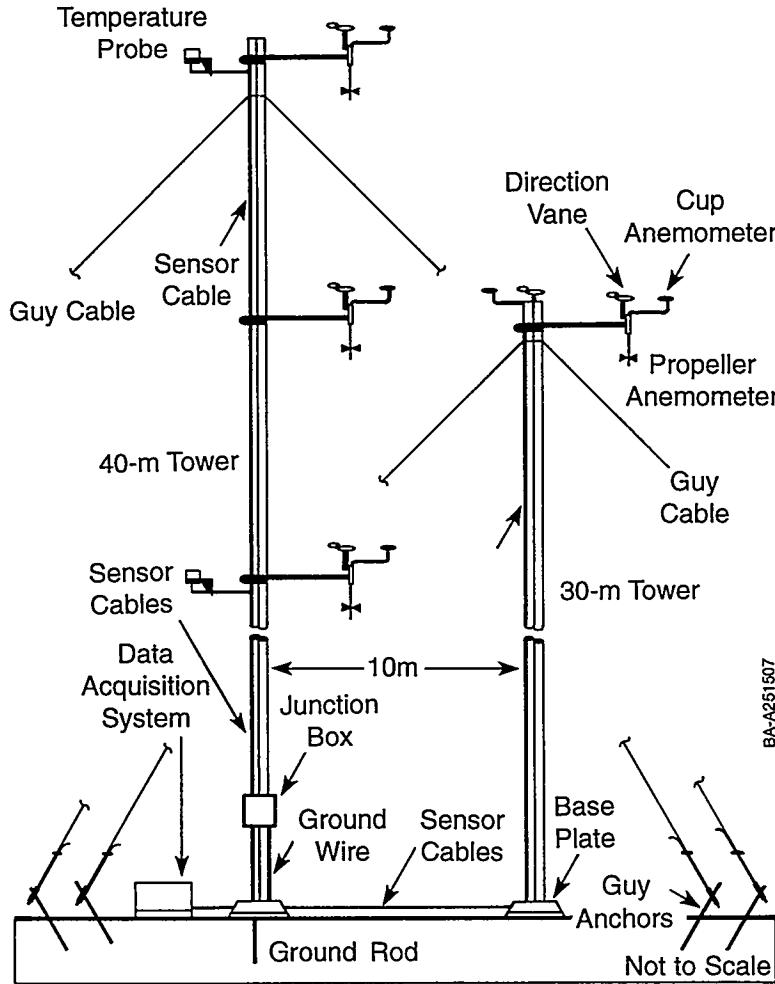
Wendell, L.L.; Barnard, J.C.; Morris, V.R.; Gower, G.L. (1993). "Turbulence Characteristics in Complex Terrain." *Wind Energy 1993*. SED-Vol. 14, Wind Energy. New York, NY: The American Society of Mechanical Engineers.

This paper presents the general results of the first phase of a joint effort to characterize wind turbulence at five sites. Analyses of simultaneous wind speed and direction measurements at several rotor disk locations illustrated that there is much more complexity than can be described by calculations from a single-point measurement.

Kelly, N.D. (November 1992). *Full Vector (3-D) Inflow Simulation in Natural and Wind Farm Environments Using an Expanded Version of the SNLWIND (Veers) Turbulence Code*. NREL/TP-442-5225. Golden, CO: National Renewable Energy Laboratory; 8 pp.

This paper gives a general review of the development of spectral distribution, spatial coherence, and cross-axis correlation models used to expand the SNLWIND code to include the three components of turbulent wind (upwind and downwind of a large wind farm, as well as over uniform, flat terrain) over a range of atmospheric stabilities. These models are based on extensive measurements of the turbulence characteristics immediately upwind and downwind of a large wind farm in San Gorgonio Pass, California.

Morris, V.R.; Barnard, J.C.; Wendell, L.L.; Tomich, S.D. (October 1992). "Comparison of Anemometers for



*This configuration provides vertical and horizontal wind-shear data at a site, as well as data on the effect of rotational sampling of the turbulent wind.*

In another effort to gain a better theoretical understanding of how turbulence affects a wind turbine, several research teams have carried out comprehensive field tests. These tests involved wind measurements from several anemometers upstream of the wind turbine and simultaneous detailed measurements of blade stress and power output. The results of these experiments were used to develop turbulence simulation models that generate time-series data of wind speeds encountered by different points on a rotating blade. These time-series are then used as input data to blade load models.

Turbulence Characterization." *Windpower '92 Conference; October 19-23, 1992; Seattle, Washington.* Washington, DC: American Wind Energy Association; 9 pp. (NTIS no. DE93004336).

This paper focuses on tests of propeller-vane and cup anemometers for turbulence measurements. The cup anemometer may prove to be an inexpensive and rugged sensor appropriate for turbulence measurements used in wind energy applications.

Kelley, N.D.; Wright, A.D. (October 1991). *A Comparison of Predicted and Observed Turbulent Wind Fields Present in Natural and Internal Wind Park Environments.* NREL/TP-257-4508. Golden, CO: National Renewable Energy Laboratory; 9 pp.

This paper discusses data on wind turbulence collected by five systems in complex terrains that are existing or potential sites for wind turbines. Preliminary analyses of the rotating wind turbine blade show that the turbulence at a site can be caused by engulfing eddies larger than the rotor and by fluctuating shear owing to eddies smaller than the rotor disk. Comparison of the time series depicting these quantities at two sites showed that intensity, commonly used to describe turbulence, did not adequately characterize it at these sites.

Kelley, N.D. (September 1989). *An Initial Look at the Dynamics of the Microscale Flow Field Within a Large Windfarm in Response to Variations in the Natural Inflow.* SERI/TP-257-3591. Golden, CO: National Renewable Energy Laboratory; 5 pp.

This paper discusses a study that examined the influence of the natural inflow structure on the internal microscale turbulence environment of a large wind farm. Two fully equipped, high-resolution boundary-layer measurement systems documented the alteration of the turbulent structure as the flow entered and left a wind park containing 41 rows of turbines. Results of these hub-height summaries are discussed in this paper.

Connell, J.R.; Powell, D.C. (August 1989). *User's Guide for Personal Computer Model of Turbulence at a Wind Turbine Rotor.* PNL-6959. Richland, WA: Pacific Northwest Laboratory.

This document helps the user operate a model to predict turbulence at a wind turbine rotor.

Veers, P.S. (1988). *Three-Dimensional Wind Simulation.* SAND-88-0152. Albuquerque, NM: Sandia National Laboratories; 36 pp. (NTIS no. DE88009793/XSP).

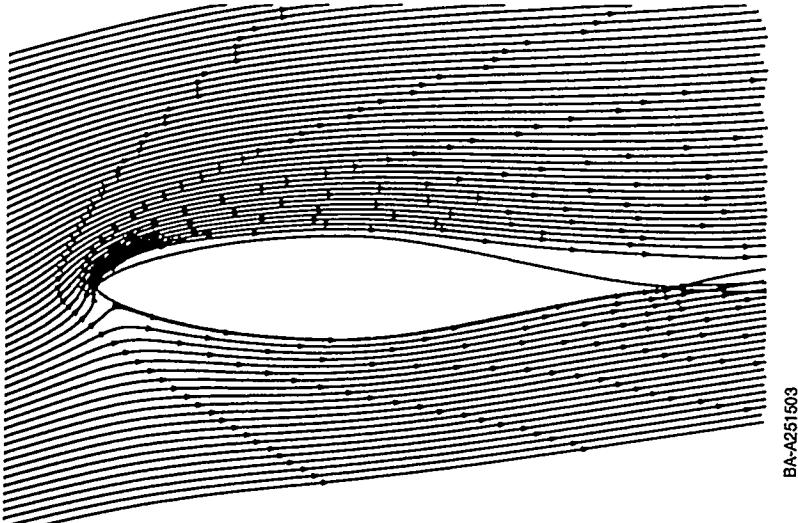
This paper presents a method for numerically simulating a three-dimensional field of turbulent wind speed to make structural and aerodynamic analyses of wind turbines.

## Aerodynamics

Aerodynamics research deals with the motion of air and other gaseous fluids and with the forces acting on bodies moving through such fluids. A knowledge of aerodynamics is important to design wind turbine rotor blades for optimum performance and to determine aerodynamic loads for structural design of the entire wind turbine.

Until recently, much of the information on aerodynamics was developed by the aeronautics industry. The reports published by the National Aeronautics and Space Administration (NASA) and the National Advisory Committee for Aeronautics (NACA) are excellent sources of airfoil data. The American Institute of Aeronautics and Astronautics is another important source of information. The most current data for wind turbines can be obtained from reports by the National Renewable Energy Laboratory and Sandia National Laboratories, where work continues in airfoil research.

### Model of Air Flow Around a Turbine Blade



Connell, J.R. (1988). "A Primer of Turbulence at the Wind Turbine Rotor." *Solar Energy*. (41:3). New York, NY: Pergamon Press; pp. 281-293.

This paper is written for wind turbine design engineers to understand the implications of turbulent motion: where it is generated and how it changes with differences in terrain, height above the ground, meteorological conditions, time, and distance from its source.

Connell, J.R.; George, R.L. (November 1987). "Accurate Correlation of Wind Turbine Response With Wind Speed Using a New Characterization of Turbulent Wind." *Journal of Solar Energy Engineering*. Vol. 109. New York, NY: American Society of Mechanical Engineers.

This paper reports the first successful correlation of winds and turbine response that includes the high-frequency region of the rotor response, where fatigue effects are critical.

Dini, P; Coiro, D.P.; Bertolucci, S. (1995). "Vortex Model for Airfoil Stall Prediction Using an Interactive Boundary-Layer Method." *Wind Energy 1995*. SED-Vol. 16. New York, NY: American Society of Mechanical Engineers.

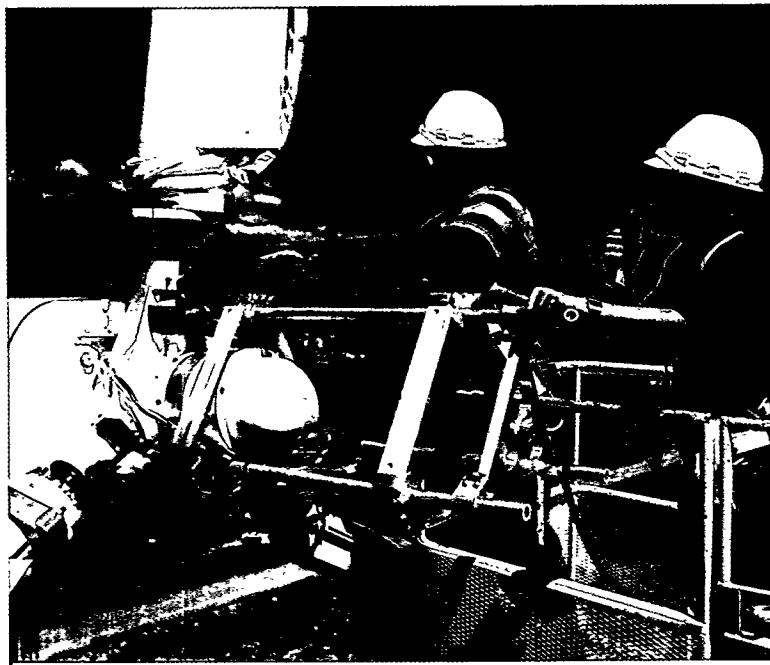
This paper explains an interactive boundary-layer method developed to predict the aerodynamic performance of airfoils throughout the stall area of a blade. Comparisons with measured lift and moment curves and pressure distributions are presented and discussed.

Selig, M.S. (University of Illinois); Tangler, J.L. (National Renewable Energy Laboratory). (1995). "Development and Application of a Multipoint Inverse Design Method for Horizontal-Axis Wind Turbines." *Wind Energy 1995*. SED-Vol. 16. New York, NY: American Society of Mechanical Engineers.

This paper describes a computer program (PROPID) that uses an inverse method for the aerodynamic design of horizontal-axis wind turbines. The desired rotor performance characteristics and blade aerodynamic characteristics can be directly specified, and the corresponding blade geometry determined, by this program.

McNerney, G.M. (U.S. Windpower, Inc.). (1994). "U.S. Windpower 56-100 Stall Operation." *Wind Energy 1994*. SED-Vol. 15. New York, NY: American Society of Mechanical Engineers; pp. 219-226.

This paper discusses that it is theoretically possible to increase the energy capture of this machine below rated wind speeds by adjusting the blade angle to the optimum pitch angle. The field test of the concept demonstrated that above rated wind speed, the optimum pitch-control logic resulted in stall operation, reducing overall energy capture and increasing system loads.



With this test machine at the National Wind Technology Center, researchers measure wind pressure distributions.

Hansen, A.C.; Butterfield, C.P. (1993). "Aerodynamics of Horizontal-Axis Wind Turbines." *Annual Review of Fluid Mechanics*. Vol. 25, pp. 115-149.

This article describes the types of rotors commonly used by the wind industry. Recent research and development into the aerodynamics of horizontal-axis wind turbine rotors is detailed. It has an excellent bibliography.

Butterfield, C.P.; Musial, W.P.; Scott, G.N.; Simms, D.A. (1992). *NREL Combined Experiment Final Report—Phase II* (draft). NREL/TP-442-4807. Golden, CO: National Renewable Energy Laboratory; 32 pp. (plus appendices).

This report describes the findings of a major field test program to understand unsteady aerodynamics in turbulent inflow. The study compared how the performance of an airfoil in a wind tunnel differs from that on an operating wind turbine. Results derived from aerodynamic pressure measurements, wind turbine load measurements, and flow visualization studies are presented.

Butterfield, C.P.; Musial, W.P.; Simms, D.A. (1992). *Combined Experiment Phase I: Final Report*. NREL/TP-257-4655. Golden, CO: National Renewable Energy Laboratory; 220 pp. (NTIS no. DE93000012).

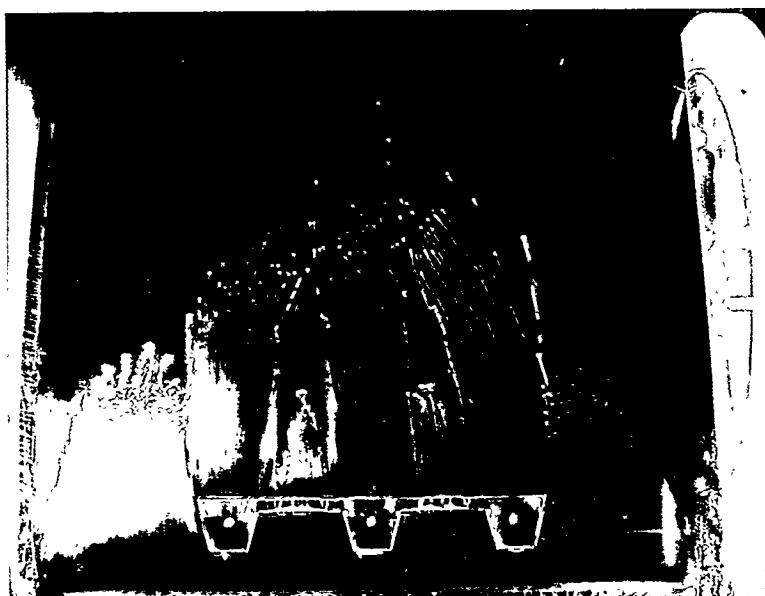
This report describes the test setup and instrumentation for a major field test program to understand unsteady aerodynamics in turbulent inflow. Wind tunnel test results and blade surface roughness testing are also described.

Barnwell, R.W.; Hussaini, M.Y. (1992). *Natural Laminar Flow and Laminar Flow Control*. New York, NY: Springer-Verlag; 411 pp.

This book discusses how the transition from laminar flow to turbulence affects every aspect of aircraft performance. Ways to delay this transition are an important part of fluid dynamics research. This transition may be delayed by shaping a body to maintain laminar flow around it (natural laminar flow), and by using techniques such as suction (laminar flow control). This volume discusses theoretical tools, wind tunnel experiments, and flight test results that have a bearing on this field.

Homicz, G.F. (September 1991). *Numerical Simulation of VAWT Stochastic Aerodynamic Loads Produced by Atmospheric Turbulence: VAWT-SAL Code*. SAND91-1124. Albuquerque, NM: Sandia National Laboratories; 73 pp.

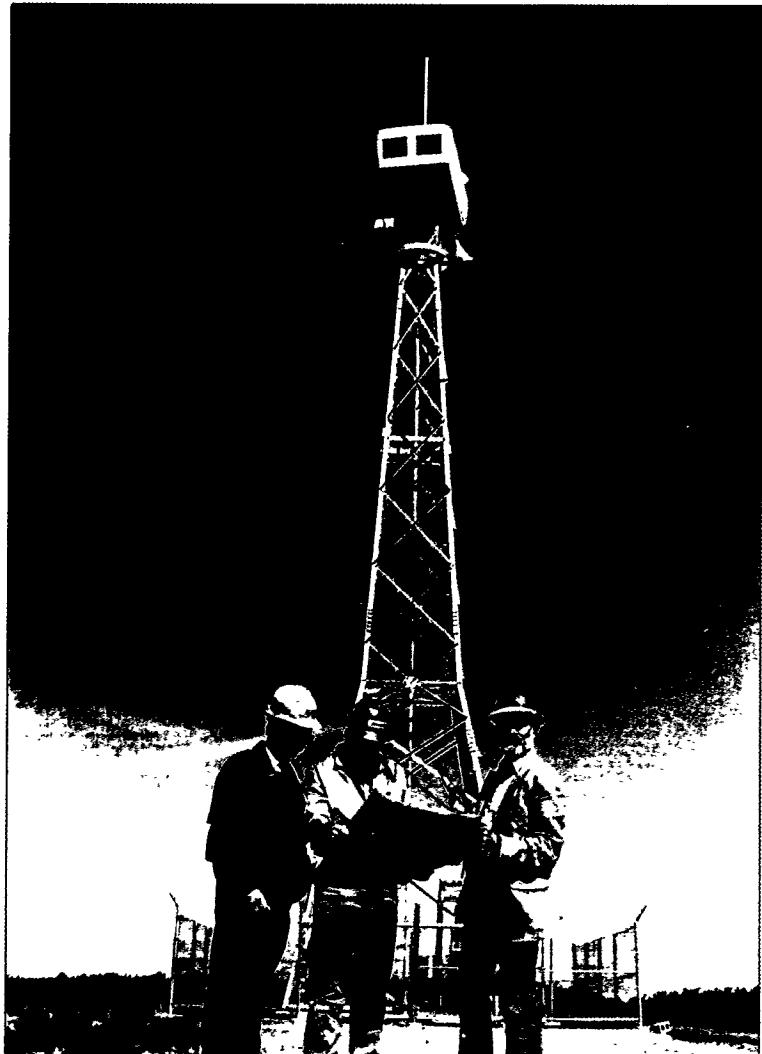
This report describes the theoretical background of the VAWT Stochastic Aerodynamic Loads (VAWT-SAL) computer code, whose purpose is to numerically simulate random loads, given the rotor geometry, operating conditions, and assumed turbulence properties. A Double-Multiple-Stream Tube analysis is employed to model the rotor's aerodynamic response.



Researchers apply liquid crystals to the surface of a wind turbine blade to see the interplay of airflow and the aerodynamic forces that lead to blade damage.

Aerodynamics researchers are improving their understanding of wind turbine aerodynamic behavior and how the variability of wind forces affects wind turbine performance and reliability. Unsteady aerodynamics testing explores the mechanisms underlying the complex interactions experienced by wind turbines. It focuses on techniques for visualizing the wind flow across the blade. In addition, wind and rotor interactions are modeled with emphasis on

refining predictive aerodynamic codes to predict forces along the blade and stresses in the structural dynamic models.



Eggleston, D.M.; Starcher, K.L. (November 1990). "A Comparative Study of the Aerodynamics of Several Wind Turbines Using Flow Visualization." *Journal of Solar Energy Engineering*. Vol. 112. New York, NY: American Society of Mechanical Engineers; pp. 301-309.

Flow visualization techniques were used to study the flows over the Enertech 21-5, Carter 25, and Enertech 44-50 turbines.

Walker, S.N.; Wade, J.E. (Pacific Wind Energy). (1988). *Effects of Precipitation on Wind Turbine Performance*. SERI/STR-217-3287. Golden, CO: Solar Energy Research Institute.

This study showed a 3% increase in wind energy production during light rain, which contradicted the findings of an earlier study and allayed concern about performance in rainy climates.

Tangler, J.L. (1987). *User's Guide. A Horizontal-Axis Wind Turbine Performance Prediction Code for Personal Computers*. Golden, CO: Solar Energy Research Institute. Available from the National Wind Technology Center.

Key features of the PROPPC code, used for performance prediction, are described.

Stoddard, F.S.; Porter, B.K. (January 1986). *Wind Turbine Aerodynamics Research Needs Assessment*. DOE/ER/30075-H1. Washington, DC: U.S. Department of Energy; 126 pp. (NTIS no. DE86009189).

Chapters of this report discuss the need for basic research in the federal program, the need for a new field of aerodynamic study (aerometeorology), other important engineering applications studies, and aspects of the recommended federal research and development program. Appendices include reports reviewed by the panel and a tutorial on aerodynamics and wind turbine engineering concepts.

Wilson, R.E.; Walker, S.N. (1985). "State-of-the-Art in Wind Turbine Aerodynamics." *Windpower '85 Conference; August 27, 1985; San Francisco, California*. Alexandria, VA: American Wind Energy Association; pp. 30-38.

This report reviews the aerodynamics of horizontal- and vertical-axis wind turbines. The review concludes with a discussion of the shortcomings of current methods and areas requiring further development.

*Horizontal-Axis Wind System Rotor Performance Model Comparison—A Compendium*. (February 1983). RFP-3508. Golden, CO: Rocky Flats Wind Energy Research Center; 381 pp. (NTIS no. DE83012265).

Four reports evaluate performance prediction methods for smaller horizontal-axis turbines.

Viterna, L.A.; Janetzke, D.C. (September 1982). *Theoretical and Experimental Power from Large Horizontal-Axis Wind Turbines*. DOE/NASA/20320-41. Cleveland, OH: NASA Lewis Research Center; 18 pp. (NTIS no. DE83001099).

This report describes a method for calculating power output from large horizontal-axis wind turbines and gives modifications to airfoil characteristics and the momentum portion of classical blade element-momentum theory.

Rohrbach, C.; Wainauski, H.; Worabel, R. (December 1977). *Experimental and Analytical Research on the Aerodynamics of Wind-Driven Turbines*. COO-2615-T2. Windsor Locks, CT: Hamilton Standard; 250 pp.

This research report is aimed at providing a reliable, comprehensive data bank on a series of wind turbine models covering a broad range of the aerodynamic and geometric variables needed for sound aerodynamic design.

Abbott, I.H.; Von Doenhoff, A.E. (1959). *Theory of Wing Sections*. New York, NY: Dover Publications, Inc.

This classic reference book for engineers and students is based on research conducted by NACA over several years. It includes data and explanations of wing-section performance. Many tables and illustrations are included.

## Airfoil Development and Blade Design

Within the field of wind turbine aerodynamics is the specialized work of designing and developing airfoils. Airfoils are cross-sectional geometric shapes designed to create lift as air flows over the blade surface. Until recently, designers used aircraft airfoils for wind turbines. Using aircraft airfoils for wind turbines is not ideal because wind turbines have significantly different aerodynamics performance requirements from those of aircraft.

Researchers have developed advanced airfoil shapes tailored to the operating conditions of wind turbines. These advanced airfoils reduce losses in rotor performance from surface roughness caused by the accumulation of bugs and dirt. They also increase energy production and improve power control.

### Thin Airfoil Family for Medium Blades

Tip Region Airfoil (95% radius)



Primary Outboard Airfoil (75% radius)



Root Region Airfoil (40% radius)



### Thick Airfoil Family for Large Blades

Tip Region Airfoil (95% radius)



Primary Outboard Airfoil (75% radius)



Root Region Airfoil (40% radius)



*NREL researchers have developed families of both thick and thin airfoils for wind turbines.*

Giguère, P.; Selig, M.S. (University of Illinois). (1996). "Desirable Airfoil Characteristics for Large Variable-Speed Horizontal Axis Wind Turbines." *Windpower '96; June 23-27, 1996; Denver, Colorado*. Washington, DC: American Wind Energy Association, pp. 295-304.

The authors performed a study to define desirable airfoil characteristics for variable-speed wind turbines.

Miller, L.S. (Wichita State University). (1995). *Experimental Investigation of Aerodynamic Devices for Wind Turbine Rotational Speed Control*. NREL/TP-441-6913.

Golden, CO: National Renewable Energy Laboratory; 48 pp. The aerodynamic performance of five trailing-edge devices to control overspeed and power modulation was evaluated using a two-dimensional wind tunnel model. The spoiler-flap control was shown to be best suited for turbine braking.

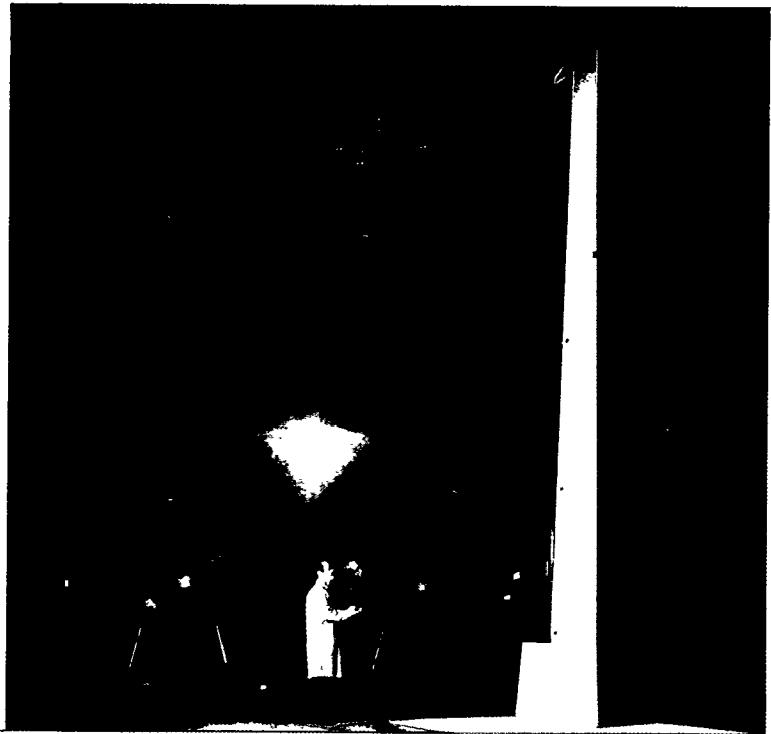
Tangler, J.L. (National Renewable Energy Laboratory); Somers, D.M. (Airfoils Incorporated). (1995). *NREL Airfoil Families for HAWTs*. NREL/TP-442-7109. Golden, CO: National Renewable Energy Laboratory; 11 pp.

This paper describes the seven airfoil families developed to reduce annual energy losses due to leading-edge roughness caused by dirt and insect accumulations on operating wind turbines. The manner in which the airfoil families address the needs of stall-regulated, variable-pitch, and variable-rpm wind turbines is described. In all, 24 airfoils are available for use on new wind turbines or for replacing less efficient blades on existing machines.

The airfoil should produce a strong torque, or rotational force, in low-to-medium winds, from 10 to 30 mph. Above 30 mph, the torque should decrease. Some blade designers incorporate aerodynamic stall of the airfoil at high wind speeds to shed excessive wind power at speeds more than 30 mph. This stall at high wind speeds reduces loads on wind turbine drivetrains, especially loads resulting from gusting, turbulent winds. Aerodynamic stall can also simplify control systems by passively controlling peak power at high wind speeds.



Researchers test new airfoils on wind turbines in wind power plants.



Researchers use wind tunnels to test airfoil performance.

Tangler, J.L.; Smith, B.; Kelley, N.D.; Jager, D. (1992). *Measured and Predicted Rotor Performance for the SERI Advanced Wind Turbine Blades*. NREL/TP-257-4594. Golden, CO: National Renewable Energy Laboratory. (NTIS no. DE92001215).

Comparison of measured and predicted performance of rotors on SERI advanced wind turbine blades showed that propeller and vane anemometers underestimated the wind speed in turbulent environments. However, measurements made by sonic or cup anemometers achieved good agreement between predicted and measured power output for wind speeds up to 8 meters per second. Prediction tools that neglected turbulence and yawed flow predicted peak rotor power at a lower wind speed than that actually measured.

Tangler, J.L.; Smith, B.; Jager, D. (1992). *SERI Advanced Wind Turbine Blades*. NREL/TP-257-4492. Golden, CO: National Renewable Energy Laboratory. (NTIS no. DE92001216).

This paper describes the work and results of efforts at the Solar Energy Research Institute (SERI) to develop inexpensive and efficient wind turbine blades. Results of atmospheric tests show that the SERI advanced blades produce 10% to 30% more energy annually than conventional blades.

Eppler, R. (1990). *Airfoil Design and Data*. New York, NY: Springer-Verlag; 562 pp.

The first third of this book describes the design and analysis of subsonic airfoils. The balance contains data on 116 aircraft airfoils that embody a wide range of Reynolds numbers. For each airfoil, design features are explained, and the input data for the computer code are given.

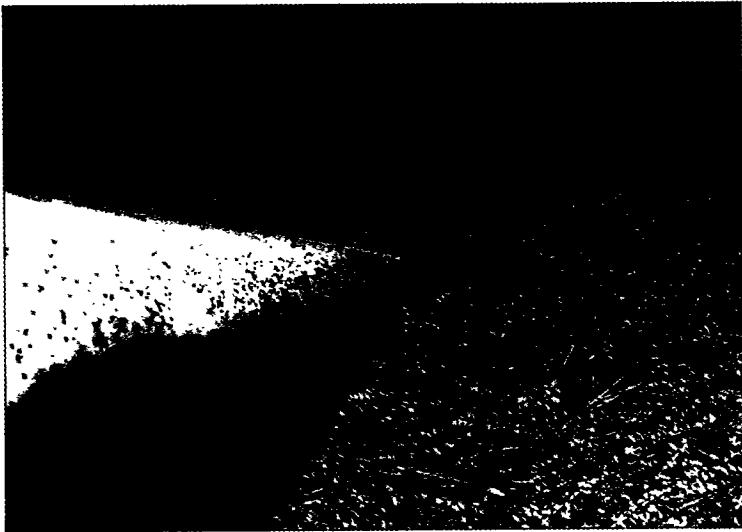
Stoddard, F.S. (1990). "Wind Turbine Blade Technology: A Decade of Lessons Learned." *Energy and the Environment, Into the 1990s, 1st World Renewable Energy Congress*. Edited by A.A.M. Sayigh. Vol. 3. Tarrytown, NY: Pergamon Press.

This paper summarizes the major advances in blade design and improvements in analytical tools being applied. Turbine operating experiences are also discussed.

Selig, M.S.; Donovan, J.F.; Fraser, D.B. (1989). *Airfoils at Low Speeds. Soartech 8*. Virginia Beach, Virginia: H.A. Stokely; 398 pp.

This book describes a new group of high-performance airfoils for model sailplanes; results of wind tunnel tests on more than 60 models are presented. Experimental methods are extensively documented, primarily for those active in low-Reynolds-number airfoil research.

Tangler, J.L. (1987). *Status of the Special-Purpose Airfoil Families*. SERI/TP-217-3264. Golden, CO: Solar Energy Research Institute; 9 pp. (NTIS no. DE88001124/XSP).



*A view of insect buildup along the leading edge of a wind turbine blade.*

These families of thick and thin airfoils for wind turbine blades (10–30 meters in diameter) improve the transfer function between the wind input and the blade structure. These airfoil families are expected to improve energy capture and operating characteristics of second-generation rotor blades.

Kocurek, D. (Computational Methodology Associates). (June 1987). *Lifting-Surface Performance Analysis for Horizontal-Axis Wind Turbines*. SERI/STR-217-3163. Golden, CO: Solar Energy Research Institute; 319 pp. (NTIS no. DE87001176).

Numerical lifting-surface theory is applied to the calculation of a horizontal-axis wind turbine's aerodynamic characteristics and performance. Correlating the method to measured wind turbine performance and comparing it to blade-element momentum theory calculations, the author highlights the extreme sensitivity of predictions to the quality of early post-stall airfoil behavior.

Yekutieli, O.; Clark, R.N. (1987). "Influence of Blade Surface Roughness on the Performance of Wind Turbines." *6th ASME Wind Energy Symposium*. New York, NY: American Society of Mechanical Engineers; pp. 181–188. This paper discusses the influence of blade surface roughness due to dirt, insects, or manufacturing techniques on wind turbine performance.

Ashwill, T.D.; Leonard, T.M. (September 1986). *Developments in Blade Shape Design for a Darrieus Vertical-Axis Wind Turbine*. SAND-86-1263. Albuquerque, NM: Sandia National Laboratories; 21 pp.

A computer code allows the user to design the optimum blade shape for a Darrieus-type vertical-axis wind turbine (VAWT) when large gravity effects and blade joints are present. This code can reduce the mean flatwise blade stresses on a large VAWT by a factor of two, increasing blade fatigue life by a factor of two to four.

Ostowari, C.; Niak, D. (Texas A&M University). (January 1985). *Post-Stall Wind Tunnel Data for NACA 44xx Series Airfoil Sections*. SERI/STR-217-2559. Golden, CO: Solar Energy Research Institute.

This technical report contains the data from wind tunnel tests of the NACA 44xx series blades.

Klimas, P.C. (November 1984). *Tailored Airfoils for Vertical Axis Wind Turbines*. SAND-84-1062. Albuquerque, NM: Sandia National Laboratories; 12 pp.

This paper describes work on a family of airfoil sections for VAWTs. The computer simulations, wind tunnel testing, and field testing indicate that using these blades could reduce system energy costs and increase fatigue lifetime for VAWT systems.

Miley, S.J. (Texas A&M University). (December 1984). *Addendum to a Catalog of Low Reynolds Number Airfoil*

Miley, S.J. (Texas A&M University). (February 1982). *A Catalog of Low Reynolds Number Airfoil Data for Wind Turbine Applications.* RFP-3387. Golden, CO: Rocky Flats Wind Energy Research Center; 615 pp. (NTIS no. DE82021712).

In this catalog, airfoil data at low Reynolds numbers, which would be applicable to small WECS, were screened. The most reliable data were compiled into this catalog. Each entry includes airfoil coordinates, lift, drag, and pitching-moment characteristics in both graphic and tabular form. The catalog also provides a review of airfoil theory and discusses the importance of Reynolds number, surface roughness, and turbulence in airfoil performance.

## Structural Dynamics

Structural dynamics is the area of research concerned with the dynamic and structural responses of wind turbines to specific wind inputs. The results of this research will be used to increase the reliability and life of wind turbine systems, as well as to reveal ways to reduce manufacturing and materials costs.

Work conducted with industry during the DOE Cooperative Field Test Program resulted in several reports based on field-test data. The data are used to exercise and validate analytic design tools as well as to verify analytical models for predicting wind turbine dynamic response.

Several innovations in the design of wind turbines are being evaluated. For example, to increase flexibility and reduce loads, wind turbine hubs are being redesigned. Teetered hubs allow motion in two directions to absorb the energy in gusts and reduce loads on the turbine drivetrain and structures. The structural responses of various hub designs are carefully simulated on computers, and the optimum designs are tested.

Another issue being explored is yaw response. Horizontal-axis wind turbines (HAWTs) must turn or yaw to take advantage of changing wind directions. The dynamic behavior of wind turbines as they yaw is an important area of study because the rotor shaft and yaw mechanism must withstand large forces, and the yaw strategy influences forces transmitted to the rest of the system.

Work is also under way on tower structures. A wind turbine tower may represent as much as 25% of the entire system cost, depending on the type and height of the tower. Taller towers are more expensive, but energy capture increases by as much as 20% to 30% if tower height doubles from 90 to 180 feet. Horizontal-axis wind turbines have traditionally been installed on freestanding lattice or

Elliott, A.S.; Depauw, T.R. (1996). "ADAMS/WT Advanced Development—Version 1.4 and Beyond." *Windpower '96 Conference; June 23–27, 1996; Denver, Colorado.* Washington, DC: American Wind Energy Association; pp. 613–622.

The authors describe improvements to ADAMS/WT, a wind turbine simulation package.

Tangler, J.L.; Kelley, N.D.; Jager, D.; Smith, B. (1994). "Measured Structural Loads for the Micon 65/13." *ETCE Conference ASME Wind Energy Symposium, January 23–26, 1994.* New Orleans, Louisiana. NREL/TP-442-6062. Golden, CO: National Renewable Energy Laboratory; 7 pp. (NTIS no. DE94006916).

Structural loads data collected for a Micon 65/13 wind turbine were used to identify operating and atmospheric conditions that resulted in the highest peak-to-peak blade and low-speed shaft loads.

Bywaters, G.L. (Northern Power Systems); Manwell, J.F. (University of Massachusetts). (1994). "Teeter Dynamics in Complex Terrain." *Wind Energy 1994.* SED-Vol. 15. New York, NY: American Society of Mechanical Engineers; pp. 147–156.

This paper reports research on the expected dynamic behavior of a free-yaw teetered rotor in complex terrain. One of the results indicated that most of the extreme teeter amplitudes were the result of high yaw errors.

Babcock, B.A.; Conover, K.E. (R. Lynette & Associates, Inc.). (1994). "Design of Cost-Effective Towers for an Advanced Wind Turbine." *Wind Energy 1994.* SED-Vol. 15. New York, NY: American Society of Mechanical Engineers; pp. 261–268.

tubular towers. The freestanding, four-legged lattice towers are relatively inexpensive to manufacture and require inexpensive foundations in most locations. Tubular towers are used for aesthetics and to avoid heavy icing, but they are more expensive and require large foundations.

To reduce tower costs and improve system performance, lighter weight, flexible towers that absorb stresses are being tested. In these tests, turbine operating speeds, turbine weights, and rotor diameters must be considered for each tower configuration and height.

Three wind turbine structural dynamics computer codes are in common use in the United States. The simplest code is called Yaw Dynamics of Horizontal-Axis Wind Turbines (YawDyn). YawDyn simulates simple blade motion and yaw motion under complex turbulent loading. The FAST (Fatigue, Aerodynamics, Structural, and Turbulence) code simulates more detailed blade motion plus tower motion for a variable-speed rotor. The most comprehensive code is the commercially available ADAMS™ (Automatic Dynamic Analysis of Mechanical Systems) model. Already used in the aerospace, robotics, and automotive industries, ADAMS™ gives the designer complete freedom to model and simulate any turbine configuration.

NREL researchers adapted the ADAMS™ computer model for use by wind turbine designers. The specialized wind turbine version, ADAMS/WT, allows designers to rapidly simulate a new wind turbine design, evaluate individual components and subsystems, and optimize the entire system—before any hardware is built.

The process of building and testing new turbine prototypes is becoming less expensive with the help of design tools and extensive field data. This translates to lower costs of energy for innovative U.S. wind technologies.

The results of a detailed analysis of the costs associated with various tower types and heights for several AWT-26 wind turbine configurations.

James, G.H., III; Carne, T.G.; Lauffer, J.P. (1993). *The Natural Excitation Technique (NExT) for Modal Parameter Extraction from Operating Wind Turbines*. SAND-92-1666. Albuquerque, NM: Sandia National Laboratories; 46 pp. (NTIS no. DE93010611).

This paper describes a code capable of determining structural loads on a flexible teetering HAWT. This report is a compilation of developments and results since 1990, and contains a new theoretical derivation of NExT, as well as a verification using analytically generated data.

Wilson, R.E.; Walker, S.N.; Smith, C.E.; Freeman, L.N. (1993). "Advanced Dynamics Code." *Wind Energy 1993: January 31–February 4, 1993; Houston, Texas*. SED-Vol. 14. New York, NY: the American Society of Mechanical Engineers; pp. 119–124.

This paper describes the Advanced Dynamics Code (FAST), which is capable of determining structural loads of a flexible, teetering HAWT.

Malcolm, D. (1993). *A User's Manual for the Program TRES4: Random Vibration Analysis of Vertical-Axis Wind Turbines in Turbulent Winds*. SAND93-7015. Albuquerque, NM: Sandia National Laboratories; 40 pp. (NTIS no. DE94009012).

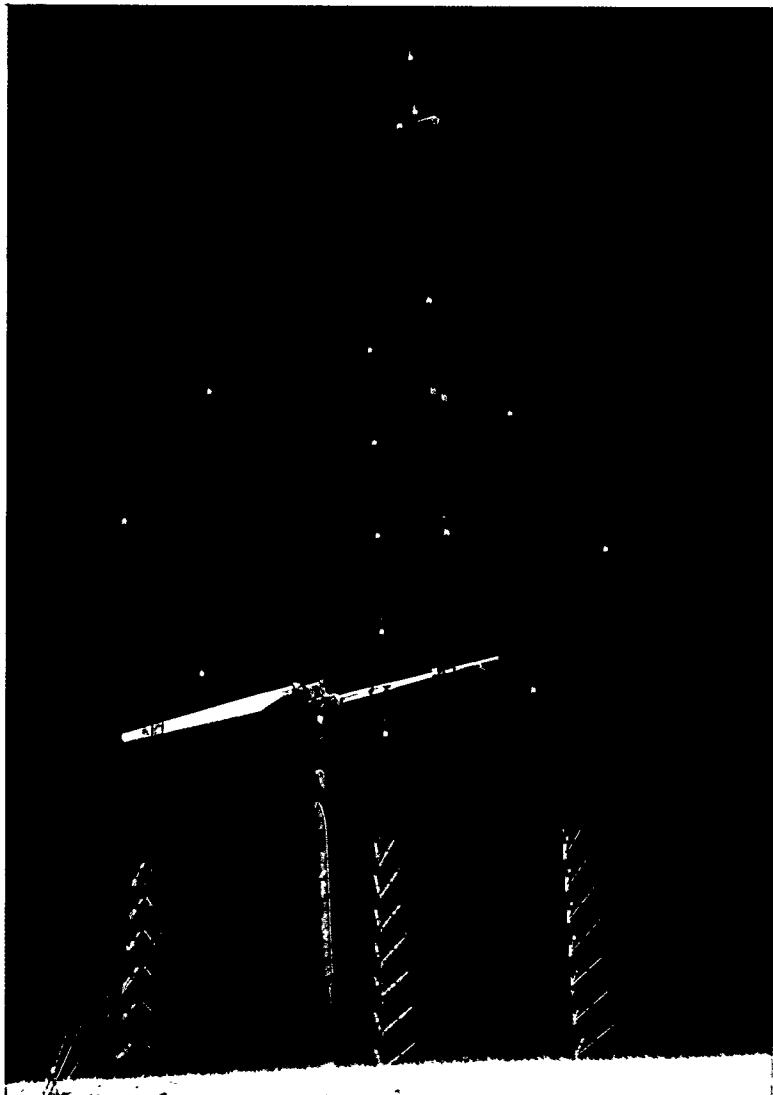
This tool is designed for analyzing loads on VAWTs. The software package works with the MSC/NASTRAN finite-element analysis code to conduct random vibration analysis of VAWTs.

Wright, A.D. (August 1992). *User's Guide for the NREL Force and Loads Analysis Program*. NREL/TP-257-4674. Golden, CO: National Renewable Energy Laboratory; 238 pp. (NTIS no. DE92010579).

This report presents an overview of and instructions on the proper use of the NREL Force and Loads Analysis Program (FLAP, version 2.2) used to predict rotor and blade loads and response for two- or three-bladed, rigid-hub wind turbines. The effects of turbulence are accounted for. The report shows methods of data input and correct code execution steps to model a two-bladed, rigid-hub turbine. The biggest change in the code since the release of FLAP version 2.01 in 1988 is the ability to include turbulent wind effects.

Hansen, A.C. (1992). *Yaw Dynamics of Horizontal-Axis Wind Turbines: Final Report*. NREL/TP-442-4822. Golden, CO: National Renewable Energy Laboratory; 175 pp. (NTIS no. DE92001245).

Free-yaw mechanics and the design concepts most effective at eliminating yaw problems are described. A design model, YawDyn, which permits both free-yaw and fixed-yaw analysis, is presented.



As part of the U.S. Department of Energy's Cooperative Field Test Program with industry, federal researchers studied the dynamic response of an innovative wind turbine built by Northern Power Systems.

Wright, A.D.; Buhl, M.L., Jr.; Elliott, A.S. (1992). "Development of a Wind Turbine System's Dynamics Model Using the Automatic Dynamic Analysis of Mechanical Systems (ADAMS™) Software." *Windpower '92 Conference; October 19-23, 1992; Seattle, Washington*. Washington, DC: American Wind Energy Association; pp. 329-338.

The authors describe the development of a model, using the ADAMS™ code, for a three-bladed, rigid-hub turbine. They then compare model results to test data for steady-state operating conditions and a machine start-up case.

Wright, A.D. (August 1992). *User's Guide for the NREL Teetering Rotor Analysis Program (STRAP)*. NREL/TP-257-4671. Golden, CO: National Renewable Energy Laboratory; 212 pp. (NTIS no. DE92010508).

Instructions on the proper use of the Teetering Rotor Analysis Program (STRAP version 2.20), used for predicting rotor and blade loads and response for two-bladed, teetering-hub wind turbines. The effects of delta-3, undersling, hub mass, and wind turbulence are accounted for. The report shows methods of data input and correct code execution steps to model a two-bladed, teetering-hub turbine. This version includes turbulent wind effects that the previous version (2.01, issued in 1988) did not. Use this report with Wright, Buhl, and Thresher (1988).

Weber, T.L.; Wilson, R.E.; Walker, S.N. (Oregon State University). (June 1991). *Analysis of a Teetered, Variable-Speed Rotor*. SERI/TP-267-4366. Golden, CO: Solar Energy Research Institute; 59 pp. (NTIS no. DE91002190).

This report describes the design and testing of a computer model that can be used to accurately predict mean and cyclic loads with a turbulent wind input.

Wright, A.D.; Butterfield, C.P. (1991). *The NREL Teetering-Hub Rotor Code: Final Results and Conclusions*. NREL/TP-257-4517. Golden, CO: National Renewable Energy Laboratory; 10 pp. (NTIS no. DE92001187).

This code predicts wind turbine blade loads and response to both deterministic and stochastic blade loads. Code modifications and comparisons of load predictions to test data are described.

Coleman, C; McNiff, B.P. (Northern Power Systems). (1990). *Dynamic Response Testing of the North Wind 100 Wind Turbine*. SERI/STR-257-3686. Golden, CO: Solar Energy Research Institute.

This report summarizes 84 hours of tests conducted under the U.S. Department of Energy (DOE) Cooperative Field Test Program to measure wind characteristics, blade mean loads, cyclical loads, yaw system loads, and power output. The flexible design of this system with its flapping and teetering two-blade rotor design did result in lower blade loading.



Thresher, R.W.; Wright, A.D. (January 1989). *Prediction of Stochastic Blade Responses Using Measured Wind-Speed Data as Input to the FLAP Code*. SERI/TP-217-3394. Golden, CO: Solar Energy Research Institute.

FLAP analyzes wind turbines with either rigid- or teetering-hub configurations. This paper describes work to predict blade response to forces exerted by actual wind-speed distributions.

Thresher, R.W.; Holley, W.E.; Wright, A.D. (January 1989). *Prediction of Stochastic Blade Responses Using a Filtered Noise Turbulence Model in the FLAP Code*. SERI/TP-217-3413. Golden, CO: Solar Energy Research Institute.

FLAP analyzes wind turbines with either rigid- or teetering-hub configurations. This paper describes work to predict blade response to forces predicted by a filtered noise turbulence model.

Snow, A.L.; Heberling, C.F., III; Van Bibber, L.E. (Westinghouse Electric Corporation). (March 1989). *The Dynamic Response of a Westinghouse 600-kW Wind Turbine*. SERI/STR-217-3405. Golden, CO: Solar Energy Research Institute; 185 pp.

This document reports data collected under the DOE Cooperative Field Test Program, including blade mean loads, blade cyclical loads, and power output performance in winds of 15 mph to more than 40 mph. These data can be used to validate aeroelastic design methods for predicting service loadings of intermediate-size, upwind, teetered-hub, horizontal-axis wind turbines.

Wehrey, M.; Redmond, I.; Anderson, C.; Jamieson, R. (Southern California Edison, James Howden and Company Ltd.). (February 1988). *Dynamic Response of a 330-kW Horizontal-Axis Wind Turbine Generator*. SERI/STR-217-3203. Golden, CO: Solar Energy Research Institute; 103 pp.

This report provides results of a combined experimental and theoretical study, conducted under the U.S. Department of Energy Cooperative Field Test Program, of the dynamic response of a Howden 330/26 wind turbine generator. The work was undertaken by Southern California Edison to extend current knowledge on the dynamic loading of wind turbines.

Wright, A.D.; Buhl, M.L., Jr.; Thresher, R.W. (January 1988). *FLAP Code Development and Validation*. SERI/TR-217-3125. Golden, CO: Solar Energy Research Institute.

This report on the development and validation of FLAP also includes instructions for proper use of the code. FLAP is a tool for predicting force and loads on wind turbine rotors.

Hansen, A.C. (University of Utah). (January 1987). *The TEETER Program—Analysis and User's Guide*. SERI/STR-217-3050. Golden, CO: Solar Energy Research Institute.

This report documents and describes a method for predicting the teetering motion of a two-bladed wind turbine rotor with a teetering hub. Two

## Controls, Generators, and Drivetrains

Controls, generators, and drivetrains must work together to ensure smooth performance and long system life. Researchers are developing new approaches to enhance wind turbine performance, lower costs, and improve efficiency.

The control system regulates turbine start-up and shutdown, as well as power output and power quality. Wind turbines are designed to operate within certain wind speeds. They start up only when there is enough energy in the wind to generate useful power, and they shut down when wind speeds exceed operational limits. Control systems protect turbines from exceeding their load and rotational speed limits and are also used for emergency stopping. In this research area, new mechanical, electrical, and aerodynamic control systems are being evaluated and tested that reduce fatigue and control performance of wind turbines.

Advanced control systems are under development to automatically manage wind power plant turbines. These expert control systems will evaluate local wind conditions, site characteristics, seasonal and diurnal wind patterns, and turbine operating requirements. The control system will turn each individual turbine on or off to maximize overall power plant output.

New developments in generators, power-electronic devices, and high-power rapid-switching circuits have made use of variable-speed wind turbines possible. These designs rely on electronic devices to regulate the frequency and quality of power being delivered by the wind turbine. Allowing the rotor to speed up in response to the wind (variable speed) reduces shock loads to the drivetrain. This development permits the use of lighter materials and smaller components in the shaft and the gearbox, resulting in reduced manufacturing costs. Another advantage of variable-speed turbines is increased efficiency of energy capture. Varying the rotor speed in response to varying wind speeds allows the airfoils to operate more efficiently.

Variable-speed operation, a relatively new approach, challenges turbine designers. A constant-speed machine is designed to operate

programs are required for a complete analysis. The codes are listed in the appendices.

Lobitz, D.W.; Ashwill, T.D. (1986). *Aeroelastic Effects in the Structural Dynamic Analysis of Vertical-Axis Wind Turbines*. SAND-85-0957. Albuquerque, NM: Sandia National Laboratories; 25 pp. (NTIS no. DE86009542/XSP).

This report describes modifications of the damping and stiffness matrices in the NASTRAN finite-element code. These add aeroelastic effects to the structural dynamic analysis of vertical-axis wind turbines.

Stuart, J.G.; Wright, A.D.; Butterfield, C.P. (1996). *Considerations for an Integrated Wind Turbine Controls Capability at the National Wind Technology Center: An Aileron Control Case Study for Power Regulation and Load Mitigation*. NREL/TP-440-21335. Golden, CO: National Renewable Energy Laboratory.

A system identification-based method for extracting and utilizing high-fidelity dynamics information, derived from a structural dynamics code (FAST), for use in active control design.

Phillips, J.A. (1995). *Power-Electronic, Variable-Speed Wind Turbine Development: 1988-1993. A Summary of the 33M-VS Wind Turbine Development Program*. EPRI/TR-104738s. Palo Alto, CA: Electric Power Research Institute.

Turbine development activities, key design decisions, and turbine electrical and mechanical systems are described.

Errichello, R.; Muller, J. (September 1994). *Application Requirements for Wind Turbine Gearboxes*. NREL/TP-442-7076. Golden, CO: National Renewable Energy Laboratory.

A guide to selecting, designing, manufacturing, procuring, operating, and maintaining gearboxes for use on wind turbines.

Veers, P.S.; Schluter, L.L. (1993). *Simulating High-Frequency Wind for Long Durations*. SAND93-1584C. Albuquerque, NM: Sandia National Laboratories.

A wind simulator was used to evaluate the effectiveness of a wind turbine control simulator. The effectiveness of control algorithms to maximize power output while creating very little fatigue damage is described.

Lauw, H.K.; Weigand, C.H.; Marckx, D.A. (Electronic Power Conditioning, Inc.). (October 1993). *Variable-Speed Wind System Design: Final Report*. DOE/BP/99893-TI. Washington, DC: U.S. Department of Energy; 81 pp. (NTIS no. DE94006210).

The cost, efficiency gain, and other operating implications of converting a modern fixed-speed

well away from any resonant frequencies of the tower or other components. If the turbine operates at these resonant frequencies for very long, they are amplified and can shake the system apart. A variable-speed rotor is more likely to operate at these resonant frequencies, amplifying them to destructive levels. Control strategies that minimize the possibility of operation at resonant frequencies are basic to the success of variable-speed wind turbines.

Power from the wind turbine rotor turns a shaft connected to a gearbox and a generator. These components—the shaft, gearbox, and generator—are commonly referred to as the drivetrain. A key component of the drivetrain is the gearbox. A wind turbine gearbox is a speed increaser that increases the relatively slow rotational speed of the rotor to the speed of the generator. The gearbox must have adequate load capacity within its design constraints of size and weight. Gearboxes are designed to maximize efficiency while minimizing sound level. Gearboxes must be reliable and easy to maintain, and they must withstand temperature extremes and resist contamination and corrosion. Gearbox reliability and cost are critical factors in the success of the overall turbine design.

wind energy conversion system to variable-speed operation. The preliminary design includes schematics for printed circuit boards and control flowcharts.

Fardoun, A.A.; Fuchs, E.F. (University of Colorado); Carlin, P.W. (1993). "A Variable-Speed, Direct-Drive Transmission Wind Power Plant." *Windpower '93 Conference; July 12-16, 1993; San Francisco, California*. Washington, DC: American Wind Energy Association; pp. 134-141.

Two different variable-speed (reluctance) generator designs were analyzed, one with the magnet on the rotor surface, the other with it buried within the rotor yoke. The buried-magnet design provides more flexibility in selecting the generator flux density, but each design has unique advantages.

Torrey, D.A. (Rensselaer Polytechnic Institute); Childs, S.E. (Atlantic Orient Corporation). (1993). "Development of Variable-Reluctance Wind Generators." *Windpower '93 Conference; July 12-16, 1993; San Francisco, California*. Washington, DC: American Wind Energy Association; pp. 258-265.

The authors describe integration of the variable-reluctance generator into variable-speed wind energy systems.

Vachon, W.A. (W.A. Vachon & Associates). (1993). *Control Algorithms for Effective Operation of Variable-Speed Wind Turbines*. SAND90-7112. Albuquerque, NM: Sandia National Laboratories.

This report describes control of variable-speed, constant-frequency wind turbines. A time-domain, dynamic-control algorithm simulation was developed that takes into account normal wind turbine operation and avoids critical rotor speed ranges that can lead to resonant vibrations.

Childs, S.E.; Hughes, P.S.; Saeed, A. (Atlantic Orient Corporation). (1993). "Development of a Dynamic Brake Model." *Windpower '93 Conference; July 12-16, 1993; San Francisco, California*. Washington, DC: American Wind Energy Association; pp. 366-373.

The dynamic brake provides an alternative braking mechanism for wind turbine induction generators.

McNiff, B.P. (Second Wind Inc.); Musial, W.P. (National Renewable Energy Laboratory); Errichello, R. (GEARTECH). (September 1990). "Gear Fatigue Life Variations for Different Wind Turbine Braking Strategies." *Windpower '90 Conference; September 24-28, 1990; Washington, DC*. Washington, DC: American Wind Energy Association; 10 pp. (NTIS no. DE91002161).

This document describes high-speed and low-speed shaft torques that were measured on a two-stage helical gearbox of a single Micon 65 turbine. A typical annual load spectrum and the pitting and bending fatigue lives of the gear teeth were calculated. The analysis showed increases in gear life by a factor of as much as 25 when the standard



*Designers use computer models to explore different designs before building expensive hardware.*

high-speed shaft brake is replaced with a dynamic brake or modified with a damper.

Herrera, J.I.; Reddoch, T.W. (Electrotek Concepts, Inc.). (February 1988). *Analysis of the Electrical Harmonic Characteristics of a Slip Recovery Variable-Speed Generating System for Wind Turbine Applications*. SERI/STR-217-3268. Golden, CO: Solar Energy Research Institute.

In this study, field data were collected on the NASA generating system, including measurements of harmonics, voltage, and reactive power characteristics.

Herrera, J.I.; Reddoch, T.W. (Electrotek Concepts, Inc.). (February 1988). *Analysis of the Electrical Harmonic Characteristics of a Westinghouse Variable-Speed Generating System for Wind Turbine Applications*. SERI/STR-217-3133. Golden, CO: Solar Energy Research Institute.

In this study, field data were collected on the Westinghouse generating system, including harmonics, voltage, and var characteristics.

*Reactive Power Management Device Assessment*. (University of Washington). (1987). AP-5210. Palo Alto, CA: Electric Power Research Institute; 98 pp.

This report presents alternative techniques for reactive power compensation. It also describes methodologies for evaluating the performance, voltage profile, reliability, and economic benefits of specific compensation approaches.

*Specification of Test Equipment for Power Electronic Drive Research*. (OMNION Power Engineering Corporation). (1987). AP-5219. Palo Alto, CA: Electric Power Research Institute; 112 pp.

This study developed specifications for an automated dynamometer system to test power conversion circuits for variable-speed applications. Variable-speed generators can advance wind turbine technology.

*Electrical Behavior of Wind Power Stations* (Zaininger Engineering Company, Inc.). (1987). RP1996-24. Palo Alto, CA: Electric Power Research Institute; 104 pp.

This study measured electrical performance of large operating wind power stations. The design of a wind power station affects the quality of power generated by that station.

## Fatigue and Failure Analysis

Fatigue is a problem in structures of all types. At roughly 100 million revolutions during the lifetime of a wind turbine, fatigue stresses on parts are much higher than those on bridges, aircraft, or automobile engines, for example. In addition, turbines experience large, fluctuating stresses from wind shear and turbulence. Structural fatigue is the main cause of structural failure in wind machines, and its prediction is a difficult task for a designer.

The best defense against fatigue problems is an accurate estimate of the fatigue life for candidate or prototype wind turbine designs. Every designer of fatigue-sensitive structures would like to know the lifetime of the design with perfect accuracy. The design could then be fine-tuned to eliminate needless costs while maintaining acceptable durability.

Fortunately, improvements in computer technology—speed and capacity for calculations—have led to increasingly sophisticated models for estimating fatigue. In addition, the field and laboratory testing of wind turbines and components to validate computer models has led to many improvements. The models listed here are powerful tools for designers to evaluate individual components. And new models are being developed each year. With the latest models, the designer can assemble the components into systems and evaluate the entire turbine lifetime.

Sutherland, H.J. (1994). *Fatigue Case Study and Loading Spectra for Wind Turbines*. SAND94-1078C. Albuquerque, NM: Sandia National Laboratories.

This monograph presents a method for calculating the fatigue life of wind turbines using the LIFE2 computer code.

Sutherland, H.J., et al. (1993). *The Application of Non-Destructive Techniques to the Testing of a Wind Turbine Blade*. SAND93-1380. Albuquerque, NM: Sandia National Laboratories.

This report describes how two nondestructive tests, acoustic emission and coherent optical, were used to monitor a quasistatic test to failure of a 7.9-m wind turbine blade.

Veers, P.S. (Sandia National Laboratories); Lange, C.H.; Winterstein, S.R. (Stanford University). (1993). "FAROW: A Tool for Fatigue and Reliability of Wind Turbines." *Windpower '93 Conference; July 12-16, 1993; San Francisco, California*. Washington, DC: American Wind Energy Association; pp. 342-349.

This paper describes FAROW (Fatigue And Reliability Of Wind Turbines), a computer program that evaluates the fatigue and reliability of wind turbine components using structural reliability methods. FAROW allows calculation of the probability of premature failure, the mean lifetime, the relative importance of each of the random variables, and the sensitivity of the results to all of the input parameters, both constant inputs and the parameters that define the random variable inputs.

Sutherland, H.J.; Linker, R.L. (1993). *User's Guide for the Frequency Domain Algorithms in the LIFE2 Fatigue Analysis Code*. SAND93-1900. Albuquerque, NM: Sandia National Laboratories; 53 pp. (NTIS no. DE94004678)

This report describes the LIFE2 code's purpose and function and guides the user through the frequency domain algorithms it applies.

Kelley, N.D.; Desrochers, G.; Tangler, J.L.; Smith, B. (October 1992). *A Discussion of the Results of the Rainflow Counting of a Wide Range of Dynamics Associated with the Simultaneous Operation of Adjacent Wind Turbines*. NREL/TP-442-5159. Golden, CO: National Renewable Energy Laboratory.

This study compared fatigue loads of NREL (SERI) thin-airfoil blades and AeroStar blades fitted on identical wind turbines. The data are based on sample load populations derived from the rainflow cycle counting of 405 10-minute records collected over a wide range of inflow turbulence conditions. The alternating load cycles on both turbines can be described as a statistical mixture of three stochastic processes. The load distributions of the two



Researchers use a dynamometer to test a wind turbine generator in the Power Electronics Laboratory at the National Wind Technology Center near Golden, Colorado.

turbines were largely similar; differences were attributed to either rotor weight or swept area.

Mandell, J.F.; Reed, R.M.; Samborsky, D.D. (Montana State University). (August 1992). *Fatigue of Fiberglass Wind Turbine Blade Materials*. SAND-92-7005. Albuquerque, NM: Sandia National Laboratories; 61 pp. (NTIS no. DE93005381).

The results of coupon testing of a variety of generic materials used in wind turbine blades is reported. Results include the effects of differing matrix materials, manufacturing methods, reinforcement structure, and ply terminations.

Masse, B.; Pastorek, H. (1992). *Stress Calculation for the Sandia 34-Meter Wind Turbine Using the Local Circulation Method and Turbulent Wind*. SAND-91-7012. Albuquerque, NM: Sandia National Laboratories.

This report describes a stress estimate procedure and its application to the Sandia/DOE 34-meter wind turbine.

Ashwill, T.D.; Sutherland, H.J.; Veers, P.S. (January 1990). "Fatigue Analysis of the Sandia 34-meter Vertical-Axis Wind Turbine." *Proceedings of the Ninth ASME Wind Energy Symposium*. Edited by D.E. Berg. SED-Vol. 9. New York, NY: American Society of Mechanical Engineers.

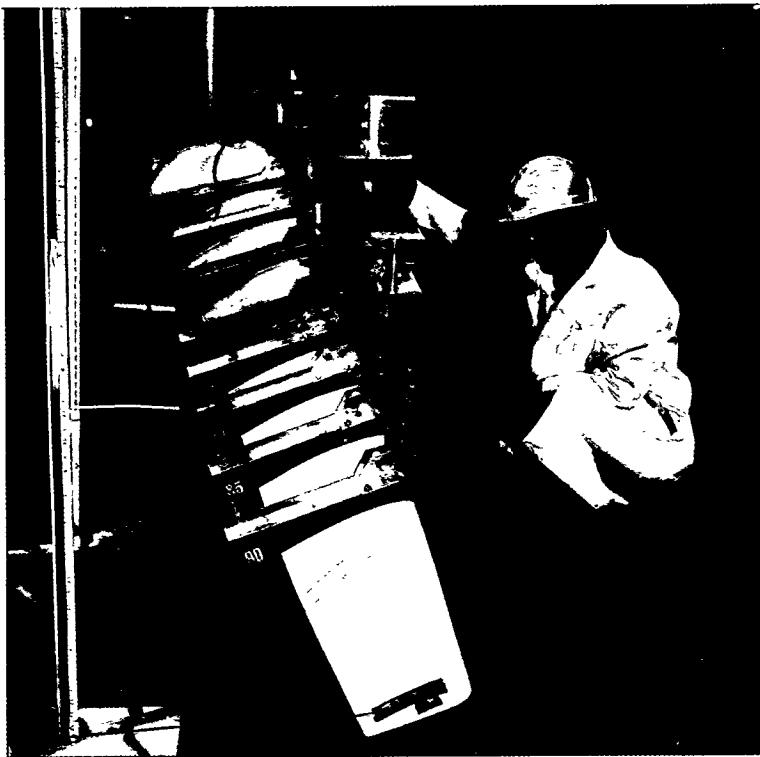
In this report, Miner's Rule is used to estimate the service lifetime of a blade of the Sandia 34-meter wind turbine. The results illustrate the sensitivity level of the estimates to wind regimes, constitutive properties, stress states, and operational algorithms.

*International Recommended Practices for Wind Energy Conversion Systems Testing: 3. Fatigue Characteristics; 1. Edition 1984.* (1984). Edited by J.M.W. Dekker, E. Jensen, H.H. Ottens, S.E. Thor, and U. Hassan; 19 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

This document describes recommended practices for evaluating fatigue characteristics of a wind energy conversion system. The aim is to provide a standard method so the levels of fatigue damage from different modes of WECS operation can be determined.

Waldon, C.A.; Hansen, A.C. (June 1983). *Fatigue Modeling for Small Wind Systems: Basic Theory*. RFP-3564. Golden, CO: Rocky Flats Wind Energy Research Center; 56 pp. (NTIS no. DE84013191).

This report discusses the theory of fatigue as applied to horizontal-axis wind systems and reviews current techniques for predicting fatigue loads and fatigue life.



*Researchers work with manufacturers to test the performance of new materials and designs at the National Wind Technology Center. Performance under carefully controlled stress tests is compared with computer-aided design predictions to improve the design process.*

## Instrumentation and Testing

Research to improve wind turbine performance and system life relies heavily on sophisticated test and measurement equipment. Improvements in test instruments have contributed significantly to the quality and precision of the investigations being conducted on wind turbine components and systems.

Simms, D.A. (National Renewable Energy Laboratory); Cousineau, K.L. (Zond Systems, Inc.) (June 1993). *A Rugged, Low-Cost, Advanced Data Acquisition System for Field Test Projects*. NREL/TP-442-5617. Golden, CO: National Renewable Energy Laboratory; 11 pp. (NTIS no. DE93010041).

This paper describes a data collection system that was used to acquire data from large wind turbines operating in arrays. The system data acquisition modules are mounted on rotating blades, turbine towers, nacelles, control modules, meteorological towers, and electrical stations.

Connell, J.R. (Colorado State University); Morris, V.R. (1991). *Calibration Data for Improved Correction of UVW Propeller Anemometers*. PNL-7824. Richland, WA: Pacific Northwest Laboratory.

This paper describes new calibrations for propeller anemometers based on wind tunnel tests. The new calibrations are compared with those in previous publications.

## Recommended Practices for Performance Testing and Analysis

Researchers across the United States and throughout the world are advancing the technology of wind turbine generators. Standards for testing allow these researchers to compare their results and exchange information. Indeed, collaborative research efforts involving organizations from several nations are proving beneficial.



*Thanks to cooperative research with industry, the performance of wind turbines improves each year and manufacturing costs continue to decline.*

Simms, D.A.; Butterfield, C.P. (April 1990). *A Low-Cost PC-Based Telemetry Data-Reduction System*. SERI/TP-257-3737. Golden, CO: Solar Energy Research Institute.

The data-reduction system described in this report offers promise for taking sophisticated measurements with a lower cost system.

*Safety of Wind Turbine Generator Systems*. (1994). Draft International Standard: TC-88. Geneva, Switzerland: International Electrotechnical Commission.

This draft international standard addresses safe practices for the design, installation, and operation of wind turbine generators.

*Power Performance Measurement Procedure*. (1994). Draft International Standard: TC-88. Geneva, Switzerland: International Electrotechnical Commission.

This draft international standard addresses procedures for measuring the performance of wind turbine generators.

*Acoustic Noise Measurement Techniques for Wind Turbine Generator Systems*. (1994). Draft International Standard: TC-88. Geneva, Switzerland: International Electrotechnical Commission.

This draft international standard addresses procedures for measuring the noise generated by wind turbine generators.

*Standard Performance Testing of Wind Energy Conversion Systems*. (1988). AWEA Standard: AWEA 1.1-1988. Arlington, VA: American Wind Energy Association; 32 pp.

This document describes a standard method of determining and reporting primary performance characteristics. It includes definitions, units of measurement, field test procedures used to determine power production performance and noise levels, procedures for deriving performance parameters, and a proposed test report to be used as part of certification.

*Recommended Practices for Wind Turbine Testing; 4. Acoustics. Measurement of Noise Emission from Wind Energy Conversion Systems (WECS); 2. Edition 1988*. (1988). Edited by S. Ljunggren and A. Gustafsson; 23 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development for Wind Energy Conversion Systems.

This document describes the procedures to be used for measurement and description of noise emission from wind energy systems.



*Recommended Practices for Wind Turbine Testing and Evaluation: 8. Glossary of Terms; Issue 1, March 1987.* (March 1987). Edited by G. Elliot; 11 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

This document provides a glossary of wind energy terms.

*International Recommended Practices for Wind Energy Conversion Systems Testing: 3. Fatigue Characteristics; 1. Edition 1984.* (1984). Edited by J.M.W. Dekker, E. Jensen, H.H. Ottens, S.E. Thor, and U. Hassan; 19 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

This document describes recommended practices for evaluating fatigue characteristics of a wind energy conversion system. The aim is to provide a standard method so the levels of fatigue damage from different modes of WECS operation can be determined.

*Recommended Practices for Wind Turbine Testing: 7. Quality of Power. Single Grid-Connected WECS; 1. Edition 1984.* (1984). Edited by L.J. Ballard and R.H. Sivansborough; 24 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

This document describes the recommended practices for determining the quality of power delivered by a single grid-connected WECS. It provides a methodology for obtaining power quality data that can be used to compare WECS of different types. Topics covered in these recommendations relate to the quality of power in terms of power variation, reactive power demand, voltage variations during generation, voltage variations on cut-in, switching operations, and harmonics.

*Recommended Practices for Wind Turbine Testing: 2. Estimation of Cost of Energy from Wind Energy Conversion Systems; 1. Edition 1983.* (1983). Edited by J. Nitteberg, A.A. deBoer, and P.B. Simpson; 23 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems. (NTIS no. DE84901132).

This document describes the recommended procedure for estimating energy costs from WECS. It provides a standard methodology for comparing the costs of energy produced by WECS that are available in the market.

*Recommended Practices for Wind Turbine Testing: 1. Power Performance Testing; 1. Edition 1982.* (1982). Edited by S. Frandsen, A.R. Trenka, and B. Pedersen; 17 pp.

Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems. (NTIS no. DE84901417).

This document describes the recommended practices for testing and reporting power performance characteristics of WECS. It provides a standard methodology for comparing energy production characteristics.

# Chapter 5

## Applications

### General

Wind turbine applications vary from large, megawatt-sized utility power plants to small wind turbines for home, farm, or village use. Wind energy systems may be either grid-connected or stand-alone. This chapter describes utility-scale wind plants, agricultural wind energy uses, stand-alone and hybrid systems, and applications for industrialized and developing countries.

For utility-scale applications, wind turbines operate like utility power plants, feeding electricity into the grid for distribution to utility customers. Utility-scale wind power plants represent the largest market for wind turbines in the United States and the industrialized world.

Wind turbines can supplement power delivered by utility lines. The owner of a grid-connected wind turbine buys and sells electricity as appropriate. Electricity generated by the wind system is used on site, and any excess is fed through a meter into the utility grid. When a home or business requires more electricity than the wind turbine is generating (for example, when wind speeds are low), the demand is automatically met by power from the utility grid.

Wind turbine generators can meet electrical demand where there is no utility-supplied electricity. These stand-alone wind turbines are usually small machines under 50 kilowatts (kW). Small turbines may operate alone or in hybrid configurations with batteries, diesel generators, and other solar energy systems. For village power installations, mini-grids of multiple wind turbines can supply power, often with diesel generator backup, to isolated communities. Developing countries provide the most promising markets for small turbines and hybrid systems.

*Wind Energy in the U.S.: A State By State Survey.* (current). Washington, DC: American Wind Energy Association; 183 pp.

This survey outlines government and utility programs available for wind energy development throughout the United States. It is written as a tool for state regulators, energy offices, utility representatives, wind energy developers, and prospective owners of individual wind turbines.

American Wind Energy Association. (1996). *American Wind Energy Association's Directory of Industry Members.* Washington, DC: American Wind Energy Association; 48 pp.

This directory contains domestic and international member companies including wind turbine and accessory parts manufacturers; wind power plant developers and operators; consultants; repair and maintenance companies; electric utilities; and research centers.

Spera, D.A. (May 1994). *Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering.* No. 100368. Fairfield, NJ: American Society of Mechanical Engineers; 700 pp.

This collection of articles compiled by the American Society of Mechanical Engineers provides an advanced look at all aspects of the modern wind turbine, including airfoils, rotor wakes, acoustics, system configuration, and fatigue design.

Interstate Renewable Energy Council; Solar Energy Industries Association; and Sandia National Laboratories. (1993). *Procurement Guide for Renewable Energy Systems.* Available from the American Solar Energy Society. 2400 Central Avenue, G-1, Boulder, CO 80301; 140 pp.

This handbook guides state and local government procurement officials in the specification and purchase of commercially available renewable energy systems, including wind systems.

Gipe, P. (1993). *Wind Power for Home & Business.* Post Mills, VT: Chelsea Green Publishing Company; 413 pp.

This is a reference on many aspects of post-1970s wind energy machines. The book contains tables to guide estimation of annual electricity production from any size wind turbine for various wind conditions. Also included are wind resource maps of all 50 states and a list of manufacturers of wind machines.



*Recommended Practice for the Installation of Wind Energy Conversion Systems.* (1989). AWEA Standard: AWEA 6.1-1989. Washington, DC: American Wind Energy Association; 49 pp.

This is a general guide to be used with manufacturers' installation manuals and is organized to follow the installation sequence. These recommended practices include concern for the safety of installation personnel and the public.

Jaras, T. (1988). *Wind Energy 1988: Wind Turbine Shipments and Applications.* Great Falls, VA: Stadia, Inc. (Wind Data Center); 316 pp.

This book updates the statistical information presented in 1987 on worldwide wind turbine manufacturing, installations, and markets, with data from 150 manufacturers.

Jaras, T. (1987). *Wind Energy 1987: Wind Turbine Shipments and Applications.* Great Falls, VA: Stadia, Inc. (Wind Data Center); 316 pp.

This book presents statistical information on worldwide wind turbine manufacturing, installations, and markets, with data from 150 manufacturers.

*Status of Commercial Wind Power: 1986 Survey.* (Strategies Unlimited). (1986). AP-5084. Palo Alto, CA: Electric Power Research Institute; 308 pp.

The result of a survey of turbine developers and manufacturers, this report includes data on 122 operating wind power stations and information on 25 turbine vendors.

Moment, R.L. (February 1983). *Performance and Size Estimating for Wind Systems.* RFP-3586. Golden, CO: Rockwell International Corporation; 69 pp.

In this report, a method is described for estimating wind energy conversion system (WECS) performance, given rated wind speed and annual energy production, in common wind regimes (10 to 18 mph) for rotor diameters ranging from 10 to 140 feet. Curves for the various wind regimes and rotor sizes allow the reader to estimate performance for a given size machine, or to select the rotor size required to produce a given amount of energy.

Park, J. (1981). *The Wind Power Book.* Palo Alto, CA: Cheshire Books; 253 pp.

This book provides the potential user of a small-scale wind system with information about design and construction; appendices contain detailed charts, tables, and diagrams.

*Wind Energy Mission Analysis.* (February 1977). COO/2578-1/1-3. Philadelphia, PA: General Electric Company.

*Wind Energy Mission Analysis.* (April 1976). SAN-1075-1/1-3. Burbank, CA: Lockheed-California Company.

These parallel studies assessed the potential for WECS on a national scale; identified high-potential applications; defined functional, performance, operational, and cost goals; evaluated the impact of wide-scale WECS use on energy suppliers and users; and identified the institutional and nontechnical problems associated with the acceptance of wind energy systems.

## Operation, Maintenance, and Performance of Wind Power Plants

A modern wind power plant is a group of wind turbines interconnected to a single utility through a system of transformers, transmission lines, and substations. Operation, control, and maintenance functions are often centralized through a network of computerized monitoring systems, supplemented by visual inspection. And performance is carefully monitored.

Performance, the power that can be extracted from the wind, varies with machine design and wind power plant location. Performance data can help the wind industry and potential users by identifying necessary modifications in machine design, demonstrating reliable operation, and providing information useful in the selection of a system to meet user needs. Such data usually include basic features of the machine such as design output, rotor configuration, and operating wind speeds; characteristics and problems of the machine in operation; and results of specific tests of machine capabilities.

The performance of a wind turbine can be determined by actual power output measurements obtained through either long-term atmospheric testing or short-term wind tunnel testing. Otherwise, performance can be estimated or predicted through the use of models, especially computer models. Equations and models used for wind performance calculations can be found in the papers referenced here.

OEM Development Corporation. (1994). *The Zond Victory Garden Phase IV Windfarm*. TR-103584. Palo Alto, CA: Electric Power Research Institute; 48 pp.

This report documents the planning, installation, and energy production of a utility-scale wind farm. The installation illustrates the levels of performance and reliability attainable by well-designed installations employing reliable, state-of-the-art turbines. This report is part of ongoing Electric Power Research Institute efforts to track wind power experiences on a worldwide basis.

Pasquariello, P. (1994). "Utilizing Windfarm Networks for Engineering Data Acquisition." *Windpower '94 Conference; May 9-13, 1994; Minneapolis, Minnesota*. Washington, DC: American Wind Energy Association.

This paper describes how performance data from wind power plants can be used to improve machine design.

*Experiences With Commercial Wind Energy Development in Hawaii*. (R. Lynette & Associates, Inc.). (1993). EPRI TR-102169. Palo Alto, CA: Electric Power Research Institute; 116 pp.

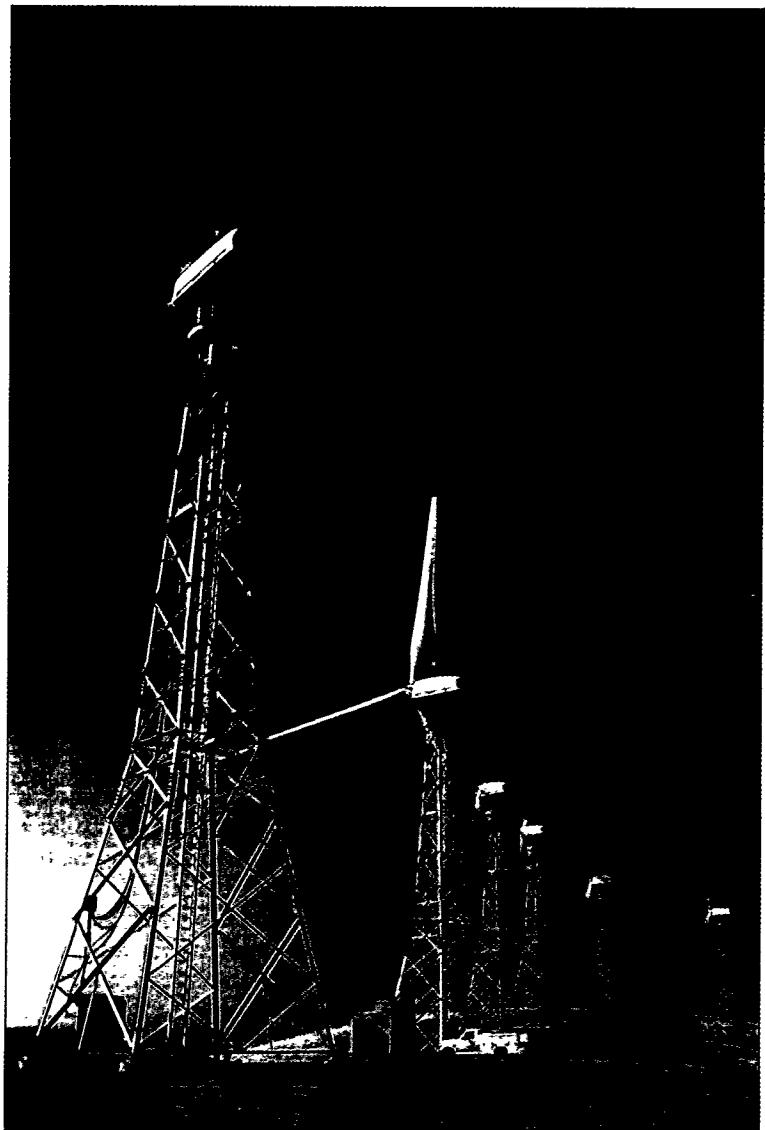
Wind power stations in Hawaii produced approximately 0.5% of the state's electricity in 1988. This report contains data on project performance, maintenance, and problems encountered.

Clark, R.N.; Davis, R.G. (1993). "Performance of an EnerTech 44 During 11 Years of Operation." *Windpower '93 Conference; July 12-16, 1993; San Francisco, CA*. Washington, DC: American Wind Energy Association; pp. 204-212.

This paper reports detailed information on the long-term operation of a 13.4-meter (44-foot) diameter rotor wind machine at Bushland, Texas. It includes power curves, energy production data, and descriptions of repairs and maintenance.

California Energy Commission. (1992). *1992 Energy Technology Status Report*. P500-92-007E. Sacramento, CA: California Energy Commission; 82 pp.

This report includes technology evaluations for more than 230 electrical generation and end-use



*Maintenance programs at large wind power plants have taken advantage of economies of scale to keep unit operation and maintenance costs down.*

technologies, including wind. The status of new and existing technologies is evaluated.

*Assessment of Wind Power Station Performance and Reliability.* (R. Lynette and Associates, Inc.). (1992). EPRI TR-100705. Palo Alto, CA: Electric Power Research Institute; 144 pp.

This report provides information on commercial wind power stations, including current operating and maintenance experience, and projections for future power stations.

Spera, D.A. (Sverdrup Technology, Inc.); Miller, M.W. (Hawaiian Electric Renewable Systems). (1992). "Performance of the 3.2-MW Mod 5B Horizontal-Axis Wind Turbine During 55 Months of Commercial Operation in Hawaii." *Windpower '92 Conference; October 19-23, 1992; Seattle, Washington.* Washington, DC: American Wind Energy Association; pp. 231-238.

This paper reports on the long-term performance of a DOE prototype machine installed in 1987 that incorporated a variable-speed, constant-frequency generating system.

*Experiences With Commercial Wind Turbine Design, Volumes 1 and 2.* (R. Lynette & Associates, Inc.). (1989). RP1590-12. Palo Alto, CA: Electric Power Research Institute; Vol. 1; 204 pp.; Vol. 2; 100 pp.

This status report reviews technical difficulties with earlier wind power plant designs, providing vital information for designers, purchasers, and operators.

*Solano MOD-2 Wind Turbine Operating Experience Through 1988.* (Pacific Gas and Electric Company). (1989). RP1590-06. Palo Alto, CA: Electric Power Research Institute; 60 pp.

This study by the nation's largest investor-owned utility summarizes experiences with the longest-running 2500-kW MOD-2 wind turbine.

*Standard Performance Testing of Wind Energy Conversion Systems.* (1988). AWEA Standard: AWEA 1.1-1988. Arlington, VA: American Wind Energy Association; 32 pp.

This document describes a standard method of determining and reporting primary performance characteristics. It includes definitions, units of measurement, field-test procedures used to determine power production performance and noise levels, procedures for deriving performance parameters, and a proposed test report to be used as part of certification.

*Altamont Wind Power Plant Evaluation for 1986.* (Pacific Gas and Electric Company). (1988). AP-5824. Palo Alto, CA: Electric Power Research Institute; 96 pp.

This report includes empirical data on the wind power stations at Altamont Pass, including economics, wind resources, and turbine performance.

## Integrating Wind Systems with Electric Utility Grids

Using wind power plants to supply electricity to utilities is a familiar concept in California. Several of the state's large utility companies have contracted to buy significant amounts of power from private wind power plant developers. Today, more than 16,000 turbines represent about 3% of California's total installed capacity for electricity generation.

Electricity for utilities is also being supplied by wind power plants in Hawaii, Iowa, Massachusetts, Minnesota, Montana, New Hampshire, New York, Oregon, Texas, and Vermont. Economies of scale and simplified logistics favor the use of wind power plants or arrays, rather than dispersed individual turbines, for large utility applications. Such wind power plants are connected to high-voltage transmission lines in much the same way as are conventional power plants, operating as part of the overall generation mix.

Unlike conventional generating sources, the wind is an intermittent resource. Such intermittency can cause the output of a wind power plant to fluctuate, often by the minute. These changes in output must be compensated for by adjusting the output of other generators. These effects can be magnified if wind power comprises a large proportion of the system's generating capacity.

However, if the output fluctuations of a wind power plant are limited or can be anticipated, or if the wind power plant is coupled with versatile generating sources, the effects of wind power fluctuations on the grid can be reduced significantly.

Milligan, M.R. (1996). *Alternative Wind Power Modeling Methods Using Chronological and Load Duration Curve Production Cost Models*. NREL/TP-441-8171. Golden, CO: National Renewable Energy Laboratory; 43 pp.

The report examines two production cost models that represent the two major model types.

Milligan, M.R. (1996). *Measuring Wind Plant Capacity Value*. NREL/TP-441-20493. Golden, CO: National Renewable Energy Laboratory; 9 pp.

The article evaluates common methods of evaluating capacity credit.

Milligan, M.R.; Miller, A.H.; Chapman, F. (1995). *Estimating the Economic Value of Wind Forecasting to Utilities*. NREL/TP-441-7803. Golden, CO: National Renewable Energy Laboratory; 10 pp.

The economic impact for utilities of an accurate wind forecast is examined. A range of estimates based on real utility data is presented.

*Modeling Needs for Evaluating the Effects of Wind Power Plants on the Electric Power System*. (Electrotek Concepts, Inc.). (1994). TR-104338. Palo Alto, CA: Electric Power Research Institute; 36 pp.

This report describes the current methods for judging a wind plant's capacity contribution to a utility. The report assesses the strengths and weaknesses of each method and the planning contexts for each method's application. The report recommends future research to improve methods for evaluating potential wind plant capacity credit.

*Evaluating the Effects of Wind Power Plants on an Electric Power System*. (1994). (Decision Focus, Inc.). TR-104339. Palo Alto, CA: Electric Power Research Institute; 20 pp.

This report reviews standard models and tools designed to analyze electromagnetic transients, power flow calculations, short-circuit features, harmonics, transient and steady-state stability, and power system operations and scheduling. The tools were evaluated for their suitability to analysis of proposed wind power plants. Research to develop better representation of wind power plant equipment and of the wind resource is proposed.

*Wind as a Utility-Grade Supply Resource: A Planning Framework for the Pacific Northwest*. (Decision Focus, Inc.; Litchfield Consulting Group). (1993). EPRI-TR-102094. Palo Alto, CA: Electric Power Research Institute; 44 pp.

This report emphasizes planning as fundamental to any wind power development. Originally published by the Pacific Northwest Utilities Conference Committee, this report provides a



*The hardware used to interconnect wind power plants with the utility grid is the same as that used for conventional power plants.*

framework for evaluating developer information from a planning perspective.

Grubb, M.; Meyer, N.I. (1993). "Wind Energy: Resources, Systems, and Regional Strategies." Chapter 4 in *Renewable Energy: Sources for Fuels and Electricity*. Washington, DC: Island Press, pp. 157-212.

Kelly, H.; Weinberg, C.J. (1993). "Utility Strategies for Using Renewables." Chapter 23 in *Renewable Energy: Sources for Fuels and Electricity*. Washington, DC: Island Press, pp. 1011-1069.

The authors consider the implications of integrating renewables into electric power systems and conclude that relatively large amounts can be accommodated without energy storage.

Milligan, M.R.; Miller, A.H. (1993). *The Value of Windpower: An Investigation Using a Qualified Production Cost Model*. NREL/TP-441-5730. Golden, CO: National Renewable Energy Laboratory; 8 pp.

A production cost model can treat wind energy in several ways, affecting the value of wind energy.

*Integrating an Ever-Changing Resource.* (1992). Produced under the auspices of the Utility Wind Interest Group; published by the Electric Power Research Institute; 4 pp. Available from the National Renewable Energy Laboratory, Golden, CO, order no. UWIG 2.

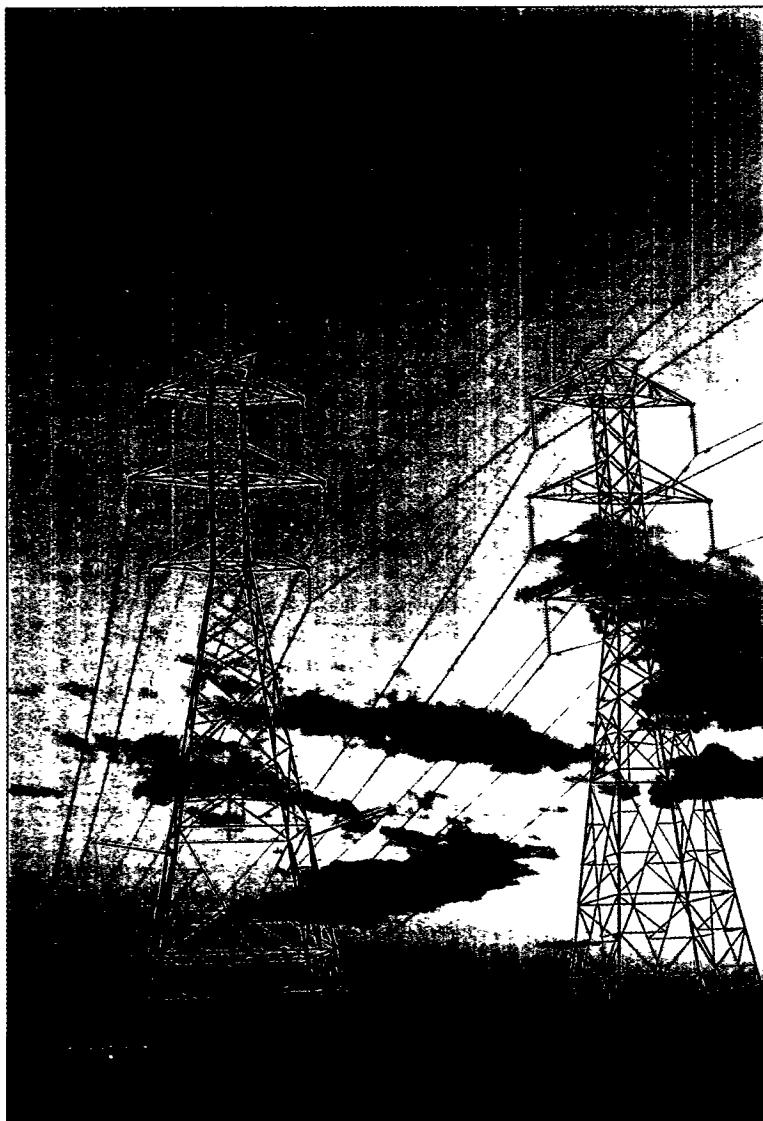
This brochure answers basic questions about integrating wind power plants into the utility network. The Utility Wind Interest Group has also published the following brochures referenced as appropriate throughout this document:

*An old idea takes new shape for electric utilities*, November 1990, order no. UWIG 4; *Economic lessons from a decade of experience*, August 1991, order no. UWIG 1; *America takes stock of a vast energy resource*, February 1992, order no. UWIG 3; *The evolving wind turbine*, March 1993, order no. SP-440-5954; *Windpower and the environment*, August 1993, order no. SP-336-5898; *Utilities move wind technology across America*, February 1994, order no. SP-336-5916; *Another asset in the utility resource portfolio*, October 1994, order no. SP-440-5954; *The European Wind Experience*, 1995, order no. SP-440-6139.

Wade, J.E.; Walker, S.N.; Baker, R.W. (Oregon State University) (February 1990). *Integration of Wind Energy into the Electrical Utility System: An Overview of the Issues*. DOE/BP/63406-11. Washington, DC: U.S. Department of Energy; 35 pp. (NTIS no. DE90009468/XAB).

Integration problems examined in this report refer to the quantity of energy available, its value to a utility, and the quality of energy delivered.

Halberg, N. "Wind Energy Research Activities of the Dutch Electricity Generating Board." Proceedings of the European Community Wind Energy Conference, Madrid, Spain, September 1990, pp. 713-718.



Grubb, M.J. (1989). "Valuing Wind Energy on a Utility Grid." Excerpted from *WIND Directions*, the newsletter of the British and European Wind Energy Association, and published in the May 6, 13, 20, 1989 issues of *Wind Energy Weekly*. Washington, DC: American Wind Energy Association.

Grubb, M.J. (1988). "The Economic Value of Wind Energy at High Power System Penetration Levels: An Analysis of Models, Sensitivities, and Assumptions." *Wind Engineering*. Vol. 12, No. 1. The Netherlands: Elsevier Science.

Younkins, T.D. (April 1987). *Methodology for Control and Operation of Wind Arrays in Utility Systems: Final Report*. ORNL/Sub/81-7242/1. Oak Ridge, TN: Oak Ridge National Laboratory; 290 pp. (NTIS no. DE87008546).

Javid, S.; Younkins, T.; Hauth, R.L.; et al. (June 1985). "A Method for Determining How to Operate and Control Wind Turbine Arrays in Utility Systems." *IEEE Transactions*, Vol. PAS-104, No. 6, pp. 1335-1341.

Taking a non-traditional approach to wind turbine array control, the authors show that there are major opportunities for control of wind turbine arrays to reduce undesirable power fluctuations. They postulated three control regimes.

*Recommended Practices for Wind Turbine Testing: 7. Quality of Power. Single Grid-Connected WECS; 1. Edition 1984.* (1984). Edited by L.J. Ballard and R.H. Sivansborough; 24 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

This document describes the recommended practices for determining the quality of power delivered by a single grid-connected WECS. It provides a methodology for obtaining power quality data that can be used to compare WECS of different types. Topics covered in these recommendations relate to the quality of power in terms of power variation, reactive power demand, voltage variations during generation, voltage variations on cut-in, switching operations, and harmonics.

McCabe, T.; Henry, G.; Tennis, M.W.; Goldenblatt, M. (January 1984). *Early Utility Experience with Wind Power Generation*. EPRI-AP-3233. Vol. 1; 50 pp.; Vol. 2; 118 pp.; Vol. 3; 150 pp. Palo Alto, CA: Electric Power Research Institute.

This report presents the experiences of Pacific Gas and Electric Company and Bonneville Power Administration with wind turbine projects.

Chan, S.M.; Powell, D.C.; et al. (1983). "Operations Requirements for Utilities with Wind Power Generation." Presented at the 1983 IEEE Winter Power Meeting, New York, NY.

The authors quantified the spinning reserve/unloadable generation impacts as a function

of power system and wind parameters. Adding, say, 400 MW of wind would require considerably less additions to spinning reserve and unloadable generation than the total nameplate capacity.

Chan, S.M.; Curtice, D.; Chang, S.K. (October 1983). *Methods for Wind Turbine Dynamic Analysis*. EPRI-AP-3259. Palo Alto, CA: Electric Power Research Institute; 272 pp.

The analytical tools needed to study the effects of wind turbines on utility networks and system operations are described in this report. Methods for computing additional costs are also identified.

Goldenblatt, M.K.; Wegley, H.L. (March 1983). *Analysis of the Effects of Integrating Wind Turbines into a Conventional Utility: A Case Study*. PNL-3962-Rev. Richland, WA: Pacific Northwest Laboratory; 66 pp.

This report analyzes the impact of wind speed sampling frequency, wind turbine model accuracy, and wind speed forecasting accuracy on integrating wind turbines into an existing utility system.

Kaupent, B.M. (February 1983). *Assessment of Distributed Wind Power Systems*. EPRI AP-2882. Palo Alto, CA: Electric Power Research Institute; 364 pp.

This project developed a method for assessing the potential impacts of connecting wind turbines to a utility system at distribution and subtransmission voltage levels.

Marah, F.; Dlott, E.H.; Korn, D.H. (1982). *Wind Power for the Electric-Utility Industry*. Lexington, MA: D.C. Heath and Company, Lexington Books; 159 pp.

This book discusses the economics of wind power as a fuel-saving investment for electric utilities.

Reddock, T.W.; Barnes, P.R.; Lawler, J.S.; Skroski, J.C. (May 1982). "Strategies for Minimizing Operational Impacts of Large Wind Turbine Arrays on Automatic Generation Control Systems." *Journal of Solar Energy Engineering*. (104:2); New York, NY: American Society of Mechanical Engineers; pp. 65-69.

This work develops the conceptual basis for analysis of impacts of wind on utility operating practices.

Hinrickson, E.N.; Nolan, P.J. (November 1981). *Dynamics of Single- and Multi-Unit Wind Energy Conversion Plants Supplying Electric Utility Systems*. DOE/ET/20466-78/1. Washington, DC: U.S. Department of Energy; 139 pp.

This study analyzes the dynamic performance of single and multiple wind turbine generators connected to electric utility power systems.

*Wind Power Generation Dynamic Impacts on Electric Utility Systems*. (November 1980). EPRI-AP-1614. Palo Alto, CA: Electric Power Research Institute; 90 pp.

This study assesses potential dynamic impacts on electric utility systems from integrating clusters of

large wind turbines. It looks at short-term transient stability, system frequency excursions, and minute-to-minute, unit-ramping limitations of conventional system generation.

*Requirements Assessment of Wind Power Plants in Electric Utility Systems.* (January 1979). EPRI-ER-978-SY. Palo Alto, CA: Electric Power Research Institute; 3 Vols.

This report describes a method of assessing the prospects for wind generation in the service areas of individual electric utilities. It assesses the interaction between wind generation and electric energy storage, develops preliminary penetration scenarios, and recommends areas for further research and development.

## Agricultural Applications

Wind machines have been extracting mechanical energy from the wind to pump water for thousands of years. There is still a brisk commerce in mechanical water pumping windmills in the United States and other countries. These machines with ten or more blades are well suited to the low-speed, high-torque requirements of water pumps. Storage tanks are sized to keep water available when the wind is not blowing.

Wind electric generators, first introduced to farmsteads in the United States in the 1920s, can provide a greater variety of services for agriculture. Wind-generated electricity can be used for lighting, heating, pumping, refrigeration, running processing equipment, and producing hot water.

Most of these wind electric applications for agriculture require small wind systems ranging in size from 10 kW to 50 kW. Field tests have indicated that, in general, the wind system must be used throughout the year to be economically viable. However, some applications that include a storage system also may be viable.

Since 1976, the Agriculture Research Service of the U.S. Department of Agriculture has been conducting field experiments to identify, develop, and test applications of wind power in agriculture. Additional studies have been conducted on economics and load requirements for wind machines.

Nelson, V.; Gilmore, E.H.; Starcher, K. (1994). *Introduction to Wind Energy.* 93-3. Canyon, TX: Alternative Energy Institute; 28 pp.

This book introduces and explains how wind machines operate and how they can be used. It includes chapters on wind characteristics, wind energy conversion systems, and economics. It discusses instrumentation for wind measurement and describes the wind industry.

Wyatt, A. (Research Triangle Institute). (1992). *Wind Electric Pumping Systems: Sizing and Cost Estimation.* Washington, DC: American Wind Energy Association; 39 pp.

This document presents step-by-step procedures for sizing and estimating the costs of an electric water-pumping system. Sections address estimating water-pumping requirements, assessing the wind resource, selecting components, predicting output, and preparing bid specifications. (Also available in Spanish.)

Clark, R.N.; Mulh, K.E. (1992). "Water Pumping for Livestock." *Windpower '92 Conference; October 19-23, 1992; Seattle, Washington.* Washington, DC: American Wind Energy Association; pp. 284-290.

A mechanical multibladed windmill was compared to a wind-electric system for pumping water for livestock. Using historical wind data, the wind electric pumping system would have produced more than twice as much water as the mechanical system, and their costs were almost the same.

Gilley, J.R. (July 1985). "Potential Use of Wind Power for Pumping Irrigation Water." *Energy Agriculture* (4:2); pp. 133-146.

This report computes potential energy savings for three types of wind-powered irrigation pumping plants. The wind systems analyzed were wind-assist combustion engines; wind-assist electric



Systems like this one in Bushland, Texas, can supply all the electricity needed by a water pump without being connected to the utility grid.

motors, with and without the sale of surplus electricity; and a stand-alone turbine with a reservoir for water storage.

Wschenbach, W. (1984). *Wind Systems for Pumping Water: A Training Manual*. Washington, DC: Peace Corps; 83 pp.

This manual on the design and construction of wind systems is divided into 21 training sessions and includes illustrations, tables, and a bibliography.

Stafford, R.W.; Soderholm, L.H. (March 1983). *Analysis of Problems of Interfacing Wind Systems to Rural Power-Distribution Systems: Final Report*. DOE/ARS-3408-20691/83/1. Ames, IA: Agricultural Research Service; 216 pp. (NTIS no. DE83013803).

This report includes a survey and prioritization of interconnection problems and issues.

Marjan, P.L.; Clark, R.N. (November 1982). *Evaluation of Pumps for Wind-Driven Irrigation*. DOE/ARS-7315-20741/83/1. Washington, DC: U.S. Department of Energy; 174 pp. (NTIS no. DE83013438).

This survey evaluates wind-powered irrigation pumps.

Stafford, R.W.; Greeb, F.J.; Smith, M.F.; Des Chenes, C.; Weaver, N.L. (January 1981). *Economic Analysis of Wind-Powered Farmhouse and Farm Building Heating Systems: Final Report*. DOE/SEA-3408-20691/81/1. Washington, DC: U.S. Department of Energy; 360 pp. Available from NTIS.

This study evaluates the break-even value of wind energy for selected farmhouses and farm buildings, focusing on the effects of thermal storage on the use of WECS production and value.

Clark, R.N.; Schneider, A.D.; Nelson, V.; Gilmore, E.; Barieau, R.E. (January 1981). *Wind Energy for Irrigation—Wind-Assisted Pumping from Wells: Final Report*. DOE/SEA-7315-20741/81/1; 60 pp. Available from NTIS.

This report evaluates water-pumping equipment on U.S. farms by geographic region and potential wind power zones.

David, M.L.; Buzenberg, R.J.; Glynn, E.F.; Johnson, G.L.; Shultis, J.K.; Wagner, J.P. (August 1979). *Wind Energy Applications in Agriculture, Final Report; Executive Summary*. DOE/SEA-1109-20401/79/2. Beltsville, MD: U.S. Department of Agriculture, Science and Education Administration; 210 pp.

The economics and market potential for wind turbine applications in U.S. agriculture are analyzed in this report.

## Stand-Alone and Wind/Diesel Hybrid Systems

Wind energy has traditionally been a source of power for sites where no other power source is readily available. The most familiar of these traditional applications is the mechanical water pumper, which is still in use today. But in the first half of the 20th century, there were also many small (less than 1 kW) electricity-generating machines operating on the Great Plains of the United States.

The technology available for small stand-alone installations has improved greatly since the 1940s, and today's modern small machines have been used in thousands of installations worldwide. Very small direct current systems are used to charge batteries, while larger systems (up to 20 kW) are used as stand-alone, alternating current generators for agriculture and remote residences.

The applications for stand-alone wind energy systems are almost unlimited. U.S.-manufactured wind turbine systems have been used throughout the world for diverse applications:

- Microwave repeaters in Paraguay, Oman, and the Arctic Circle
- Water pumping in Pakistan and Morocco
- Marine navigation in Canada
- Pipeline telemetry in Chile
- Cathodic protection in Texas
- Individual homes in Mexico
- Dedicated productive uses and community facilities in South America.

Wind machines have also been used for power at the South Pole since the 1930s. Wind is supplying power at sites that would be costly to serve with conventional means or at sites so remote or harsh that other power systems might not work reliably over long periods.

Wind/diesel hybrid systems are becoming important in areas where it is advantageous to reduce conventional fuel use and lower maintenance costs. In many of these hybrid systems, photovoltaic (PV) panels that convert sunlight directly into electricity are also included. In the most common hybrid application, wind turbines and PV panels meet energy needs and charge batteries when the wind is blowing. If the batteries run low, the diesel engine-generator runs at full power—its most cost- and fuel-efficient mode of operation—until they are charged. In some systems, the generator makes up the difference when electrical demand exceeds the combined output of wind turbines, PV, and batteries.

Baring-Gould, E.I. (1996). *Hybrid2 User Manual, The Hybrid System Simulation Model, Version 1.0*. NREL/TP-440-21272. Golden, CO: National Renewable Energy Laboratory.

This report describes how to use Hybrid2, a simulation code used to analyze wind/diesel hybrid power system performance and costs. The model includes a user-friendly, windows-based graphical user interface and a library of input data.

University of Massachusetts. "Wind/Diesel Bibliography." Current part of *Endnote Plus* database available from Niles & Associates, Inc., 200 Hearst Street, Berkeley, CA 94709.

This bibliography of publications relating to using wind turbines in tandem with diesel generators is kept current.

*Wind-Diesel Systems: A Guide to the Technology and its Implementation.* (1994). Prepared under the auspices of the International Energy Agency Wind Turbine Agreement. Edited by R. Hunter and G. Elliot. Cambridge, England: Cambridge University Press.

This book helps the reader understand the prospects and technical details of using wind turbine generators with diesel generators.

Cramer, G.; Kleinkauf, W.; Schott, T. (1994). "Wind/Diesel/Battery Systems—Applications, Experience, Economy of Different System Configurations and Sizes." *Wind Engineering* (17:5); p. 228. Brentwood, England: Multi-Science Publishing Company, LTD.

This article chronicles the experience and improvements made to a wind/diesel hybrid system on the Irish island of Cape Clear. Cost of energy calculations are included.

Rogers, A; Manwell, J.F.; Stein, W.M.; McGowan, J.G. (1993). "Experimental Testing of Variable Speed Diesels for Wind/Diesel System Applications." *Wind Energy—1993; January 31–February 4, 1993; Houston, Texas.* SED-Vol. 14. New York, NY: American Society of Mechanical Engineers; pp. 67–74.

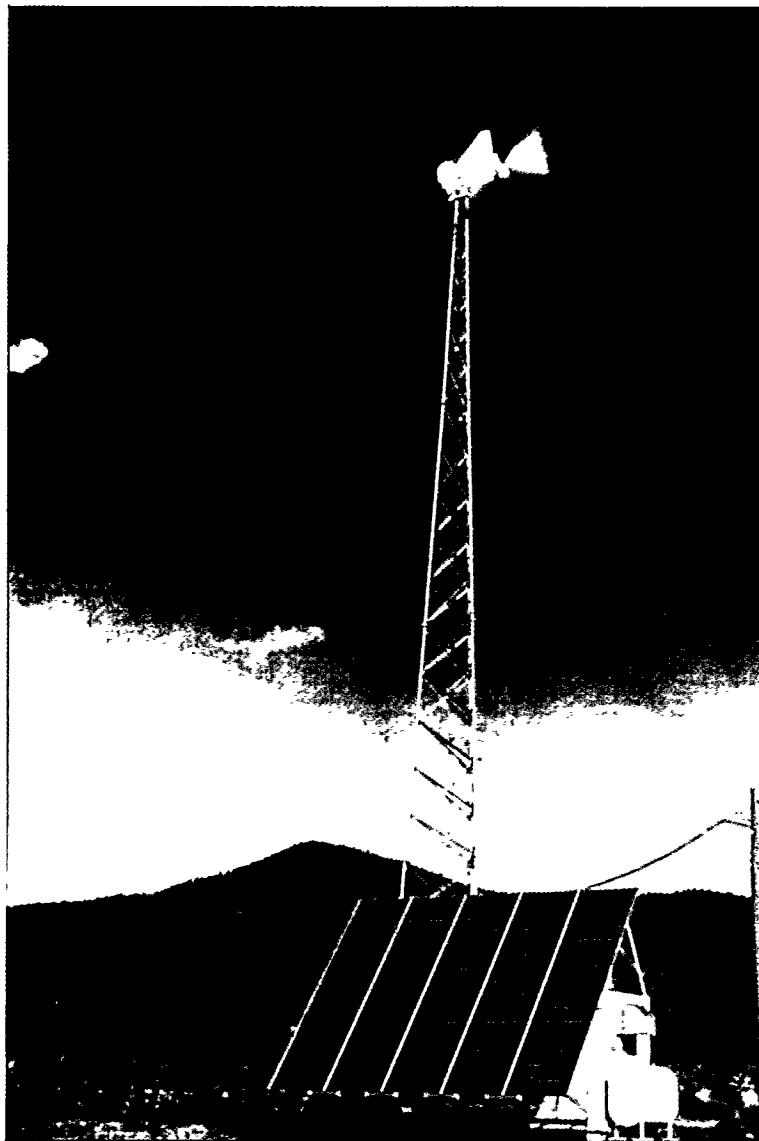
This paper summarizes recent work at the University of Massachusetts on the development of variable-speed diesel generators for wind/diesel systems.

Qi, G. "Mathematic Programming Models for Economic Design and Assessment of Wind/Diesel Systems." *Windpower '93 Conference; July 12–16, 1993; San Francisco, CA.* Washington, DC: American Wind Energy Association; pp. 501–507.

The author used a mathematical programming model to calculate optimal component sizes given initial conditions, such as average wind speed and typical daily load requirements.

Market studies have identified thousands of islands and communities remote from utility grids that are using electric power generated by diesel generators. In communities in which the minimum load exceeds 100 kW, and the average annual wind speed exceeds 4 meters per second (9 miles per hour), the isolated, small-grid, or village systems could benefit from adding wind turbine generators. Wind turbines working in conjunction with existing generators and batteries could reduce fuel costs and expand generation capacity for these growing communities.

Hybrid systems can be constructed in a broad range of sizes for a wide variety of applications. The size of the appropriate wind turbine is related to the size of the diesel installation and to expected variations in the system load. For example, a 400-kW diesel facility might be operated in parallel with several 10- to 50-kW wind turbines.



*This 50-kilowatt village power system runs a manufacturing facility in Waitsfield, Vermont.*

Manwell, J.F.; McGowan, J.G. (January 1992). "Advances in Quasi-Steady Wind Diesel System Simulation." *Eleventh ASME Wind Energy Symposium*. New York, NY: American Society of Mechanical Engineers; pp. 119-124.

This paper describes improvements made to HYBRID1, a model used to simulate and aid in the design of wind/diesel systems. The improvements allow a storage or no-storage case, one or more diesels, multiple wind turbines, a flexible battery model, and different control strategies.

King, W.R.; Johnson, B.L., III. (Science Applications International Corporation). (1991). *Worldwide Wind/Diesel Hybrid Power System Study: Potential Applications and Technical Issues*. SERI/TP-257-3757. Golden, CO: Solar Energy Research Institute; 104 pp. (NTIS no. DE91002160).

This study describes certain areas where wind turbines can be combined with diesel generators to produce electricity at a cost lower than that using diesel alone. The world market for such hybrid systems depends on the need for electric power, the wind resource, and the availability of investment dollars. This study provides data on each of these factors for nine countries and Alaska.

*Wind/Diesel Systems Architecture Guidebook*. (1991). AWEA Standard: AWEA 10.1-1991. Washington, DC: American Wind Energy Association; 41 pp.

One of a series, this guidebook is intended for the designer, manufacturer, installer, and user of wind/diesel systems.

Coleman, C. (Northern Power Systems). (1990). *Wind Hybrid System Research and Testing: Telecommunications Systems*. SERI/STR-257-3686. Golden, CO: Solar Energy Research Institute.

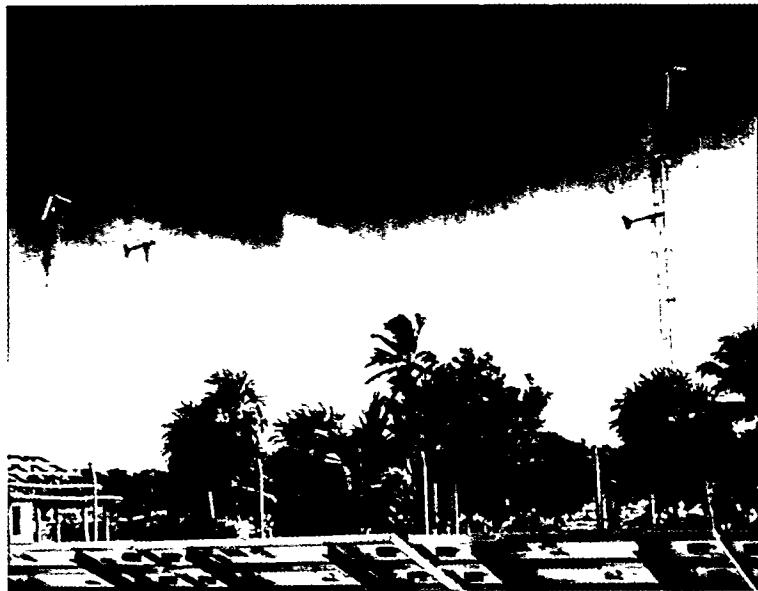
This work, funded under the DOE Cooperative Field Test Program, focused on understanding the value of hybrid power system architectures for telecommunications and remote village users. A new approach that allowed the wind turbine to remain on-line without the diesel generator operating offered the best value.

Hughes, P.S.; Johnson, B.; Sherwin, R.; Stern, W. (Atlantic Orient Corporation). (1990). *System Stability and Penetration Study for Wind Diesel Hybrid Systems*. SERI/STR-257-3982. Golden, CO: Solar Energy Research Institute.

As part of the DOE Cooperative Field Test Program, engineers at Atlantic Orient Corporation tested the practicality of designing a simple, low-cost system using only the diesel to control voltage frequency. The tests demonstrated that a simple, high-penetration, no-storage wind/diesel system is technically feasible.

Lundsager; Norgaard. (August 1988). *The 55/30 kW Experimental Wind/Diesel System at Risø National*

Because of operating constraints on diesel systems, the hybrid system must be designed carefully and must include continuous control systems. The U.S. Department of Energy (DOE) is now assisting industry with systems modeling and testing for small, remote communications and village power systems.



*This hybrid generation system in Mexico includes six 10-kW wind turbines, 12-kW photovoltaic modules, batteries, a 40-kW inverter to convert power to alternating current, a diesel generator, and an operational control system.*

## International Applications

International applications of wind energy in industrialized as well as developing nations offer potential markets to U.S. industry. Wind power plant applications in industrialized nations are similar to those used in the United States. In the developing world, applications include small, stand-alone systems; hybrid, village systems; and wind power plants connected to large electric distribution grids.

Many developing countries have social and economic development programs aimed at stemming migration from rural areas to urban centers. Programs to keep people from moving to the cities are designed to reduce the social and economic costs of urban unemployment and overcrowding. Supplying electric energy for productive rural activities and social services is one approach to make life in the countryside more profitable and appealing for the population.

Renewable energy technologies can often supply electricity for a lower cost than building new transmission lines or operating diesel generators far from fuel supplies and maintenance personnel. Government-sponsored pilot projects to install and evaluate renewable energy systems are under way in Brazil, Bolivia, the Caribbean,

*Laboratory. RISØ-M-2717. Roskilde, Denmark: Risø National Laboratory.*

This paper describes the basic principles and philosophy of the Risø experimental system and presents theoretical and experimental results of the system.

**Dawson, R.E.; Cowan, R.A. (March 1987). *Multisource Energy System Project.* SERI/SP-217-2950. Golden, CO: Solar Energy Research Institute; 35 pp.**

This project investigated methods of providing uninterrupted power to Army communications and navigational facilities. A system incorporating wind and photovoltaics with a diesel backup generator and battery storage system was installed and tested.

**Clark, R.N. (1985). "Wind-diesel Hybrid System for Water Pumping." *Proceedings of the Wind Energy Exposition and National Conference of the American Wind Energy Association.* Washington, DC: American Wind Energy Association; pp. 221-225.**

This paper evaluates a wind-diesel hybrid system for water pumping.

**Wilreker, V.F.; Stiller, P.H.; Scott, G.W.; Kruse, V.J.; Smith, R.F. (February 1984). *Wind Turbine Generator Interaction with Conventional Diesel Generators on Block Island, Rhode Island. Vol. 1, Executive Summary.* DOE/NASA-0354-1. Cleveland, OH: NASA Lewis Research Center; 45 pp. (NTIS no. DE84015874).**

This report summarized results of a three-part study of the effects of connecting a MOD-0A wind turbine generator to an isolated diesel power system.

## Industrialized Nations

*The European Wind Experience. (1995). Produced under the auspices of the Utility Wind Interest Group; published by the Electric Power Research Institute; 6 pp. Available from the National Renewable Energy Laboratory, Golden, CO, order no. SP-440-6139.*

The brochure describes utility involvement in European wind projects, summarizes siting issues, and includes a map of European wind projects.

*National Renewable Energy Laboratory. (1995). *International Energy Agency Wind Energy Annual Report 1994.* NREL/SP-440-7810. Golden, CO: National Renewable Energy Laboratory.*

This report includes reports from 12 member countries on national activities, and summaries of cooperative projects undertaken by member countries.

*Van Wijk, A.J.M.; Coelingh, J.P. (1993). *Wind Power Potential in the Organization of Economic Cooperation and**



*A wind turbine in Stiikajoki, Finland, near a small fishing harbor.*

Guatemala, India, Indonesia, Mauritania, Mexico, and the Philippines. These programs will generate the experience and performance data required to develop loan requests to international lending organizations such as the World Bank.

The federal government works to increase the use of U.S. technology to supply renewable energy worldwide. For example, the Committee for Renewable Energy Commerce and Trade assists U.S. companies in exporting renewable energy technologies, including wind. The U.S. Agency for International Development, the Export-Import Bank, and the U.S. Department of Commerce are involved in technology export issues.

*Development (OECD) Countries.* 93091. Utrecht, The Netherlands: Utrecht University; 35 pp.

This report reviews the status of wind energy technology, the potential for large-scale electricity production, and the economics of wind energy for OECD countries.

OEM Development Corporation. (March 1993). *European Wind Technology.* EPRI-TR-101391. Palo Alto, CA: Electric Power Research Institute; 88 pp.

This contractor report describes wind turbine development projects under way in Europe and includes information about government support of these efforts.

Commission of the European Community's Directorate and Fraunhofer-Institute for Solar Energy Systems (1990-1991). *Eurowin-European Wind Turbine Data Base Annual Reports.* Available from: American Wind Energy Association, Washington, DC.

These reports provide statistical information about European wind energy developments. They focus on technical development, electricity generation, economics, and failure analysis.

#### Developing Nations

United States Export Council for Renewable Energy (US/ECRE). (1994). *Strategic Plan.* Washington, DC: U.S. Export Council for Renewable Energy; 20 pp.

This plan outlines the activities and goals of US/ECRE to advance U.S. renewable energy technologies in appropriate applications worldwide. The American Wind Energy Association is one of the industry association members of US/ECRE.

American Wind Energy Association. (1993). *Small Wind Energy Systems Applications Guide.* Washington, DC: American Wind Energy Association; 8 pp.

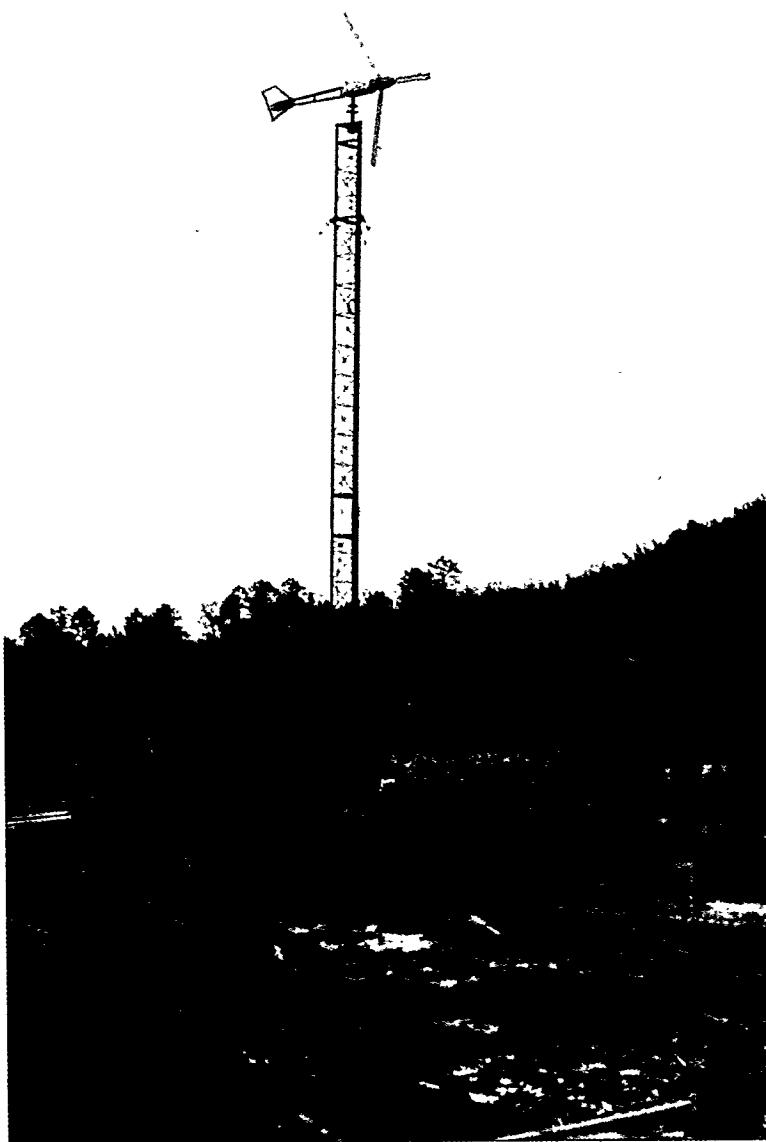
This publication describes a variety of potential applications for small and large wind energy technologies, using case studies from around the world.

Flowers, L.T. (National Renewable Energy Laboratory); Rackstraw, K. (American Wind Energy Association); Bergey, M.L.S. (Bergey Windpower Company); Lilley, A. (Westinghouse); Pate, R. (Sandia National Laboratories). (1993). "Decentralized Wind Electric Applications for Developing Countries." *Windpower '93 Conference; July 12-16, 1993; San Francisco, CA.* Washington, DC: American Wind Energy Association; pp. 421-428.

This paper discusses the market for wind turbines in developing countries, as well as appropriate system options and design considerations. Two installations in Mexico are described and discussed.

American Wind Energy Association. (1992). *Wind Energy for Sustainable Development.* Washington, DC: American Wind Energy Association; 22 pp.

Private associations are also working to promote U.S. technology. The wind industry trade association, the American Wind Energy Association, is active in promoting U.S. technology abroad. The U.S. Export Council for Renewable Energy, supported by government and private organizations, works to make U.S. capabilities known to governments and funding organizations around the world.



*This 1-kilowatt wind turbine provides electricity to a village in India.*

This publication highlights the ways wind energy can supply the energy needs of a utility, a community, or an individual home. The book includes discussions of wind energy economics, environmental impacts, and basic turbine operating principles, as well as a list of organizations that offer assistance to those interested in wind energy.

Wyatt, A. (Research Triangle Institute). (1992). *Wind Electric Pumping Systems: Sizing and Cost Estimation*. Washington, DC: American Wind Energy Association; 39 pp.

This book describes wind system configurations for water pumping and explains how to select components and estimate the cost of energy for systems.

*Wind Energy Applications and Training Symposium. Final Report.* (1990). Conference proceedings. Arlington, VA: American Wind Energy Association; 120 pp. (NTIS no. TI91006703).

These proceedings contain papers by foreign officials about actual and potential wind energy development in countries all over the world.

Swisher, R. (American Wind Energy Association); Ancona, D.F. (U.S. Department of Energy); and Edworthy, J. (Canadian Wind Energy Association). (September 1990). "Wind Energy Developments in the Americas." *European Community Wind Energy Conference and Exhibition; September 10-14, 1990; Madrid, Spain*. Bedford, England: H.S. Stephens & Associates; pp. 43-48.

This paper highlights the key activities and programs of Argentina, Costa Rica, Colombia, Mexico, and several Caribbean countries.

Clark, R.N. (1989). "Stand-alone Wind Electric Water Pumping." *Proceedings of the European Wind Energy Conference, EWEC '89*. Amsterdam: Elsevier; pp. 650-654.

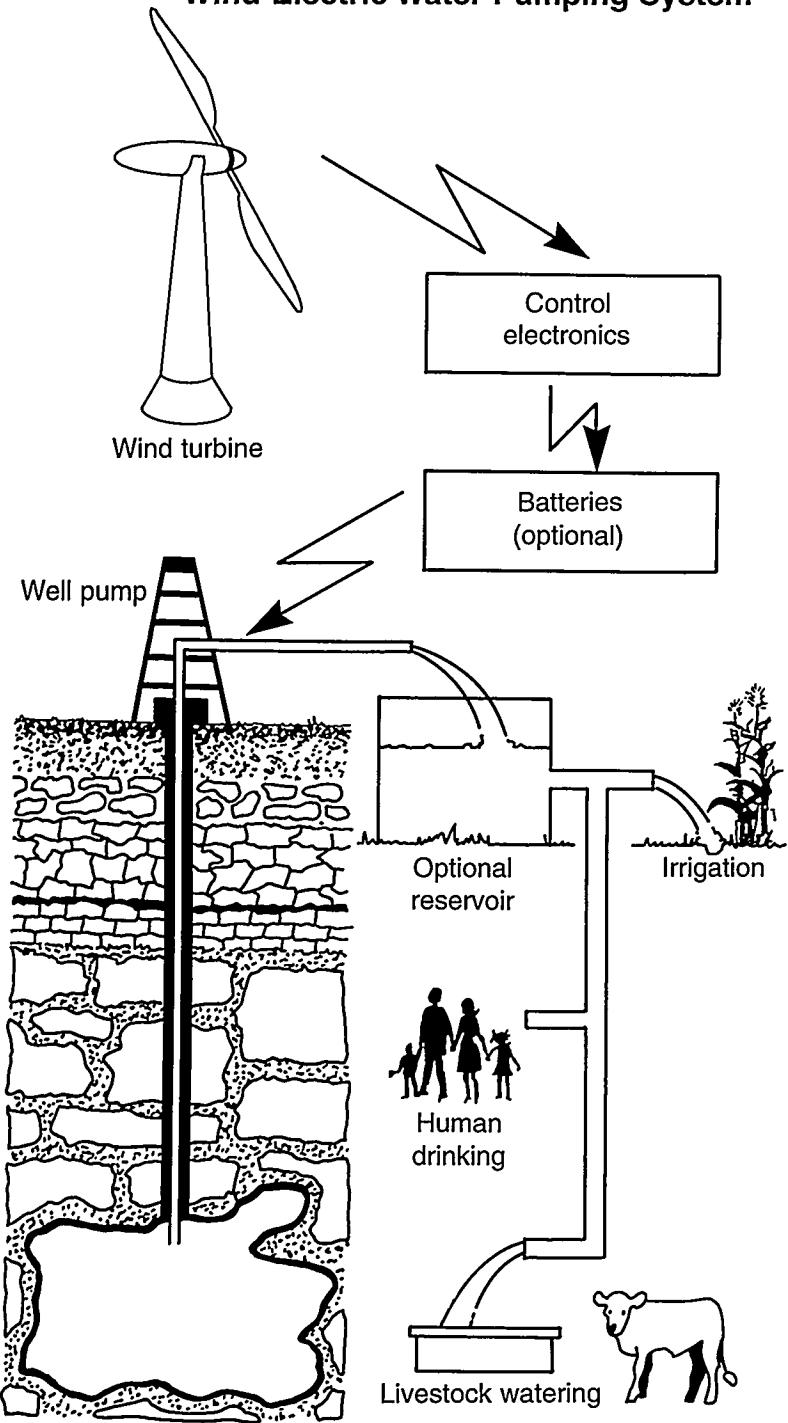
This paper describes how wind turbines are used in the United States to supply water for ranch and farm animals. System design procedures and operating characteristics are discussed.

Gilley, J.R. (July 1985). "Potential Use of Wind Power for Pumping Irrigation Water." *Energy Agriculture* (4:2); pp. 133-146.

In this report, potential energy savings were computed for three types of wind-powered irrigation pumping plants in selected areas of the United States. The wind systems analyzed were wind-assist combustion engines; wind-assist electric motors, with and without the sale of surplus electricity; and a stand-alone turbine with a reservoir for water storage.

Wschenbach, W. (1984). *Wind Systems for Pumping Water: A Training Manual*. Washington, DC: Peace Corps; 83 pp.

## Wind-Electric Water Pumping System



This manual contains information on design and construction of wind systems. It is divided into 21 training sessions and includes illustrations, tables, and a bibliography.

Smil, V.; Knowland, W. (1980). *Energy in the Developing World, The Real Energy Crisis*. Oxford, England: Oxford University Press.

# Chapter 6

## Environmental Issues of Wind Power

### General

Using wind turbines to generate electricity contributes no net carbon dioxide (CO<sub>2</sub>) or other greenhouse gases to the atmosphere and produces no pollutants of soil or water. In 1994 alone, wind-generated electricity kept more than 2.5 million tons of CO<sub>2</sub> and 15,000 tons of other pollutants out of the air. And the expansion of wind-powered generation can help reduce the risk of global warming.

Although generation of electricity with wind turbines does not contribute to global warming, no human activity is without environmental consequences. Possible environmental effects of wind turbine usage can include impacts on bird and animal habitat, behavior, and survival rates; noise; television interference; impacts on aesthetics; need for worker safety; and effects on vegetation.



*Wind, a clean source of energy, can help a utility reduce its net emissions on a per kilowatt-hour basis.*

*Wind Power and the Environment.* (1993). Produced by the Utility Wind Interest Group; published by the Electric Power Research Institute; 4 pp. Golden, CO: National Renewable Energy Laboratory.

This brochure outlines the environmental issues affecting wind power from a utility perspective.

Hohmeyer, O. (1988). *Social Costs of Energy Consumption.* Berlin-Heidelberg, Federal Republic of Germany: Springer-Verlag; 126 pp.

This study systematically examines the environmental (or "social") costs and benefits of electricity generation by wind and solar systems; it also compares them with electricity generation based on fossil or nuclear fuels, drawing on available literature where possible. Effects such as disease caused by air pollution and rising sea levels because of global warming are considered. An attempt is made to quantify monetary impact.

Lawrence, K.A.; Strojan, C.L. (May 1980). *Environmental Effects of Small Wind Energy Conversion Systems (SWECS).* SERI/TP-743-628. Golden, CO: Solar Energy Research Institute; 16 pp.

This paper reviews the potential pollution releases and risks that might result from the manufacture, operation and maintenance, and decommissioning of small wind energy conversion systems (SWECS) (power ratings of 2, 8, and 50 kilowatts [kW]). Investigated environmental impacts include noise, collision of flying species, television interference, and aesthetic considerations. Serious environmental effects were not evident for any of the three wind energy conversion systems (WECS) in the study.

Rogers, S.E.; Cornaby, B.W.; Redman, C.W.; Sticksel, P.R.; Talle, D.A. (December 1977). *Environmental Studies Related to the Operation of Wind Energy Conversion Systems.* COO-0092-77/2. Columbus, OH: Battelle Columbus Laboratory; 108 pp.

This assessment explores the possible environmental impacts determined through field studies at the National Aeronautics and Space Administration (NASA) Lewis Research Center near Sandusky, Ohio. A micrometeorological field program monitored changes in the downwind wake of a 100-kW U.S. Department of Energy (DOE)/NASA experimental wind turbine. Measurements of wind speed, temperature, CO<sub>2</sub> concentration, precipitation, and incident solar radiation showed only minor variations for precipitation and wind speed; effects

## Wildlife

The greatest impacts on the environment can be expected from the largest and most concentrated installations of wind turbines called wind power plants. These wind power plants are usually erected on pasture or prairie land with good wind exposure. These areas also tend to be good habitat for birds and ground-dwelling rodents, as well as deer, coyotes, and ranch animals such as cows and sheep. Researchers have been studying the areas around wind power plants to determine the environmental impacts of the turbines.

After more than a decade of wind power plant operation in California, the only discernable negative impact on wildlife involves rare, but fatal interactions between birds of prey and wind turbines. The U.S. Department of Energy (DOE) and the wind power industry are sponsoring research to understand the causes of these incidents and develop mitigation strategies.



Wind power plants are compatible with land uses such as ranching and farming.

were negligible beyond the tower pad, access, and control structures. The wind turbine was not shown to be a high risk to birds.

Predatory Bird Research Group, University of California, Santa Cruz. (May 1995). *A Pilot Golden Eagle Population Project in the Altamont Pass Wind Resource Area, California*. NREL/TP-441-7821. Golden, CO: National Renewable Energy Laboratory.

This report details field studies conducted during 1994 at Altamont Pass. The investigation lays the groundwork for determining if turbine strikes and other wind-energy-related hazards may affect golden eagle populations. The authors studied physical and biotic circumstances that attract golden eagles to the Altamont Pass Wind Resource Area.

*Proceedings of National Avian-Wind Power Planning Meeting, Denver, Colorado, July 20-21, 1994*. (May 1995). NREL/TP-441-7814. Golden, CO: National Renewable Energy Laboratory, 146 pp.

This meeting was convened to focus on research into bird deaths in wind power plants. Participants reviewed the status of wind power in the United States, developed lists of research questions, reviewed past and ongoing avian research at wind plants in the United States and Europe, discussed general design concepts for avian-wind power research, discussed desirable components of an integrated national research program, and identified steps to be taken. The proceedings include a meeting summary, plus more detailed descriptions of the presentations, discussions, and conclusions on each topic.

Whalen, W. (KENETECH). (1994). "Siting Wind Plants and the Avian Issue." *Windpower '94 Conference; May 9-13, 1994; Minneapolis, Minnesota*. Washington, DC: American Wind Energy Association.

This paper chronicles U.S. Windpower's efforts to reduce bird fatalities around wind farms. Measures include capping all exposed terminals on risers and studying bird behavior to understand the causes of other casualties.

Jacobs, M. (Massachusetts Department of Public Utilities). (1994). "Avian Mortality and Windpower in the Northeast." *Windpower '94 Conference; May 9-13, 1994; Minneapolis, Minnesota*. Washington, DC: American Wind Energy Association.

This paper combines a number of methodologies to understand the limited information available about specific windpower sites in the Northeast.

*Proceedings: Avian Interactions with Utility Structures.*

(December 1993). EPRI-TR-103268. Palo Alto, CA:  
Electric Power Research Institute; 428 pp.

This workshop provided understanding and research directions to reduce avian mortality caused by collisions with power lines. Topics include wind turbine effects on avian activity, habitat use, and mortality.

*Wind Turbine Effects on Avian Activity, Habitat Use, and Mortality in Altamont Pass and Solano County Wind Resource Areas, 1989-1991.* (March 1992). Sacramento, CA: California Energy Commission; 145 pp.

Wind power plants and their supporting networks of transmission lines may harm birds by causing changes in migrating or foraging patterns, by reducing bird habitats, and by causing collision or electrocution. The fate of raptors, which are protected by law, is of particular concern. Researchers studied the impact of wind power plants on birds, identified factors contributing to avian deaths, and recommended mitigation measures.

## Acoustics

Like all mechanical systems, including those that generate electricity, wind turbines are not silent when they operate. The sound of the wind moving over the wind turbine blades, called aerodynamic noise, can be heard. In addition, the mechanical components of wind turbines generate sound. Engineers have reduced aerodynamic noise in recent years by design changes such as decreasing the thickness of the trailing edge of the blades and by orienting the blades upwind of the tower. The sound from wind rushing through towers can also be lessened through design changes.

A wind turbine generator may produce noise with both impulsive (thumping) and broadband (swishing) characteristics. The low-frequency impulsive noise tends to be the most annoying because it dominates other sounds and can cause structures such as houses to shake. However, not all types of machines produce this noise. The effects of wind turbine noise on the listener may be modified by factors such as the background noise level, location of the listener (indoors versus outdoors), and the presence of any perceptible house vibrations induced by the noise. Any noise from a wind turbine tends to be masked by the noise of the wind itself, and, of course, the machines do not run when there is no wind.

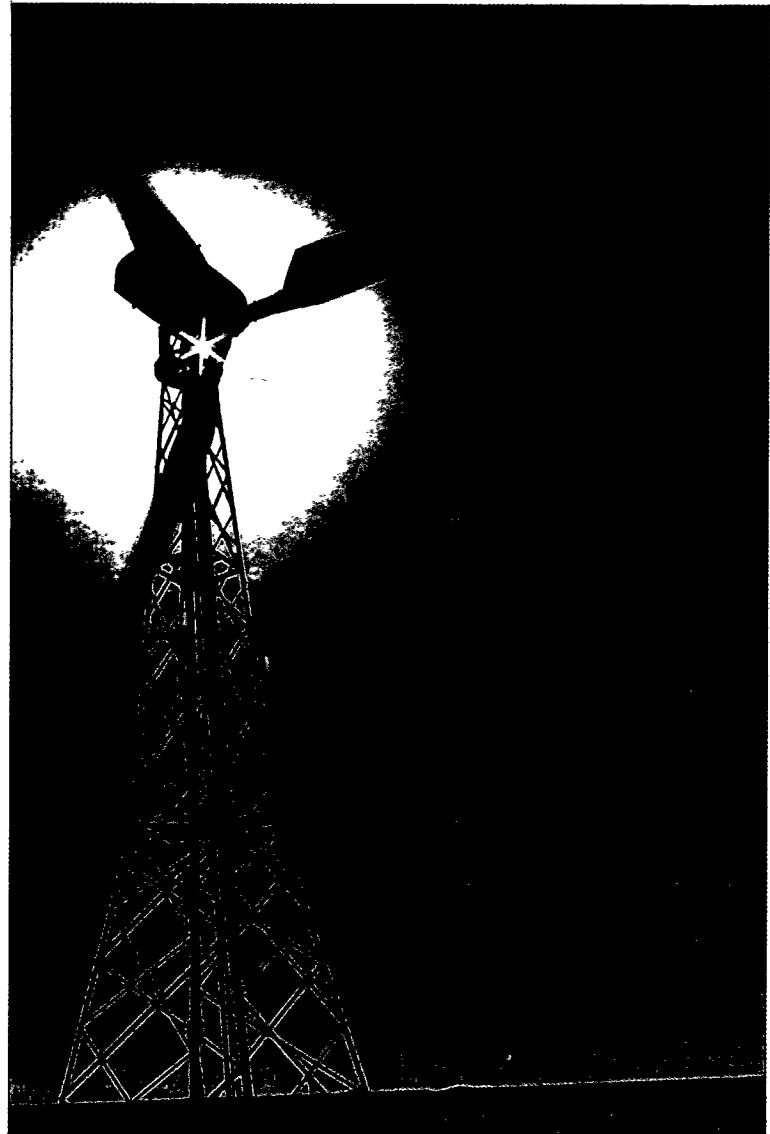
*Acoustic Noise Measurement Techniques for Wind Turbine Generator Systems.* (1994). Draft International Standard: TC-88. Geneva, Switzerland: International Electrotechnical Commission.

This draft international standard addresses procedures for measuring the noise generated by wind turbine generators.

Wolsink, M.P.; Sprengers, M.; Westra, C.A.; Pedersen, T.H.; Keuper, A. (1994). "Annoyance from Wind Turbine Noise on Sixteen Sites in Three Countries." *Proceedings of the European Community Wind Energy Conference, Lubeck-Travemunde, Germany, March 8-12, 1993.* Bedford, United Kingdom: H.S. Stephens & Associates; p. 273.

Hubbard, H.H.; Shepherd, K.P. (June 1991). "Aeroacoustics of Large Wind Turbines." *Journal of the Acoustic Society of America* (89:6); pp. 2495-2508.

This paper reviews the literature on noise generated aerodynamically by large horizontal-axis wind turbines operated for electric power generation. It includes methods for predicting both the discrete frequency rotational noise components and the broadband noise components. Predictions are compared with measurements. Refraction effects that result in the formation of high-frequency shadow zones in the upwind direction and channeling of low frequencies downwind are illustrated. Special topics such as distributed source effects in prediction and the role of building dynamics in perception are also included.



*Procedure for Measurement of Acoustic Emissions from Wind Turbine Generator Systems. Vol. I: First Tier. (1989). AWEA Standard: AWEA 2.1-1989. Washington, DC: American Wind Energy Association; 35 pp.*

This document presents procedures for measuring and reporting sound-pressure levels from wind turbines.

*Recommended Practices for Wind Turbine Testing; 4. Acoustics. Measurement of Noise Emission from Wind Energy Conversion Systems (WECS); 2. Edition 1988. (1988). Edited by S. Ljunggren and A. Gustafsson; 23 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development for Wind Energy Conversion Systems.*

This document describes the procedures to be used for the measurement and description of noise emission from wind energy systems.

Kelley, N.D.; McKenna, H.E.; Jacobs, E.W.; Hemphill, R.R.; Birkenheuer, N.J. (January 1988). *The MOD-2 Wind Turbine: Aeroacoustical Noise Sources, Emissions, and Potential Impact.* SERI/TR-217-3036. Golden, CO: Solar Energy Research Institute.

This report details the methods and results of a measurement program at the MOD-2 wind turbine site in Goodnoe Hills, Washington.

Kelley, N.D. (November 1987). *A Proposed Metric for Assessing the Potential of Community Annoyance from Wind Turbine Low-Frequency Noise Emissions.* SERI/TP-217-3261. Golden, CO: Solar Energy Research Institute.

Interior low-frequency noise is difficult to measure but may annoy communities near wind turbines. Researchers developed a method to quantify low-frequency noise suitable for wind turbine noise applications. Researchers electronically simulated the noise and correlated the responses of listeners with descriptors that have been proposed for predicting low-frequency-noise annoyance. Based on this work, a procedure for establishing the potential for annoyance is proposed.

Kelley, N.D. (February 1985). *Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact, and Control.* SERI/TR-635-1166. Golden, CO: Solar Energy Research Institute.

This report summarizes the extensive research conducted to establish the causes, effects, and mitigation approaches to acoustic disturbances associated with the wind turbine near Boone, North Carolina.

Hemphill, R.R. (May 1983). *An Acoustic Ranging Technique With Application Assessment of Low-Frequency Acoustic Noise of Wind Turbines.* SERI/TP-215-1954. Golden, CO: Solar Energy Research Institute.

This report describes a technique and its application to the type of low-frequency noise generated by megawatt-sized wind turbines.

Stephens, D.G.; Shepherd, K.P.; Hubbard, H.H.; Grosveld, F.W. (March 1982). *Guide to the Evaluation of Human Exposure to Noise from Large Wind Turbines*. NASA/TM-83288. Hampton, VA: NASA Langley Research Center; 70 pp.

This document provides guidance for evaluating human exposure to wind turbine noise. It includes consideration of source characteristics, propagation to the listener's location, and exposure of the listener to the noise.

## Electromagnetic Interference

In the past, older horizontal-axis wind turbines with metal blade components caused television interference in predictable areas near the turbine. The rotating metal components of older wind turbines reflected broadcast television signals. Cable signals and satellite reception are unaffected. Interference from modern turbines is less likely because many of the components that were formerly made from metal are now made from composite materials, such as fiberglass and plastics, that do not reflect television signals as much as metal does. However, most modern machines have lightning protection on the blade surfaces, which increases electromagnetic interference.

*Recommended Practices for Wind Turbine Testing and Evaluation; 5. Electromagnetic-Interference; Preparatory Information; Issue 1, February 1986.* (1986). Edited by R.J. Chignell; 16 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

Sengupta, D.L.; Senior, T.B.; Ferris, J.E. (University of Michigan). (1983). *Large Wind Turbine Siting Handbook: Television Interference Assessment, Final Subcontract Report*. SERI/STR-215-1879. Golden, CO: Solar Energy Research Institute.

Sengupta, D.L.; Senior, T.B.; Ferris, J.E. (University of Michigan). (November 1983). *Television Interference Measurements Near the Mod-2 WT Array at Goodnoe Hills, Washington: A Subcontract Report*. SERI/STR-211-2086. Golden, CO: Solar Energy Research Institute; 64 pp.

Sengupta, D.L.; Senior, T.B.; Ferris, J.E. (January 1983). *Measurements of Television Interference Caused by a Vertical Axis Wind Machine*. SERI/STR-215-1881. Golden, CO: Solar Energy Research Institute; 90 pp.

Sengupta, D.L.; Senior, T.B.; Ferris, J.E. (January 1983). *Study of Television Interference by Small Wind Turbines: Final Subcontract Report*. SERI/STR-215-1881. Golden, CO: Solar Energy Research Institute; 47 pp.

Television signal interference by wind turbines rated at about 5 kW was studied using scale models in conjunction with a microwave television system inside an anechoic chamber. Results are extrapolated to give the interference effects of the full-scale machine.

Senior, T.B.; Sengupta, D.L.; Ferris, J.E. (February 1977). *TV and FM Interference by Windmills*. EOE/TIC-11348. Washington, DC: Energy Research and Development Administration.

# Chapter 7

## Institutional Issues

### Legal and Regulatory Issues

Although wind-electric generation is one of the most cost-effective options in regions where there is a good wind resource, many utilities and regulators have not had direct experience with wind technology. They may be unfamiliar with issues associated with wind energy use such as calculating the costs and benefits and determining how wind generation will be integrated into the utility system.

Developers must address legal and institutional issues related to large-scale wind energy development. Land-use policies, environmental regulations, and zoning laws must be considered. New regulations may be necessary to guarantee access to the wind or to protect "wind rights."

In addition to conforming to regulations designed for general construction and energy projects, wind project developers must consider federal legislation designed to promote and regulate development of alternative energy. A major piece of legislation, the Public Utility Regulatory Policies Act (PURPA), became federal law as part of the National Energy Act in 1978 (16 U.S.C. 2601 *et seq.*). To encourage small power production, the law mandates that electric utilities purchase from and sell to cogeneration and small power-producing facilities. The law exempts these small facilities or independent producers from certain regulations.

Increasing generation capacity is still a priority for many lawmakers. Although the tax shelter provisions that financed many of California's wind power plants during the 1980s no longer apply, production tax credits and accelerated depreciation rules can benefit wind developments. The National Energy Policy Act of 1992 provides a credit against income of 1.5 cents per kilowatt hour (kWh). This tax law applies to energy sold during the first 10 years of a project built after 1993 and before July 1, 1999. Accelerated depreciation allowed under the tax code can work to make viable wind power plant developments even more cost effective.

In addition, several states (see the second reference in this section) offer reductions in sales taxes, property taxes, or other incentives to encourage wind energy development. To encourage job creation, municipalities may offer incentives to manufacturers or developers who set up new operations in their jurisdiction.

*Renewing Our Energy Future.* (September 1995). OTA-ETI-614. U.S. Congress Office of Technology Assessment. Washington, DC: Government Printing Office.

*Wind Energy in the U.S.: A State By State Survey.* (current). Washington, DC: American Wind Energy Association; 183 pp.

This survey outlines government and utility programs available for wind energy development throughout the United States. It is written as a tool for state regulators, energy offices, utility representatives, wind energy developers, and prospective owners of individual wind turbines.

*Wind Energy Regulators Handbook.* (1994). Washington, DC: American Wind Energy Association.

This three-ring binder contains current information about the state of wind energy including cost and performance information, environmental issues, economic development impacts of wind projects, and utility regulatory issues.

Ing, E.T.C. (July 1993). "Making Sense of the Federal Tax Code: Incentives for Windfarm Development." *Windpower '93 Conference; July 12-16, 1993; San Francisco, CA;* Washington, DC: American Wind Energy Association; pp. 40-46.

This paper outlines the financial effect of the production credit for wind-generated electricity and the accelerated depreciation treatment for wind equipment; discusses the chief issues that developers and investors must face in structuring a wind farm deal; and describes the Internal Revenue Service procedure for obtaining an advance ruling on a project's tax results that investors can rely on.

Hamrin, J.; Rader, N. (1993). *Investing in the Future: A Regulator's Guide to Renewables.* Washington, DC: National Association of Regulatory Utility Commissioners; 322 pp.

This report, commissioned by the National Association of Regulatory Utility Commissioners (NARUC), assesses current regulatory trends and developments and the degree to which they hinder or enhance opportunities for renewables. It identifies key barriers and opportunities for greater consideration and selection of renewable energy technologies in the resource planning and acquisition process.



*Removing Barriers to Wind Energy: Directions for State Regulatory Action.* (1993). Washington, DC: American Wind Energy Association; 16 pp.

This pamphlet is a condensed version of the full report referenced above.

Oberg, K.W. (ESI Energy, Inc.). (1992). "Impact of Production Incentives on Financing Wind Energy Projects." *Windpower '92 Conference; October 19-23, 1992; Seattle, Washington.* Washington, DC: American Wind Energy Association; pp. 167-172.

This paper presents a case study calculation of the impacts of the 1992 Comprehensive National Energy Policy Act tax credit. The production credit against income tax liability is 1.5 cents per kWh of energy produced during the first 10 years after the facility is placed in service. The benefits and restrictions of this incentive are discussed.

Bain, D. (Oregon State Department of Energy); Bloomquist, R.G. (Washington State Energy Office). (December 1992). *Wind/Solar: A Regulatory Guide to Leasing, Permitting, and Licensing in Idaho, Montana, Oregon, and Washington.* DOE/BP-2015. Bonneville Power Administration. Washington, DC: U.S. Department of Energy; 177 pp. (NTIS no. DE93012372).

This handbook introduces the reader to the regulations and institutions that affect the development of physical facilities in the Pacific Northwest.

*PURPA Handbook.* (1992). Washington, DC: American Wind Energy Association; 14 pp.

This summary of the Public Utility Regulatory Policies Act of 1978 (PURPA) emphasizes the value of PURPA to the U.S. electric utility system. It is an easy reference to the legislation.

National Association of Regulatory Utility Commissioners. (April 1991). *Renewable Energy and Utility Regulation.* DOE/CE/28301-T6. Washington DC: U.S. Department of Energy; 48 pp. (NTIS no. DE92013626).

This report summarizes the results of a review of renewable energy technologies to evaluate their potential and identify key policy lessons learned so far in the deployment of these technologies.

Lornell, R.; Schaller, D.A. (January 1982). *Small Power Production and Wind Energy: Regulatory Actions Under PURPA.* SERI/SP-635-794. Golden, CO: Solar Energy Research Institute; 64 pp.

This report provides electric utilities and their regulatory authorities with a clear perspective of Section 201 and 210 rules under PURPA as they may affect decisions on the integration of small wind energy systems into electric distribution networks. Key issues of wind energy development affected by these rules include interconnection, capacity displacement, and power purchase rates. The report includes a summary of selected utility

and state commission decisions, an overview of wind energy conversion systems, and a section-by-section discussion of the federal rules.

Dodge, D.M.; Lawless-Butterfield, C. (May 1982). *Small Wind Systems Zoning Issues and Approaches*. RFP-3386. Golden, CO: Rocky Flats Wind Energy Research Center; 60 pp. (NTIS no. DE83007195).

This report discusses the zoning requirements for siting wind turbines as well as common safety and environmental issues. The appendix includes an annotated series of approaches to zoning issues taken from ordinances proposed or enacted in various localities throughout the United States.

Phillips, P.D. (May/June 1979). "NEPA and Alternative Energy: Wind as a Case Study." *Solar Law Reporter* (1:1); pp. 29-54. Golden, CO: Solar Energy Research Institute.

The National Environmental Policy Act (NEPA) of 1969, which requires an environmental impact statement, is a key part of the legal system of environmental protection. Basic legal requirements of this statute are identified and a methodology given for determining when it applies to an alternative energy project. Wind energy serves as a case study. Two wind energy conversion system scenarios are examined—one involving a single 1.5-megawatt wind machine and the other examining the impact of a wind power plant.

## Safety Issues

The construction of wind plants requires continued attention to safety issues. Safety analysis involves determining known risks and establishing reasonable protections. Hazards are posed during the installation, operation, repair, and maintenance of wind machines. Most of these hazards have been encountered and analyzed in other industries, and the lessons learned there are directly transferable to the wind industry.

The wind industry has developed consensus standards and recommended practices specific to the technology. The safety procedures outlined by these standards are only binding if a regulatory or oversight agency—such as a utility or building department—adopts and enforces them. In addition to these consensus standards on safety, the industry is working to add sections to existing codes such as the National Electrical Code.

Certification testing of wind turbines can help reassure consumers and workers about safety and reliability. Several wind turbine manufacturers and their component suppliers are submitting their products to Underwriters Laboratories for testing. Work is also under way at the National Wind Technology Center to develop a U.S. wind turbine certification testing program that will allow U.S. manufacturers to meet certification requirements of some foreign markets.

*Safety of Wind Turbine Generator Systems*. (1994). Draft International Standard: TC-88. Geneva, Switzerland: International Electrotechnical Commission.

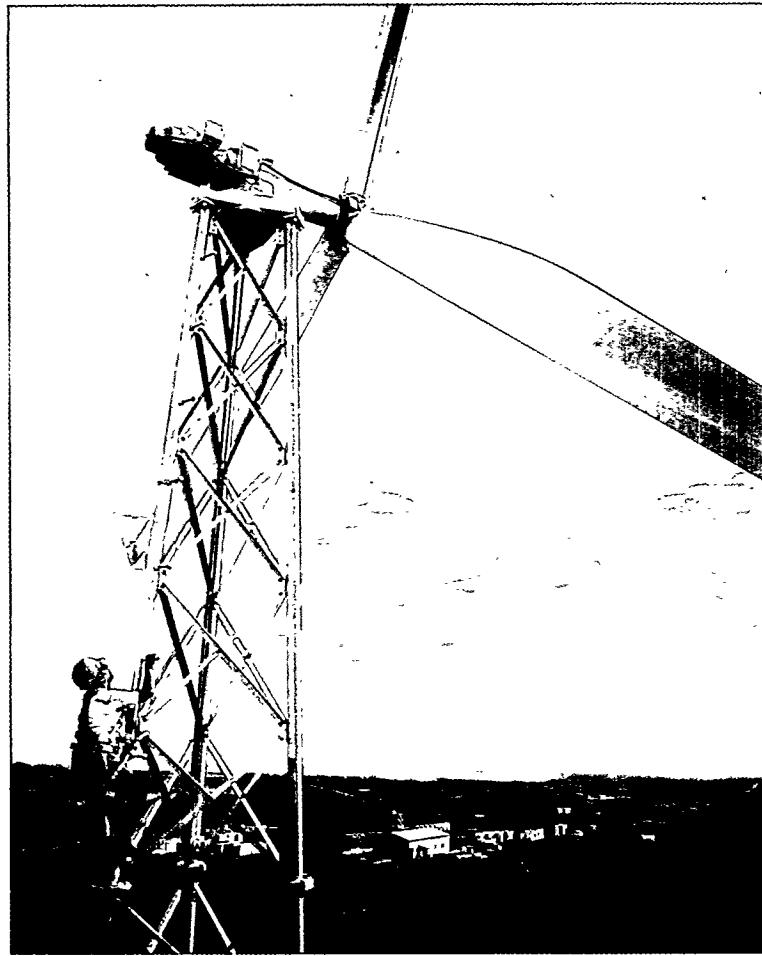
This draft international standard addresses safe practices for the design, installation, and operation of wind turbine generators.

*Recommended Practice for the Siting of Wind Energy Conversion Systems*. (1993). AWEA Standard: AWEA 8.2-1993. Washington, DC: American Wind Energy Association; 24 pp.

This document provides guidelines for proper siting programs including large-scale land assessments and site-specific applications. The standard addresses siting topics such as meteorological measurements at candidate sites, instrumentation, and wind-flow modeling.

*National Electrical Code Handbook*. (1993). NFPA No. 70HB93. Quincy, Massachusetts: National Fire Protection Association. (ISBN 0-87765-384-4).

This reference volume of the National Electrical Code addresses safe practices recommended by the National Fire Protection Association. It contains safe practices relevant to the installation and operation of wind turbine generators.



*The safety issues posed by wind power plant construction, operation, and maintenance are similar to those for other utility operations.*

## Standards and Recommended Practices

As the industry trade association, the American Wind Energy Association (AWEA) has been developing consensus standards and recommended practices for wind systems since the early 1980s. Under a cooperative agreement with the U.S. Department of Energy (DOE), each set of standards approved by AWEA's membership is sent to the American Society for Testing and Materials (ASTM). After ASTM approval, these standards and recommended practices will eventually become national standards. In conjunction with the International Electrotechnical Commission and AWEA, DOE is also supporting the development of international standards.

The designation "AWEA Standard" implies a consensus of those substantially concerned with its scope and provisions. An AWEA Standard is intended as a guide to aid the manufacturer, the user, and the general public. The existence of an AWEA Standard does not in any respect preclude anyone from manufacturing, marketing,

*Occupational Safety and Health Standards for General Industry.* (1989). Chicago, Illinois: Commerce Clearing House, Inc.

This reference volume describes industrial safety and health standards. It contains safe practices relevant to the installation and operation and maintenance of wind turbines.

*Recommended Practice for the Installation of Wind Energy Conversion Systems.* (1989). AWEA Standard: AWEA 6.1-1989. Washington, DC: American Wind Energy Association.

This standard developed by a committee of the American Wind Energy Association specifically addresses procedures for installing wind energy systems.

Kurtz, E.B.; Shoemaker, T.M. (1986). *The Lineman's and Cableman's Handbook, Seventh Edition.* New York, NY: McGraw-Hill Book Company. (ISBN 0-07 035686-6).

This reference volume addresses safe practices for climbing and working with electrical lines and equipment. It contains information relevant to the installation, operation, and maintenance of wind turbine generators.

Bankaitis, H. (1981). *Lightning Accommodation Systems for Wind Turbine Generator Safety.* NASA TM-82601. Cleveland, OH: NASA Lewis Research Center; 13 pp.

In support of the wind turbine safety program, several candidate methods of lightning accommodation for each blade were designed, analyzed, and tested by submitting sample blade sections to simulated lightning strikes. This activity was directed at defining design and procedural constraints, requirements for safety devices and warning methods, special procedures, protective equipment, and personnel training.

### Issued by the American Wind Energy Association:

*Recommended Practice for the Siting of Wind Energy Conversion Systems.* (1993). AWEA Standard: AWEA 8.2-1993. Washington, DC: American Wind Energy Association; 24 pp.

This document provides guidelines for proper siting programs, including large-scale land assessments and site-specific applications. The standard addresses siting topics such as meteorological measurements at candidate sites, instrumentation, and wind-flow modeling.

*Wind/Diesel Systems Architecture Guidebook.* (1991). AWEA Standard: AWEA 10.1-1991. Washington, DC: American Wind Energy Association; 41 pp.

This publication consists of six sections: introduction, components of wind/diesel systems,

purchasing, or using products, processes, or procedures not conforming to the standard. AWEA Standards are subject to periodic review, and users are cautioned to obtain the latest edition.

For the latest AWEA standards or draft standards documents, contact

AWEA Standards Program  
American Wind Energy Association  
122 C Street, NW, Fourth Floor  
Washington, DC 20001  
(202) 383-2500

The International Energy Agency (IEA) is developing internationally agreed-upon testing and reporting practices for wind energy conversion systems. DOE represents the United States in IEA. Recommended practices approved or in draft form are listed here. Although the standards-making process takes years, new documents are issued each year.

For the latest international standards or draft documents, contact

U.S. Department of Energy  
Wind/Hydro/Ocean Division, EE-121  
1000 Independence Avenue, SW  
Washington, DC 20585

The American Society of Mechanical Engineers publishes performance test codes for wind turbines. The codes provide standard instructions for conducting tests and are based on the use of accurate instruments and the best analytical and measurement methods.

For the latest documents, contact

American Society of Mechanical Engineers  
United Engineering Center  
345 East 47th Street  
New York, NY 10017  
(800) 843-2763

system architectures, glossary of terms, bibliography, and references.

*Procedure for Measurement of Acoustic Emissions from Wind Turbine Generator Systems. Vol. I: First Tier.* (1989). AWEA Standard: AWEA 2.1-1989. Washington, DC: American Wind Energy Association; 35 pp.

*Recommended Practice for the Installation of Wind Energy Conversion Systems.* (1989). AWEA Standard: AWEA 6.1-1989. Washington, DC: American Wind Energy Association; 48 pp.

*Standard Performance Testing of Wind Energy Conversion Systems.* (1988). AWEA Standard: AWEA 1.1-1988. Arlington, VA: American Wind Energy Association; 32 pp.

This document describes a standard method of determining and reporting primary performance characteristics. It includes definitions, units of measurement, field test procedures used to determine power production performance and noise levels, procedures for deriving performance parameters, and a proposed test report to be used as part of certification.

*Design Criteria Recommended Practices: Wind Energy Conversion Systems.* (1988). AWEA Standard: AWEA 3.1-1988. Arlington, VA: American Wind Energy Association; 25 pp.

This document describes the criteria used to design wind energy conversion systems. It includes general design criteria, system design considerations, component design criteria, and mechanical, structural, and electrical attachment conditions.

*Standard Procedures for Meteorological Measurements at a Potential Wind Turbine Site.* (1986). AWEA Standard: AWEA 8.1-1986. Alexandria, VA: American Wind Energy Association; 18 pp.

This document provides procedures and methods for obtaining meteorological measurements. It presents standards for meteorological measurement systems as well as the installation, operation, and calibration of equipment. Appendices contain guidelines for sampling strategies, data processing, and site evaluation.

*Wind Energy Conversion Systems Terminology.* (1985). AWEA Standard 5.1-1985. Alexandria, VA: American Wind Energy Association; 11 pp.

Issued by the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems:

*Recommended Practices for Wind Turbine Testing; 4. Acoustics. Measurement of Noise Emission from Wind Energy Conversion Systems (WECS); Third Edition, 1994.* (1994). Edited by S. Ljunggren and A. Gustafsson; 23 pp.



Submitted to the Executive Committee of the International Energy Agency Program for Research and Development for Wind Energy Conversion Systems.

*Recommended Practices for Wind Turbine Testing and Evaluation: 8. Glossary of Terms; Second Edition, 1993.* (1993). Edited by G. Elliot; 11 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

*Recommended Practices for Wind Turbine Testing and Evaluation; 5. Electromagnetic-Interference; Preparatory Information; First Edition, February 1986.* (1986). Edited by R.J. Chignell; 16 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

*International Recommended Practices for Wind Energy Conversion Systems Testing: 3. Fatigue Characteristics; Second Edition, 1989.* (1989). Edited by J.M.W. Dekker, E. Jensen, H.H. Ottens, S.E. Thor, and U. Hassan; 19 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

*Recommended Practices for Wind Turbine Testing: 7. Quality of Power. Single Grid-Connected WECS; First Edition 1984.* (1984). Edited by L.J. Ballard and R.H. Sivansborough; 24 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems.

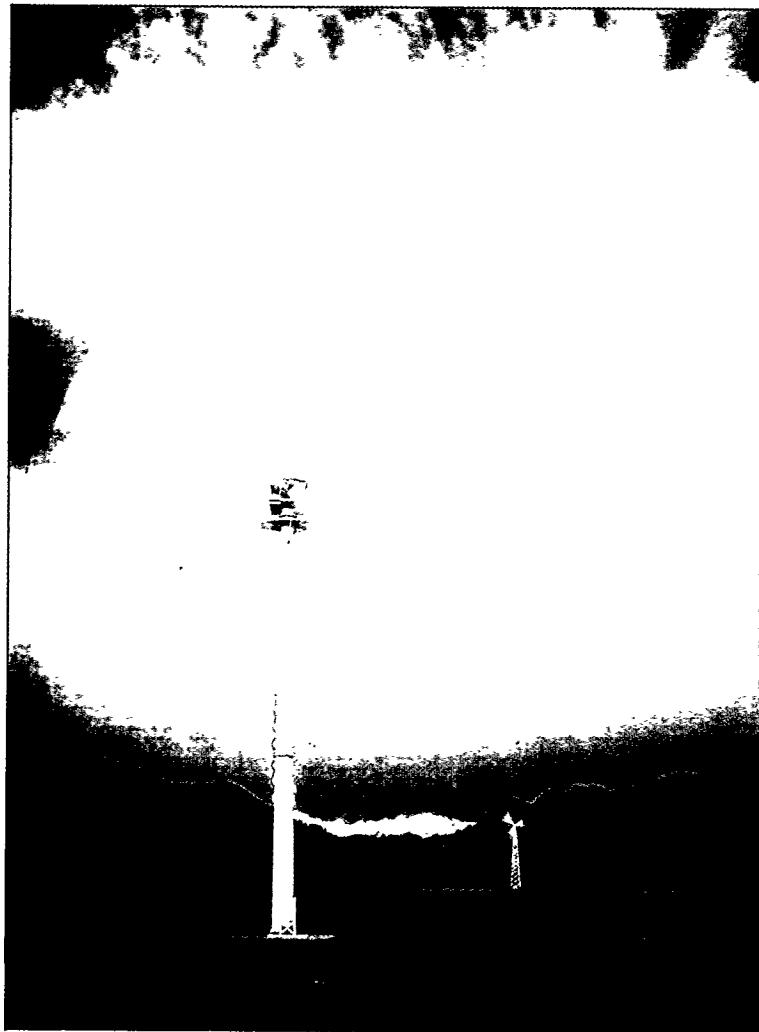
*Recommended Practices for Wind Turbine Testing: 2. Estimation of Cost of Energy from Wind Energy Conversion Systems; Second Edition 1994.* (1994). Edited by J. Nitteberg, A.A. deBoer, and P.B. Simpson; 23 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems. (NTIS no. DE84901132).

*Recommended Practices for Wind Turbine Testing: 1. Power Performance Testing; Second Edition 1990.* (1990). Edited by S. Frandsen, A.R. Trenka, and B. Pedersen; 17 pp. Submitted to the Executive Committee of the International Energy Agency Program for Research and Development on Wind Energy Conversion Systems. (NTIS no. DE84901417).

Issued by the American Society of Mechanical Engineers (ASME) and the American National Standards Institute (ANSI):

*Wind Turbines: Performance Test Codes.* (1989). ASME/ANSI PRC 42-1988. New York, NY: The American Society of Mechanical Engineers; 61 pp.

Issued by the International Electrotechnical Commission:



*Safety of Wind Turbine Generator Systems.* (1994). Draft International Standard: TC-88. Geneva, Switzerland: International Electrotechnical Commission.

*Power Performance Measurement Procedure.* (1994). Draft International Standard: TC-88. Geneva, Switzerland: International Electrotechnical Commission.

*Acoustic Noise Measurement Techniques for Wind Turbine Generator Systems.* (1994). Draft International Standard: TC-88. Geneva, Switzerland: International Electrotechnical Commission.

# Chapter 8

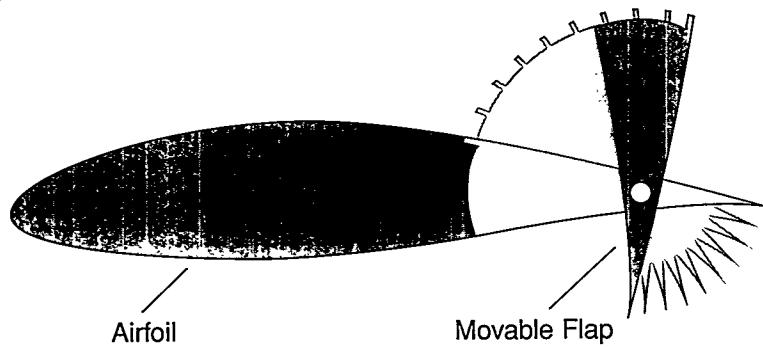
## Wind Energy Systems Development

### Turbine Development Program

The wind turbines in California's power plants make good use of 1970s and 1980s technology. Improving on that technology can lower the cost and improve the reliability of wind turbines. The U.S. Department of Energy (DOE) Turbine Development Program sponsors a range of projects to assist the wind industry to design, develop, and test turbines. The overall goal is to develop turbines for the U.S. utility market capable of producing electricity for 2.5¢ per kilowatt-hour (kWh) by the year 2000, with a good wind resource and favorable financing. The DOE Turbine Development Program assists U.S. industry to develop and integrate innovative technologies into utility-grade wind turbines for the mid-1990s. In addition, projects are funded to help industry develop a new generation of turbines for 2000.

The Turbine Development Program began in 1990 with Conceptual Design Studies. Several companies assessed the state of wind energy technology and identified two types of improvements—those that could be implemented by 1990 and more advanced concepts that could produce the next generation of machines for the market in 2000. As a result of these studies, NREL awarded subcontracts in 1992 to develop prototype turbines that implement improvements to baseline turbines currently running at wind power plants.

In addition to these projects to develop prototype turbines, the DOE Turbine Development Program supports development of cutting-edge technology for key wind turbine components. One key component that can be refined to increase wind turbine productivity is the blades. Since 1984, National Renewable Energy Laboratory (NREL) researchers have developed seven families of thick and thin airfoils specifically designed for wind turbine blades. In 1994, NREL



*The spoiler-flap in this drawing shows promise for regulating power production in high winds and protection against rotor overspeeding.*

Milles, L.S. (Wichita State University). (1995). *Experimental Investigation of Aerodynamic Devices for Wind Turbine Rotational Speed Control*. NREL/TP-441-6913.

Golden, CO: National Renewable Energy Laboratory; 48 pp. The aerodynamic performance of five trailing-edge devices to control overspeed and power modulation was evaluated using a two-dimensional wind tunnel model. The spoiler-flap control was shown to be best suited for turbine braking.

Tangler, J.L.; Somers, D.M. (1995). *NREL Airfoil Families for HAWTS*. NREL/TP-442-7109. Golden, CO: National Renewable Energy Laboratory; 10 pp.

This technical paper describes the NREL airfoil families developed for wind turbine blade applications and the benefits under varying conditions of using these airfoils.

Atlantic Orient Corporation. (1994). *Advanced Wind Turbine Design Studies, Advanced Conceptual Study, Final Report*. NREL/TP-442-4740. Golden, CO: National Renewable Energy Laboratory; 245 pp.

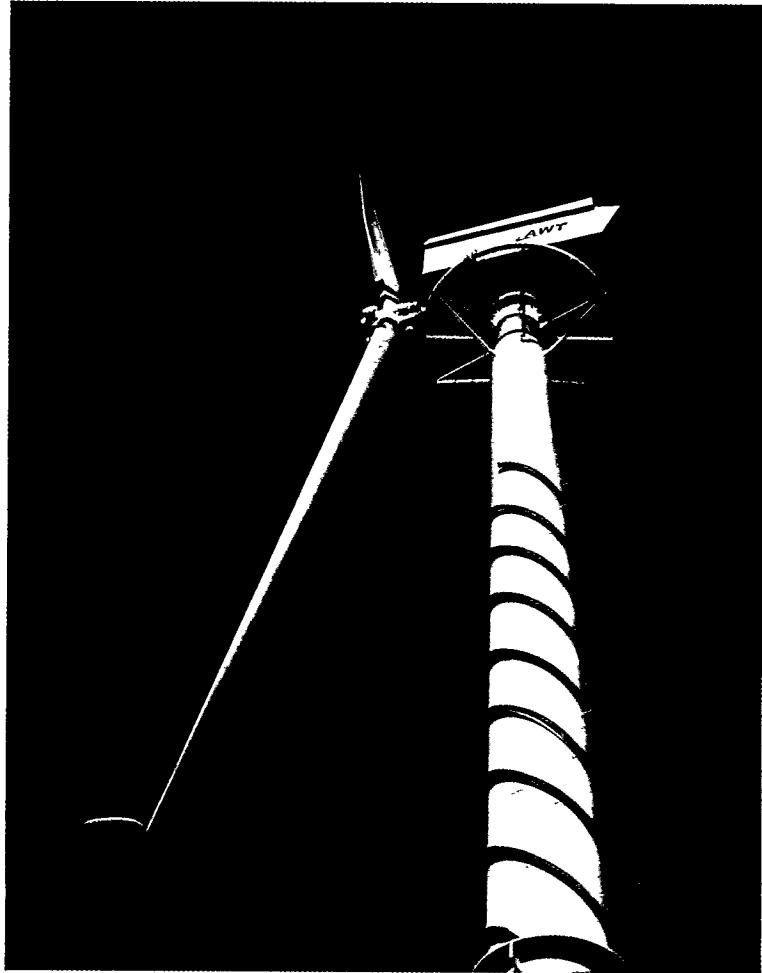
The operating and maintenance history of the EnerTech E44 series commercial wind turbines was evaluated for design improvements. Ten of 15 potential improvements were incorporated into a new design, the AOC 15/50. The report presents the detailed analyses and design conclusions.

Bell, B. (FloWind Corporation). (1994). "FloWind's Advanced EHD-Series Wind Turbine." *CanWEA Conference; October 17-19, 1994; Regina, Saskatchewan, Canada*. Ottawa, Ontario: Canadian Wind Energy Association.

The author describes his company's advanced, utility-grade vertical-axis wind turbine undergoing tests in Tehachapi, California. The EHD (extended height-to-diameter) rotor height and diameter are varied depending on the wind site and the position of the turbine in the array to optimize energy capture.

Hughes, P.S. (Atlantic Orient Corporation). (1994). "Component Testing for the AOC 15-50." *Windpower '94 Conference; May 10-13, 1994; Minneapolis, Minnesota*. Washington, DC: American Wind Energy Association.

This paper describes tests of the advanced components of the AOC turbine, a 15-meter-diameter (49.4-foot-diameter), downwind, passive-yaw, induction generator machine. Chief among



*Advanced Wind Turbines, Incorporated, of Seattle, Washington, developed the AWT-26 with assistance from the U.S. Department of Energy. The AWT-26 improves on the ESI-80 turbine developed in the 1980s.*

designed a new airfoil family for large wind turbines using pitch-controlled blades and variable-speed rotors. The new airfoil family could improve annual energy capture by 8% to 10%. DOE also supports research into blade aerodynamic devices that regulate power production in high winds and provide protection against rotor overspeeding. The device, known as a spoiler-flap, can rotate up or down on the blade to control rotor speed. Wind tunnel tests in 1994 were promising. (See Airfoil Development and Blade Design in Chapter 4 for more references.)

Another key wind turbine component is the generator. DOE is sponsoring work with industry to develop direct-drive generators that eliminate the need for costly gearing and transmissions. In addition, variable-speed generators, which allow the turbine rotor to speed up or slow down with the wind, are being tested. Variable-speed generators promise to extract more energy from the wind during the year. Advanced control systems and power electronics are also being developed to work with these advanced generators. (See Controls, Generators, and Drivetrains in Chapter 4 for more references.)

these components tested are the blades, which use NREL advanced airfoils.

Link, H.; Laxson, A.; Smith, B.; Goldman, P. (1995). *The U.S. Department of Energy Wind Turbine Development Program*. NREL/TP-441-7390. Golden, CO: National Renewable Energy Laboratory; 7 pp.

This paper describes the details of DOE's approach to enhancing the technology and market acceptance of wind turbine generators.

Coleman, C. (Northern Power Systems). (1993). "Northern Power Systems Advanced Wind Turbine Development Program." *Windpower '93 Conference; July 12-16, 1993; San Francisco, CA*. Washington, DC: American Wind Energy Association; pp. 152-154.

This paper describes the 3-year development program to build the North Wind 250 advanced wind turbine to be installed in Palm Springs, California. Under the program, economic and design analyses were conducted.

Swift, A. (University of Texas); Hock, S.M.; Thresher, R.W. (National Renewable Energy Laboratory). (February 1993). "Advanced Wind Turbine Performance and Cost Projections: A Configuration Survey." *Windpower '92 Conference; October 19-23, 1992; Seattle, Washington*. Washington DC: American Wind Energy Association; pp. 431-447 (NTIS no. DE93004336).

This paper examines the projected performance and cost for the next generation of utility-scale wind turbines using a survey of experienced designers and evaluators of wind turbine technology.

Lynette, R. (R. Lynette & Associates, Inc.). (1992). *Advanced Wind Turbine Conceptual Study Final Report*. NREL/TP-441-6924. Golden, CO: National Renewable Energy Laboratory, 336 pp. plus appendices.

The ESI-80 wind turbine was evaluated for design improvements to develop a utility-scale, commercial machine. The report concludes that the best approach to reducing energy costs is to increase production rather than to reduce wind turbine hardware costs. Design changes to increase energy production are detailed for several variations on the baseline turbine.

Rodgers, J. (R. Lynette Associates, Inc.). (1992). "WC-86 Advanced Wind Turbine Development." *Eleventh ASME Wind Energy Symposium; January 1992*. Fairfield, NJ: American Society of Mechanical Engineers; pp. 135-140.

This paper describes the preliminary design work, supported by DOE, to configure a machine to generate electricity economically in large groupings of the turbines. The designers began with the baseline ESI-80 wind turbine to develop a 26.2-meter-diameter (86-foot-diameter) rotor for a machine rated at 275 kilowatts (kW).

These and other advanced components will be integrated into the next generation of wind turbines to be developed by industry with DOE research support and testing assistance.

*Advanced Wind Turbines: Electricity for the 1990s and Beyond.* (April 1992). Available from the National Renewable Energy Laboratory, Golden, CO; 8 pp.

This brochure describes the elements of the advanced wind turbine program and the benefits expected from the effort.



*FloWind Corporation, San Rafael, California, continues development of the 17 EHD vertical-axis wind turbine.*

*New World Power Technology Company, Moretown, Vermont, is developing the North Wind 250 in cooperation with the U.S. Department of Energy. The North Wind 250 improves on the North Wind 100 built in the 1980s.*

*Zond Systems, Incorporated, of Tehachapi, California, applied its experience as a wind power plant operator to design the 500-kilowatt Z-40, which uses NREL airfoils.*

## Development of Small Systems

Small wind turbines have power ratings of less than 100 kW; most are rated below 50 kW. An average U.S. home located in an area with average wind speeds greater than 12 miles per hour could meet most of its electricity needs with a 3- to 5-kW wind turbine.

Although most small machines are designed to produce electricity, they also are used to produce mechanical shaft power, especially for water pumping and thermal energy.

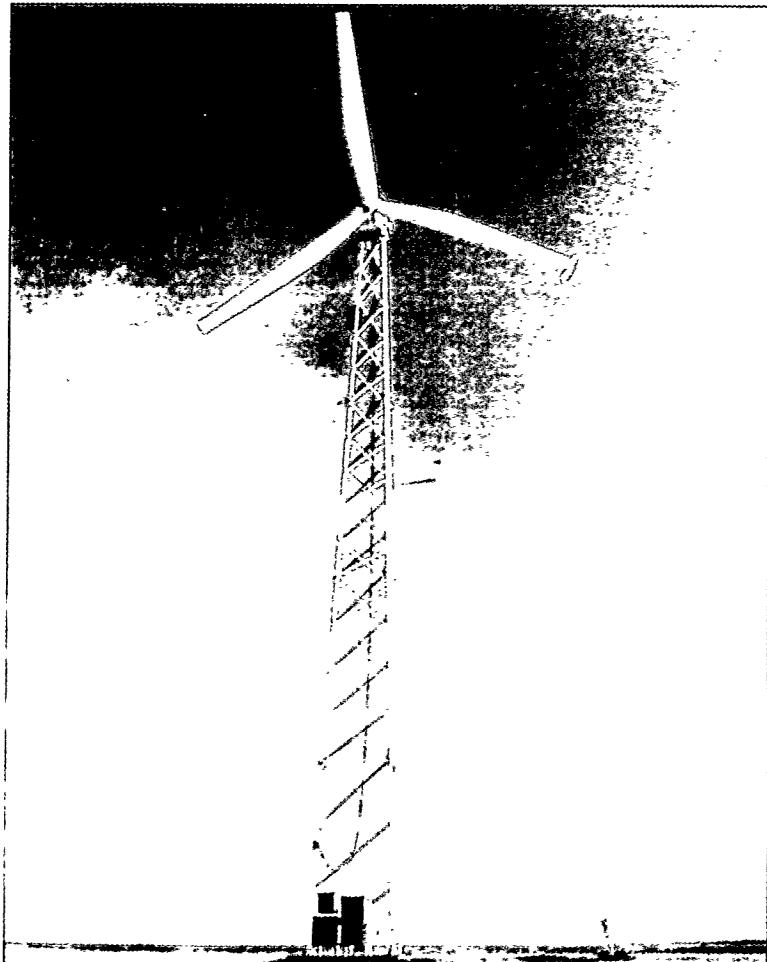
The typical small wind machine has two or three propeller-type blades oriented on a horizontal axis. Some machines operate downwind with the turbine body, or nacelle, and blades acting to control yaw, while others use a tail to point them upwind of their tower. Manufacturers often use strong, lightweight blades constructed of metal, wood, or fiberglass.

Until the late 1970s, most small wind machines were designed for locations with no utility power. They produced direct current (dc) that could be stored in batteries. During the 1970s, a new kind of machine was developed for use in conjunction with utility-delivered

Lynch, J.; Coleman, C.; Mayer, D.J. (North Wind Power Company, Inc.). (January 1983). *North Wind 4-kW Wind System Development, Phase II—Fabrication and Test.* RFP-3516. Golden, CO: Solar Energy Research Institute. (NTIS no. DE83017774).

Lynch, J.; Coleman, C.; Mayer, D.J. (North Wind Power Company, Inc.). (May 1982). *North Wind 4-kW Wind System Development, Phase I—Design and Analysis.* RFP-3424. Golden, CO: Solar Energy Research Institute. (NTIS no. DE83012271).

This volume documents the design and fabrication of a cost-effective wind turbine of 3–6 kW. Design work used scale-model testing of critical components and concepts to develop analytical tools, design guidelines, and experience for implementation on the full-scale prototype. The soft rotor/control system and the electric power generation scheme were designed, tested, and verified.



*Atlantic Orient Corporation of Norwich, Vermont, developed the AOC 15/50 based on the Enertech 44/40 and 44/60 turbines now operating in California wind power plants.*

power. Rather than generating dc, these new wind turbines use either an induction generator or a synchronous inverter to produce alternating current (ac)—the form of electricity found in most utility lines. As a result, when there is ample wind, but little electricity is needed, excess power can be fed into the utility lines. When the machine is not producing enough power for the user's needs, the user can draw power from the utility lines just like any other customer.

The DOE Federal Wind Energy Program supported the development of several small wind machines in the 1970s and 1980s. Some of these designs were perfected for the small machine market. Other companies increased the scale of the designs they were testing and went on to build bigger machines for the utility wind power plant market.

Small wind machines are also used in conjunction with diesel generators and photovoltaics in village power applications. Village power systems function as a small utility supplying electricity for as many as several hundred users through a small grid. Often, because

Zickefoose, C.R. (Enertech Corporation). (December 1982). *Enertech 15-kW Wind System Development; Phase II—Fabrication and Test*. RFP-3515. Golden, CO: Rocky Flats Wind Energy Research Center; 58 pp. (NTIS no. DE83017773).

This report describes the fabrication of the Enertech 15-kW prototype wind system. It includes results of tests conducted at Norwich, Vermont, and the Rocky Flats Wind Energy Research Center. Despite several operational problems, the design concept was demonstrated, and the system met the contract design specifications for power output.

Enertech Corporation. (September 1981). *Enertech 15-kW Wind System Development, Phase I—Design and Analysis Volume II. Technical Report*. RFP-3341. Golden, CO: Solar Energy Research Institute. (NTIS no. DE82018403).

Mayer, D.J.; Norton, J.H., Jr. (North Wind Power Company, Inc.). (June 1982). *North Wind 2-kW High-Reliability Wind System, Phase II—Fabrication and Test*. RFP-3426. Golden, CO: Wind Systems Program, Rockwell International Corporation; 43 pp. (NTIS no. DE83007196).

This report describes the design, fabrication, and testing of a 2-kW wind system capable of unattended operation.

Mayer, D.J.; Norton, J.H., Jr. (North Wind Power Company, Inc.). (July 1981). *North Wind Power Company 2-Kilowatt High Reliability Wind System Phase I—Design and Analysis Technical Report*. RFP-3310. Golden, CO: Solar Energy Research Institute. (NTIS no. DE82015124).

*Proceedings: Small Wind Turbine Systems*. (1981). May 12–14, 1981; Boulder, Colorado. SERI/CP-635-1212. Golden, CO: Solar Energy Research Institute; 355 pp.

Adler, F.M., et al. (Grumman Energy Systems, Inc.). (November 1980). *Grumman WS33 Wind System, Prototype Construction and Testing Phase II Technical Report*. RFP-3288. Golden, CO: Solar Energy Research Institute. (NTIS no. DE82017756).

Adler, F.M., et al. (Grumman Energy Systems, Inc.). (March 1980). *Development of an 8-kW Wind Turbine Generator for Residential Type Applications, Phase I—Design and Analysis Technical Report*. RFP-3007. Golden, CO: Solar Energy Research Institute. (NTIS no. RFP-3007[V.2]).

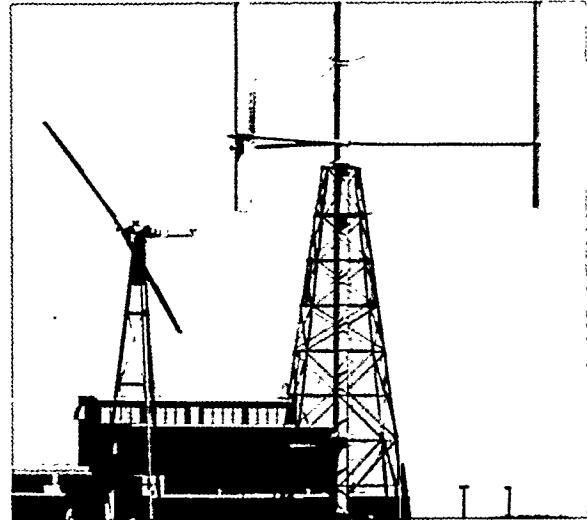
Cheney, M.C., et al. (United Technologies Research Center). (June 1979). *Development of an 8-kW Wind Turbine Generator for Residential Type Applications, Phase I—Design and Analysis*. RFP-3006. Golden, CO: Solar Energy Research Institute. (NTIS no. DOE/DP/03533-T1[V.2]).

of the high cost of diesel fuel, village power systems that operate on diesel generators alone only operate for part of the day. With the addition of wind generators and batteries, electricity can be available 24 hours a day, and diesel fuel and maintenance expenses may fall.

To accelerate the availability of wind technology for hybrid applications, DOE and NREL began a program of collaborative technology development and technical assistance in 1994. As part of this program, DOE supported Atlantic Orient Corporation to test its 50-kW turbine in a wind-diesel hybrid system on Prince Edward Island in eastern Canada. In another project, DOE and NREL supported New World Power Systems in developing a 50-kW village power system that now runs a manufacturing facility in Waitsfield, Vermont. With the U.S. Department of Agriculture, DOE is investigating hybrid power systems that rely on renewable energy resources. The data will be used to validate computer models to evaluate innovative hybrid systems.

Cheney, M.C. (United Technologies Research Center). (February 1982). *UTRC 15-kW Wind System Development, Phase II—Fabrication and Testing*. RFP-3358. Golden, CO: Solar Energy Research Institute. (NTIS no. DE83012274).

Taylor, R.B.; Cheney, M.C. (United Technologies Research Center). (December 1981). *UTRC 15-kW Wind System Development, Phase I—Design and Analysis*. RFP-3331. Golden, CO: Solar Energy Research Institute. (NTIS no. DE82021710).



*These small wind turbines, developed with support from the U.S. Department of Energy, were tested at the Rocky Flats test site in Colorado during the 1970s.*

## Development of Large Horizontal-Axis Systems

A large wind turbine is a machine with a rated capacity of 100 kW or larger. In terms of basic appearance and function, large and small turbines are similar. The greater size and weight of components in large machines demand stronger materials and special design efforts. For example, the rotor blades of very large machines could be longer than the wingspan of a jumbo jet. The latest computer technology is needed to control the angle and rotational speed of these huge blades. Made of steel, laminated wood, fiberglass, or a combination of these materials, the blades must withstand a variety of stresses and loads, including cyclical fatigue loads and random wind loads associated with turbulence. In addition to blade material, some of the technological issues currently under discussion include prediction and reduction of dynamic and fatigue loads, shape of the airfoil, number of machine blades, design of the transmission system, and selection of rigid or flexible towers.

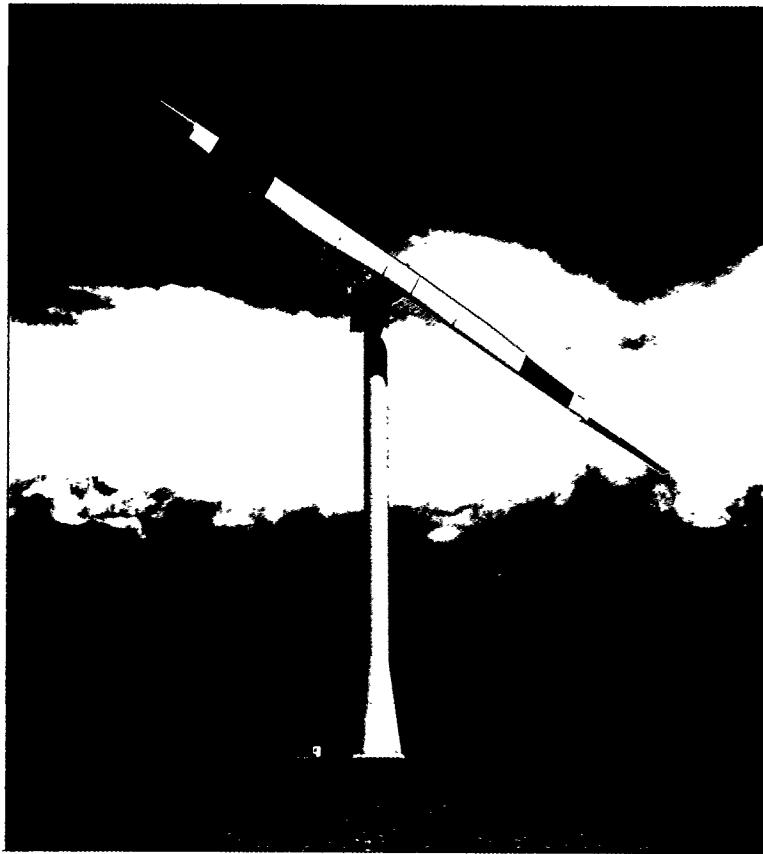
Ancona, D.F.; Spera, D.; *MOD-2 Final Technical Report*. (March 1994). NREL/SP-440-5177; Golden, CO: National Renewable Energy Laboratory; 124 pp. (NTIS no. DE93000014).

This report summarizes the lessons learned in the MOD-2 project, such as the benefits of the teetering hub, the effects of variable-speed operation, and the effect of steel blades on local electromagnetic field/television signals.

Spera, D.A. (Sverdrup Technology, Inc.); Miller, M.W. (Hawaiian Electric Renewable Systems). (1992). "Performance of the 3.2-MW Mod 5B Horizontal-Axis Wind Turbine During 55 Months of Commercial Operation in Hawaii." *Windpower '92 Conference; October 19–23, 1992*.

National research programs in Canada, Denmark, Germany, Italy, Japan, The Netherlands, Spain, Sweden, and the United Kingdom are working on machines that produce power ranging from 200 kW to several megawatts. In the United States, under the DOE-sponsored Turbine Development Program, research and development efforts with wind turbine manufacturers and wind power plant operators are directed towards designing, building, and testing utility-scale machines for bulk power production. Through cooperative research, DOE shares development costs and provides technical expertise and testing at the National Wind Technology Center. Industry then brings the product to market.

Prior to 1988, DOE sponsored development of large wind turbines through the National Aeronautics and Space Administration (NASA) Lewis Research Center in Cleveland, Ohio. Beginning in 1974, NASA worked on a series of progressively more advanced and larger horizontal-axis turbines. The 100-kW MOD-0 research turbine was built in 1975. Four machines of the second design, the 200-kW MOD-0A, were placed at utility sites around the country between 1977 and 1980. The MOD-1 was the first megawatt-scale machine in the series; rated at 2 megawatts (MW), it began operation in 1979. The 2.5-MW MOD-2 was the next machine in the series. Three of these turbines began operating in the Goodnoe Hills area near Goldendale, Washington, in 1981. Testing was successfully completed, and these turbines were decommissioned.



*This turbine was developed under the U.S. Department of Energy Large Wind Turbine Development Program.*

*Seattle, Washington.* Washington, DC: American Wind Energy Association; pp. 231-238.

This paper reports on the long-term performance of a DOE prototype machine installed in 1987 that incorporated a variable-speed, constant-frequency generating system.

*MOD-5B Wind Turbine System Final Report. Vol. I: Executive Summary.* DOE/NASA 0200-3. *Vol. II: Detailed Report.* DOE/NASA 0200-4. *Vol. III: Acceptance Testing.* (March 1988). Cleveland, OH: NASA Lewis Research Center.

This comprehensive technical report details the design, development, and acceptance testing of the 3.2-MW MOD-5B wind turbine now producing power for Hawaiian Electric Renewable Systems on Oahu, Hawaii.

*MOD-5A Wind Turbine Generator Program Design Report. Vol. I: Executive Summary.* DOE/NASA/0153-1; 63 pp. *Vol. II: Conceptual and Preliminary Design, Books 1 and 2.* DOE/NASA/0153-2; 661 pp. *Vol. III: Final Design and System Description, Books 1 and 2.* DOE/NASA/0153-3; 1145 pp. *Vol. IV: Drawings and Specification, Books 1-5.* DOE/NASA/0153-4; 2754 pp. (August 1984). Cleveland, OH: NASA Lewis Research Center.

This technical report details the design, development, and analysis of the 7.3-MW MOD-5A wind turbine from July 1980 to June 1984.

Volume 1 summarizes the MOD-5A program, with information on performance, energy cost, and descriptions of all major subsystems. Volume 2 discusses the conceptual and preliminary design phases. Volume 3 describes the final design of the MOD-5A, and Volume 4 presents drawings and specifications for the final design.

Wilreker, V.F.; Stiller, P.H.; Scott, G.W.; Kruse, V.J.; Smith, R.F. (February 1984). *Wind Turbine Generator Interaction with Conventional Diesel Generators on Block Island, Rhode Island. Vol. I. Executive Summary.* DOE/NASA/0354-1; 47 pp. (NTIS no. DE84015874). *Vol. II. Data Analysis.* DOE/NASA/0354-2; 138 pp. (NTIS no. DE84016961). Cleveland, OH: NASA Lewis Research Center.

A measurement program was conducted on the Block Island Power Company's installation in Rhode Island to assess MOD-0A performance when connected to an isolated diesel utility. This report focuses on fuel displacement (savings), dynamic interaction between the diesel utility and the wind turbine, and effects of three modes of wind turbine reactive power control. Even under severe, winter-time operating conditions, the fuel savings for the utility was significant.

Collins, J.L.; Shaltens, R.K.; Poor, R.H.; Barton, R.S. (April 1982). *Experience and Assessment of the DOE-NASA MOD-1 2000-Kilowatt Wind Turbine Generator at Boone, North Carolina.* DOE/NASA/20366-2. (NTIS no.

The last machine developed in this series was the MOD-5B, a 3.2-MW horizontal-axis turbine with a rotor diameter of 97.5 meters (m). Now operating on the island of Oahu, Hawaii, the MOD-5B incorporates advanced features, including a variable-speed generating system and new aerodynamic systems and controls. Initial test phases, conducted with Hawaiian Electric Industries, were successfully completed in 1987. The machine performed better than expected, exceeding all design requirements. The MOD-5B was sold to Hawaiian Electric Renewable Systems, Inc., and began utility operation in January 1988.

DE82020317). Cleveland, OH: NASA Lewis Research Center; 53 pp.

The design and operation of two early wind machines built under NASA's large-scale horizontal-axis wind turbine program are described in these reports. Information on NASA's first-generation design, the MOD-0A, includes descriptions of the configuration, site, utility interactions, machine performance, and project assessment accompanied by tables and figures. The report on the MOD-1 wind turbine provides information on configuration, performance, utility interaction, environmental impact, and public reaction.

*MOD-2 Wind Turbine System Development; Final Report.* (September 1982). Volume 1, Executive Summary: DOE/NASA-0002-821/1; 35 pp. (NTIS no. DE83015190); Volume 2, Detailed Report: DOE/NASA-0002-821/2; 191 pp. (NTIS no. DE83017707). Cleveland, OH: NASA Lewis Research Center.

These reports document the development of the MOD-2 wind turbine from concept and preliminary design phases through acceptance testing and initial operational evaluation. The MOD-2 design was optimized for commercial production rates which, in multiunit installations, could be integrated into a utility power grid to achieve energy costs of less than \$0.04/kWh (1977 dollars). Information on the project background, system description, testing, initial operation, conclusions, and recommendations is included.

Anderson, T.S.; Bodenschatz, C.A.; Eggers, A.G.; Hughes, P.S.; Lampe, R.F.; Lipner, M.H.; Schornhorst, J.R. (August 1980). *MOD-0A 200-kW Wind Turbine Generator Design and Analysis Report.* DOE/NASA/0163-2. Cleveland, OH: National Aeronautics and Space Administration; 393 pp. (NTIS no. DE81027625).

This report documents the design, analysis, testing, installation, and initial operating performance of the 200-kW MOD-0A wind turbine, which was designed and built near Clayton, New Mexico, by the NASA Lewis Research Center for DOE. Topics include NASA project requirements and approach, system description, system design requirements, design and analysis, system tests and installation, safety considerations, failure modes and effects analysis, data acquisition, and initial operating performance.

Ashwill, T.D. (July 1992). *Measured Data for the Sandia 34-meter Vertical Axis Wind Turbine.* SAND-91-2228. Albuquerque, NM: Sandia National Laboratories; 119 pp. (NTIS no. DE92019807).

This report documents a broad range of test data and comparisons to analytical results for the 34-m

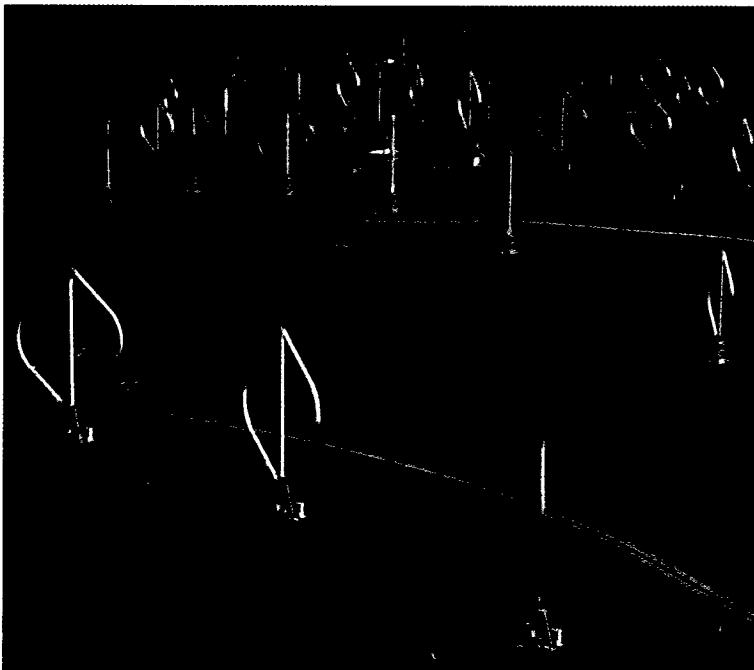
## Development of Vertical-Axis Systems

As with horizontal-axis wind turbines, vertical-axis wind turbines (VAWTs) are propelled by either drag forces or aerodynamic lift forces. Drag-type VAWTs use plates or cups as the drag device. The most common configuration is the Savonius (S-shaped rotor), which provides some lift force but is predominantly a drag device.

These machines are useful for applications requiring relatively high starting torque, such as water pumping, but they have relatively low power output in proportion to rotor size, weight, and cost.

The Darrieus rotor, invented in the 1920s by G.J.M. Darrieus of France, is a lift device characterized by vertical blades that rotate into and out of the wind. Various configurations have been conceived, including those with straight or curved vertical blades. The most common Darrieus configuration has two or three curved blades with airfoil cross sections that are attached to a central tower at the upper and lower ends. This VAWT configuration has been under development since the early 1970s by DOE in the United States through Sandia National Laboratories and in Canada at the National Research Council.

The Darrieus VAWT offers several potential advantages with respect to horizontal-axis designs. VAWTs need not be turned into or out of the wind as the wind direction changes. This eliminates the need for a yawing mechanism with its associated complexities. Because the VAWT drivetrain and generator parts are at ground level, larger components can be used, such as a direct- or linear-drive generator, which eliminates the need for a gearbox and provides the advantages of variable-speed operation. In addition, the VAWT offers easy service access because the drivetrain components and controls are close to the ground at the base of the machine.



*Vertical-axis wind turbine technology developed under the U.S. Department of Energy program was incorporated into these turbines at a wind power plant in the Altamont Pass of California.*

Test Bed. Sandia designed and built this machine to perform research in structural dynamics, aerodynamics, and fatigue.

Masse, B.; Pastorel, H. (1992). *Stress Calculation for the Sandia 34-Meter Wind Turbine Using the Local Circulation Method and Turbulent Wind*. SAND-91-7012. Albuquerque, NM: Sandia National Laboratories.

This report describes a stress estimate procedure and its application to the Sandia/DOE 34-m wind turbine.

Dodd, H.M.; Berg, D.E.; Ashwill, T.D.; Sutherland, H.J.; Schluter, L.L. (March 1992). "The Status of the U.S. VAWT Program." *Proceedings of the Seventh Annual National Conference of the Canadian Wind Energy Association*. Quebec, Canada: Ministry of Energy and Resources; pp. 375-394.

This paper presents an overview of the development of VAWTs in the United States. It concludes with information on the tests currently under way at Sandia's test bed in New Mexico.

Clark, R.N. (1991). "Design and Initial Performance of a 500-kW Vertical-axis Wind Turbine." *Transactions*. 34(3):986-991. New York, NY: American Society of Mechanical Engineers.

This paper present results of performance testing of a large VAWT that incorporates the latest technology from field experiments, wind tunnel models, and computer code simulations. Results show that the turbine's performance was slightly less than predicted but much better than previous designs.

Dodd, H.M. (January 1990). "Performance Predictions for an Intermediate-Sized VAWT Based on Performance of the 34-m VAWT Test Bed." *Proceedings of the 9th ASME Wind Energy Symposium*. Edited by D.E. Berg. SED-Vol. 9. New York, NY: American Society of Mechanical Engineers.

This paper begins with the predicted and measured performance results obtained from the 34-m VAWT test bed and applies these results to a hypothetical commercial machine of the same size.

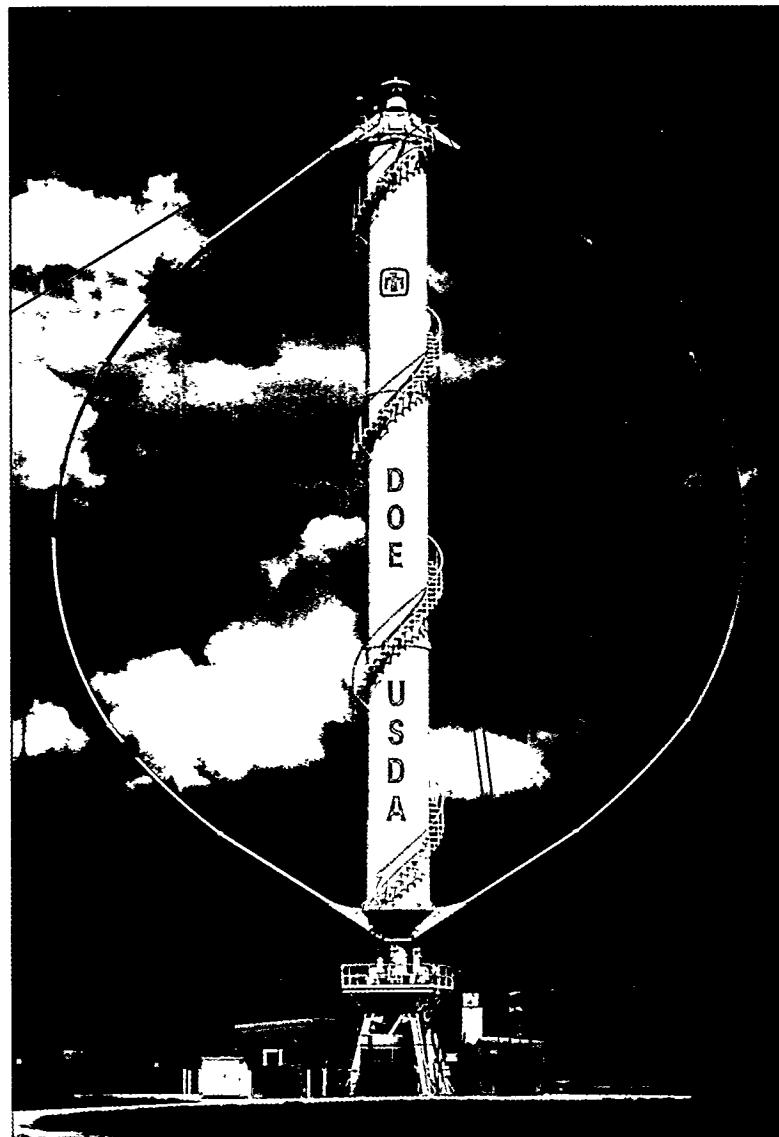
Ashwill, T.D.; Sutherland, H.J.; Veers, P.S. (January 1990). "Fatigue Analysis of the Sandia 34-meter Vertical Axis Wind Turbine." *Proceedings of the 9th ASME Wind Energy Symposium*. Edited by D.E. Berg. SED-Vol. 9. New York, NY: American Society of Mechanical Engineers.

In this report, Miner's Rule is used to estimate the service lifetime of a blade of the Sandia 34-m wind turbine. The results illustrate the sensitivity level of the estimates to wind regimes, constitutive properties, stress states, and operational algorithms.

*Selected Papers on Wind Energy Technology, January 1989-January 1990, Sandia National Laboratories Staff. (1990). SAND90-1615. Albuquerque, NM: Sandia National Laboratories.*

Darrieus blades are not geometrically complex, having no twist or taper. Making these simpler blades using manufacturing processes such as extrusion and pultrusion are possible ways to reduce costs. VAWTs do require a guyed tower, and significant vertical preloading is necessary to achieve tower stability. As a result, the cost of placing VAWTs on higher platforms to take advantage of stronger winds is apt to be quite high. VAWTs do not have a self-starting capability and must be motored up to operating speed.

The Darrieus VAWT has undergone commercial development. More than 500 commercial machines rated between 150 kW and 300 kW are now operating in the California wind power plants of Tehachapi, Altamont Pass, and San Gorgonio.



*The U.S. Department of Energy and Sandia National Laboratories use this U.S. Department of Agriculture Test Site at Bushland, Texas, to test the design of vertical-axis wind turbines.*

This volume is a collection of papers written by staff members of Sandia's Wind Energy Research Division. Many of the 12 papers focus on the DOE/Sandia 34-m test bed, a research VAWT.

Touryan, K.J.; Strickland, J.H.; Berg, D.E. (November/December 1987). "Electric Power from Vertical-Axis Wind Turbines." *Journal of Propulsion and Power*. (3:6); pp. 481-493.

This survey article critically reviews the status of the Darrieus VAWT and its aerodynamic, structural, and systems characteristics. In addition, the article briefly reviews some critical issues involved in making proper estimates for wind resources and their impact on predicting power production from VAWTs, with emphasis on micrositing and array-loss problems. An extensive bibliography is included.

Abramovich, H. (1987). "Vertical Axis Wind Turbines: A Survey and Bibliography." *Wind Engineering*. (11:6); pp. 334-343. Brentwood, England: Multi-Science Publishing Company, LTD.

This article reviews the historical development of the design and aerodynamics of VAWTs.

*Test and Evaluation of a 500-kW Vertical-Axis Wind Turbine: Final Report.* (Southern California Edison Company). (1987). AP-5044. Palo Alto, CA: Electric Power Research Institute; 124 pp.

This report describes test procedures used to determine the operational characteristics of a 500-kW machine.

Berg, D.E. (April 1985). *Structural Design of the Sandia 34-m Vertical Axis Wind Turbine.* SAND-84-1287.

Albuquerque, NM: Sandia National Laboratories; 23 pp.

This report describes the conceptual design phase for a 500-kW, research-oriented, variable-speed VAWT using VAWT-specific blade element sections and step-tapered blades.

Nellums, R.O. (February 1985). *Field Test Report of the Department of Energy's 100-kW Vertical Axis Wind Turbine.* SAND-84-0941. Albuquerque, NM: Sandia National Laboratories; 60 pp.

This report summarizes the field test results of three second-generation, Darrieus-type VAWTs built by DOE and installed in 1980-81. These turbines were heavily instrumented and had accumulated more than 9000 hours of operation at the time the report was written. Aerodynamic, structural, drivetrain, and economic data are presented. The report closes with a review of potential design improvements.

*Design and Fabrication of a Low Cost Darrieus Vertical Axis Wind Turbine System, Phase II.* (March 1983). SAND-82-7113/1-3. Albuquerque, NM: Sandia National Laboratories; 51 pp.

Under a DOE program, Sandia National Laboratories built a 34-m-diameter, 500-kW, variable-speed VAWT test bed on the Texas plains near Amarillo. This research-oriented machine has been used to validate analytical codes and support the development of new capabilities in aerodynamics, structural mechanics, and control systems.

## Innovative Wind Energy Conversion Systems

The unconventional and innovative ideas of yesterday have become the foundation for today's advanced technologies. To support inventors and developers with unusual ideas for producing electricity from the wind, DOE shares the cost of design and experimentation. Under the Advanced and Innovative Wind Energy Concepts Program, DOE solicited, investigated, and evaluated promising methods for wind energy conversion. Managed at the Solar Energy Research Institute (now NREL), the program was completed in 1983.

Innovative ideas are still supported as they are explored by component and turbine developers under other DOE cost-shared programs.

Advanced and innovative concepts for wind energy conversion usually involve some modification or augmentation to conventional horizontal-axis or vertical-axis machines. Under DOE's program, different types of airfoil and rotor designs were explored: sailwings made of cloth, and teetered rotors with stabilizing tailvanes are examples. Flow augmentation concepts ranged from the highly unconventional "tornado tower"—a slotted, upright cylinder equipped with a vertically oriented turbine—to the addition of small airfoil sections to the tips of horizontal-axis machine blades.

Devices investigated under the innovative program also included a number of theoretical concepts proposed to extract energy from drag forces imposed by the wind. For example, the electrofluid dynamic wind-driven generator was designed to extract energy from charged particles blown through an electric field. Oscillating systems would convert the kinetic energy of oscillating cables, vanes, or wings to electric power. Another unusual concept for wind energy conversion, called a humid air device, more closely resembles a heat engine that uses air as the working fluid.

Although intriguing, and even theoretically possible, none of these concepts demonstrated the ability to compete with existing technology in terms of either performance or cost. However, the knowledge gathered during the innovative program is useful to innovators and inventors who wish to become familiar with prior research in nonconventional wind concepts.

Noll, R.B.; Ham, N.D.; Azara, J. (Aerospace Systems, Inc.) (September 1985). *Flex Rotor Wind Energy Innovative System Assessment*. SERI/STR-217-1754. Golden, CO: Solar Energy Research Institute; 118 pp.

This report documents work on a wind system with a flexible rotor conducted under the DOE project to explore innovative approaches to wind turbine design.

Walters, R.E.; Migliore, P.G.; Wolfe, W.P. (West Virginia University) (September 1985). *Innovative Wind Turbines: The Circulation Control Vertical Axis Wind Turbine*. SERI/STR-217-1755. Golden, CO: Solar Energy Research Institute; 81 pp.

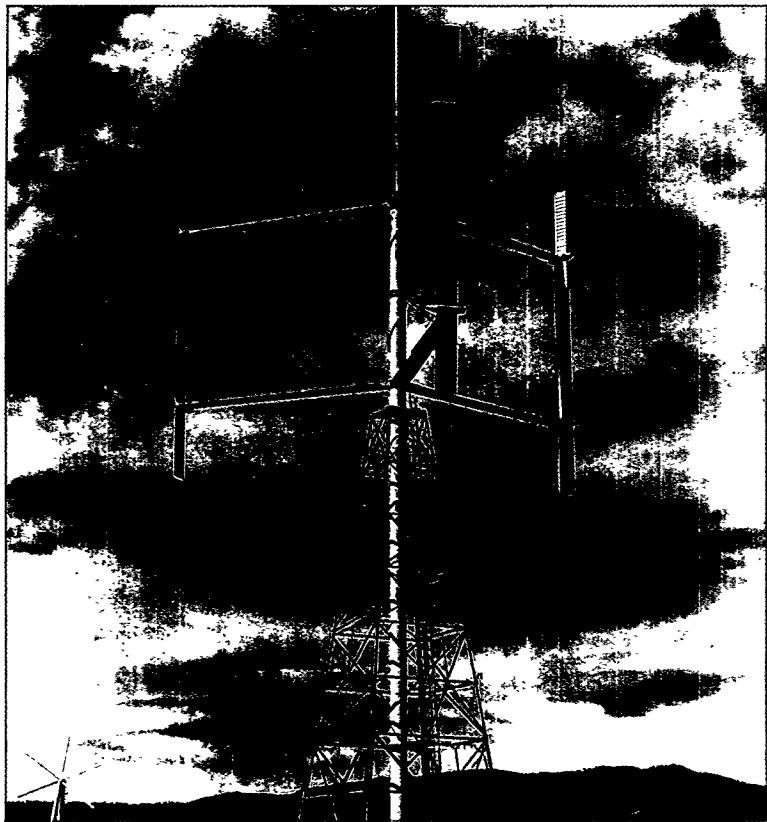
This report documents work conducted under the DOE project to explore innovative approaches to wind turbine design.

Jacobs, E.W.; Lasier, D.D. (January 1984). *A Theoretical Analysis of Solar-Driven Natural Convection Energy Conversion Systems*. SERI/TR-211-1950. Golden, CO: Solar Energy Research Institute; 37 pp.

A theoretical study of the performance of solar-powered natural convection towers. Both heated and cooled towers are analyzed; the latter uses evaporating water as the cooling mechanism. Results show that the ideal conversion efficiencies of both heated and cooled natural convection towers are linear functions of height. The performance of a heated tower in an adiabatic atmosphere ideally approaches the Carnot efficiency limit of about 3.4%/kilometer (km) (1.0%/1000 feet). Including water-pumping requirements, the ideal limit to cooled tower performance is about 2.75%/km (0.85%/1000 feet).

Jacobs, E.W. (1983). "Research Results for the Tornado Wind Energy System: Analysis and Conclusions." *Solar Engineering—1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference; April 18-21, 1983; Orlando, Florida*. New York, NY: American Society of Mechanical Engineers; pp. 606-617.

Numerous experimental and analytical research efforts have investigated the potential of the tornado wind energy device. This paper summarizes and analyzes much of the research to date. A simplified cost analysis incorporating these research results is



*Early research included the investigation of innovative concepts such as the giromill.*

included. Based on these analyses, the tornado device does not show promise for significant improvements of either the performance or the energy cost attainable by conventional wind systems. The prospects for achieving either a system power coefficient above 0.20 or an energy cost of less than \$0.50/kWh (1979 dollars) appear to be poor.

South, P.; Mitchell, R.L. (December 1983). *Oscillating Wind Energy Conversion Systems*. SERI/TR-211-1911. Golden, CO: Solar Energy Research Institute; 25 pp.

Predicted energy production was compared with likely costs of building, installing, and maintaining wind energy conversion systems applying oscillating-element designs.

Lissaman, P.B.S.; Zalay, A.D.; Hibbs, B.H. (AeroVironment, Inc.). (May 1981). *Advanced and Innovative Wind Energy Concept Development: Dynamic Inducer System*. SERI/TR-8085-1-T2. Golden, CO: Solar Energy Research Institute; 77 pp. (NTIS no. DE81024090)

This report documents tests conducted on wind turbines with and without dynamic inducer tip vanes.

*Second Wind Energy Innovative Systems Conference*. (December 1980). SERI/CP-635-1061; Vol I-III. Golden, CO: Solar Energy Research Institute.

The papers presented at this conference represent the wide variety of innovative concepts being explored at the time.

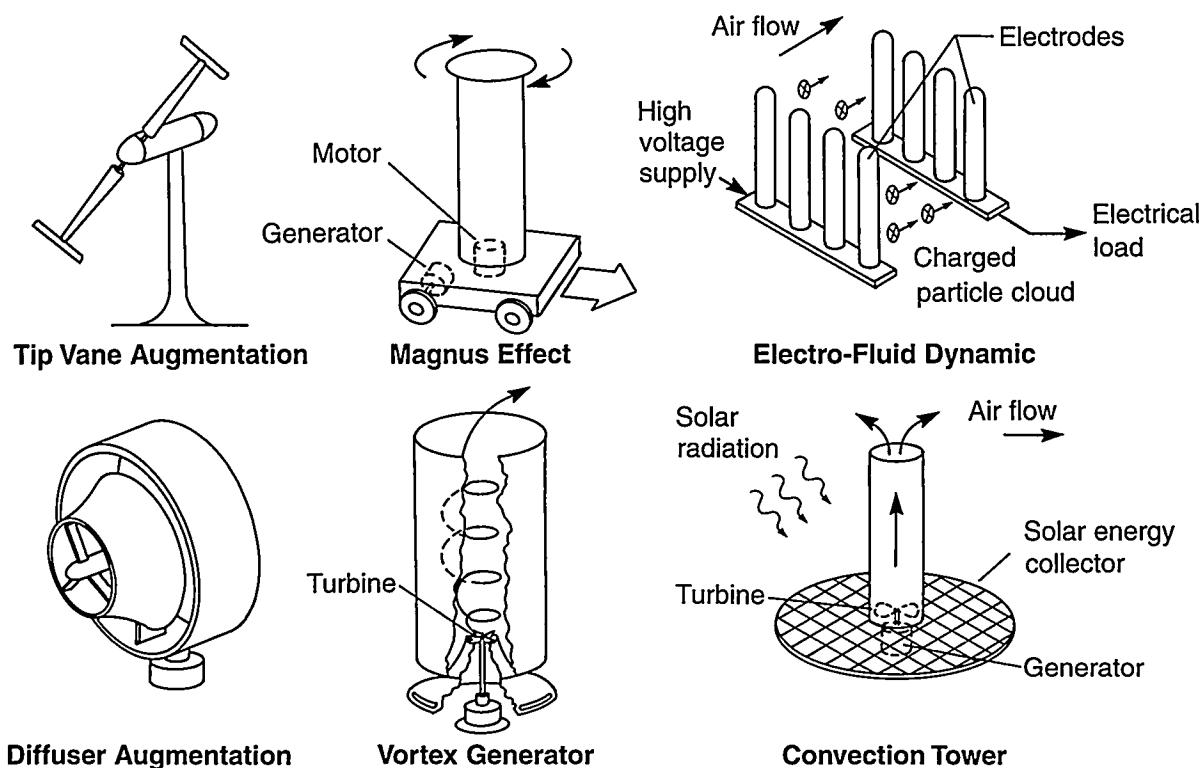
Foreman, K.M.; Gilbert, B.L. (Grumman Aerospace Corporation) (July 1979). *Further Investigations of Diffuser Augmented Wind Turbines*. COO-2616-2 (Pt.1 and Pt.2) (Rev.2). Washington, DC: U.S. Department of Energy.

This study continued design and analysis of the diffuser-augmented wind turbine explored in previous studies.

Tetra Tech, Inc. (December 1979). *Augmented Horizontal Axis Wind Energy Systems Assessment*. SERI/TR-98003-3. Golden, CO: Solar Energy Research Institute; 39 pp.

This report explores three types of augmentation to wind turbines to increase energy capture: the dynamic inducer, in which tip vanes increase flow through the rotor; the diffuser, which reduces pressure behind the rotor to increase flow; and the vortex augmenter, which creates vortices that concentrate kinetic energy. (Two turbines are placed in the vortices to extract the energy.)

## Innovative Wind Turbine Concepts



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## International Developments

The promise of wind energy in meeting part of the growing world energy demand has motivated many foreign governments, utilities, and businesses to cooperate in the development of commercial wind systems. Both developed and developing countries have expanding programs. The latest information on national research and incentive programs is contained in the current-year versions of the annual reports and conference proceedings referenced here.

In addition to development and incentive programs within countries, nations have come together to cooperate on the research and development of wind turbine systems. One such cooperative effort is conducted under the International Energy Agency (IEA). IEA, founded in 1974, is a multinational organization of industrialized, oil-consuming countries that carries out an energy program to build and sustain strong energy economies.

IEA cooperation in wind energy began in 1977 with the Implementing Agreement for Cooperation in the Research and

National Renewable Energy Laboratory (1996). *IEA Wind Energy Annual Report 1995*. NREL/SP-440-20860. Golden, CO: National Renewable Energy Laboratory.

This annual report is one of a series that reviews the annual progress in the Agreement for Cooperation in the Research and Development of Wind Turbine Systems, operated under the auspices of the International Energy Agency. The annual report also presents detailed reviews of research and development activities and incentive programs for each of the member countries, with emphasis on large-scale applications with rated power of 1 MW or more.

Tsipouridis, J.L., ed. (1994.) *EWEC '94: 5th European Wind Energy Association Conference and Exhibition, Conference Proceedings, October 10–14, 1994; Thessaloniki-Macedonia, Greece. Oral Sessions, Vol. I, II. Poster Sessions, Vol. III.*

Development of Wind Turbine Systems (or IEA R&D Wind). The participating nations include Australia, Austria, Canada, Denmark, Finland, Germany, Greece, Italy, Japan, The Netherlands, New Zealand, Norway, Spain, Sweden, the United Kingdom, and the United States.

IEA R&D Wind undertakes collaborative research and development projects, called "Tasks," and exchanges information on the planning and execution of national large-scale wind systems. By 1995, 10 out of 16 tasks initiated had been completed. Each task is managed by one of the contracting nations. For example, DOE completed two tasks. The first was entitled "Evaluation of Wind Models for Wind Energy Siting." The second, entitled "Cooperation in the Development of Large Wind Turbine Systems," established a computerized system to share information. Information is collected and disseminated on the national research, development, and demonstration programs for the design and operation of prototype large wind turbines and wind power plants using large turbines.

The combination of maturing technology and effective market incentives has expanded the use of large wind turbines. Installed capacity in IEA member countries was more than 4200 MW at the end of 1995. The average rated power of all machines installed in 1995 was about 450 kW. Commercial wind turbines of 500-kW rated power (rotor diameter 35–40 m) are marketed. Prototype megawatt-sized wind turbines are operating in nine member countries.

There is a market pull, led by some European utilities, for still larger wind turbines. The leading manufacturers are developing megawatt-sized machines. They have demonstrated the feasibility of designing and operating wind turbines with rotor diameters of as much as 100 m, but the cost of energy from these turbines has been higher than that for smaller machines.



*Europeans have overcome challenging siting constraints to take advantage of favorable wind sites.*

Conference papers focus on technical issues, physical planning, financing, economics, marketing, and environmental issues related to further development of wind energy. Topics include aerodynamics, control systems, operation and performance, national and international programs, fatigue, wind resources, wakes, design and testing of prototype wind/diesel systems, market development, dynamic loads, modeling and electrical aspects, wind pumps, environmental considerations, wind measurements, and implementation of wind power.

OEM Development Corporation. (March 1993). *European Wind Technology*. EPRI-TR-101391. Palo Alto, CA: Electric Power Research Institute; 88 pp.

This report reviews the social, political, technical, and other factors that have shaped the plans of the European countries most active in wind technology.

Garrad, A.D.; Palz, W.; Scheller, S., eds. (1993.) *Proceedings of the European Community Wind Energy Conference; March 8–12, 1993; Lübeck-Travemünde, Germany*. Bedford, England: H.S. Stephens and Associates; 824 pp.

The proceedings report on work in progress and include siting criteria, meteorological data, calculation methods, and wake effects; aerodynamics, aeroelastics, and structural dynamics; design loads, stresses, and reliability; testing and quality control; certification and standards; wind power plant experiences; large wind turbines; wind/diesel turbines; utility applications; and social and environmental costs of wind turbines.

Ancona, D.F.; Pedersen, B.M.; Pershagen, B. (October 1986). "The International Energy Agency Wind Energy Program." *Proceedings of the European Wind Energy Association Conference and Exhibition, Vol. 1; October 7–9, 1986; Rome, Italy*. Edited by W. Palz and E. Sesto. Rome, Italy: A. Raguzzi, Bookshop for Scientific Publications; pp. 129–132.

The paper reviews activities of the IEA wind energy program since 1977. Six major technical tasks have been completed, three tasks are under way, and several new ones are being discussed; six documents on Recommended Practices for Wind Turbine Testing and Evaluation have been produced; and 15 topical expert meetings have been arranged. The sharing of research and information has clearly stimulated national wind energy programs and contributed to wind technology development.

Selzer, H. (1986). *Potential of Wind Energy in the European Community: An Assessment Study*. Solar Energy R&D in the European Community, Series G, Vol. 2. Boston, MA: D. Reidel Publishing Company; 148 pp.

This book provides a technical and macro-economical assessment of European wind energy

potential. To develop reliable data, it was necessary to analyze the wind available in the various parts of Europe, study in detail all candidate sites for possible wind turbine installation, and review the technological cost-effectiveness of wind turbines. The availability of utility networks for grid connection of the wind turbines also was included in the analysis. The study concluded that there is a high wind energy potential in both northern and southern Europe, and that coastal zones were the most promising.

# Chapter 9

## Information Sources

This section includes a number of sources for information on wind energy. Included is information on associations, bibliographies, conferences, databases, directories, the Internet, periodicals, research centers, and software directories and depositories.

### Associations

This section lists membership organizations with an interest in wind energy. Often, these organizations are sponsors of the major publications, conferences, and research activities in their area. The listing is based on information from the *Encyclopedia of Associations* and a survey conducted by the National Renewable Energy Laboratory (NREL). Each entry includes the organization's name, mailing address, chief official, and description. The description might also include information on types of members, purpose, activities, awards, publications, products, and affiliations.

#### U.S. Associations

##### **Alternative Energy Resources Organization (AERO)**

Contact: Al Kurki, Executive Director  
44 North Last Chance Gulch, #9  
Helena, MT 59601  
Phone: (406) 443-7272 / Fax: (406) 442-9120

Founded: 1974. AERO encourages energy efficiency and the transition from conventional to renewable energy sources (including solar, wind, wood, biomass, microhydro, and geothermal energies). AERO promotes renewable energy development, sustainable agriculture, and sustainable economic development through research, public education outreach (community education and organizing), and citizen representation. It also sponsors workshops and seminars and maintains a library and information center. Committees: Agriculture, Economic Development, Education, Sustainable Agriculture, Technical. Publications: *AERO Sun-Times*, quarterly. Also publishes *Get Your Hands on Energy* (Vols. 1-2), *Sustainable Agriculture Resource Book*, energy activity books for children, and curriculum guides for elementary school teachers.

##### **Alternative Sources of Energy (ASE)**

Contact: Donald Marier, Director  
620 Central Avenue North  
Milaca, MN 56353  
Phone: (612) 983-6892 / Fax: (612) 983-6893

Founded: 1971. Seeks to publicize and disseminate information on the practical applications of alternative technologies for the independent power production industry. As a scientific and educational organization, ASE's particular emphasis is on cogeneration, biomass, wind power, hydro power, and photovoltaics. Publications: *Independent Energy* (formerly *ASE Magazine*), monthly. Also publishes an annual *Independent Energy Industry Directory*.

##### **American Society of Mechanical Engineers (ASME), Wind Energy Committee**

American Society of Mechanical Engineers  
United Engineering Center  
345 East 47th Street  
New York, NY 10017  
Phone: (800) 843-2763 / Fax: (201) 882-1717

Founded: 1880. Wind Energy Committee founded 1981. The committee focuses on areas of wind energy that can increase the effective and efficient use of wind power. One of the committee's major efforts is organizing annual wind energy

symposia. Each winter the Wind Energy Symposium is held in conjunction with the ASME Energy-Sources Technology Conference and Exhibition.

**American Solar Energy Society (ASES)**

Contact: Larry Sherwood, Executive Director  
2400 Central Avenue  
Unit B-1  
Boulder, CO 80301  
Phone: (303) 443-3130 / Fax: (303) 443-3212

Founded: 1970. ASES is one of the oldest and largest national sections of the International Solar Energy Society (ISES). Ten topical divisions encourage activity in specific technical disciplines. ASES provides leadership and education in all aspects of solar technology, applications, and research to speed the transition to widespread use of solar energy. The wind energy division includes the areas of meteorology, climatology, aerodynamics, and ocean waves, and the engineering and application of wind power and ocean wave systems. ASES has 29 regional chapters and more than 2000 members. The society maintains a library of 3000 volumes. Publications: *Solar Today*, bimonthly. Affiliated with: International Solar Energy Society (parent). Formerly: The American Section of the International Solar Energy Society until 1982.

**American Wind Energy Association (AWEA)**

Contact: Randall Swisher, Executive Director  
122 C Street, NW, Fourth Floor  
Washington, DC 20001  
Phone: (202) 383-2500 / Fax: (202) 383-2505

Founded: 1974. Seeks to advance the art and science of using energy from the wind. As a nonprofit organization, AWEA's goals include assisting members in the commercial development of their businesses; providing industry representation to the various governmental agencies and other institutions involved in energy-source regulation and use; and disseminating information to the users of wind energy regarding sources of equipment, technical information, and standards. There are three categories of membership: industry (corporations, associations, groups, and individuals), associate (dealers, educational institutions, and nonprofit organizations), and individual. Industry members are eligible to vote. Publications: *Windletter*, monthly; *AWEA Wind Energy Weekly*, weekly; conference proceedings; and special reports. AWEA's West Coast office acts as a liaison with the California wind industry.

**Association of Energy Engineers (AEE)**

Contact: Albert Thumann, Executive Director  
4025 Pleasantdale Road, Suite 420  
Atlanta, GA 30340  
Phone: (404) 447-5083 / Fax: (404) 446-3969

Founded: 1977. AEE promotes the advancement of the profession and contributes to the professional development of members, who are engineers, architects, manufacturers, and other industry professionals with an interest in energy management and cogeneration. It awards scholarships to outstanding students in energy engineering, conducts seminars, and sponsors The Cogeneration Institute, a division of 1400 cogeneration professionals. Committees: Education, Energy Consultants, Energy Engineers in Government, Plant and Building Energy Management. Councils: National Energy Policy. Publications: *Strategic Planning for Energy and the Environment*; *Environmental News*; *Energy Insight*; *Energy Engineering Journal*; *The Cogeneration Journal*.

**Edison Electric Institute (EEI)**

Engineering and Systems Operations Division  
Contact: Thomas R. Kuhn, Vice President  
701 Pennsylvania Avenue, NW  
Washington, DC 20004-2696  
Phone: (202) 508-5000 / Fax: (202) 508-5794

Founded: 1933. EEI is the association of America's investor-owned electric utility companies. It provides the principal forum for electric utility representatives to exchange current information and to establish liaison nationally with customers, various interest groups, regulatory bodies, other national groups, and the federal government. EEI's member utilities service approximately 75% of the electric customers in the United States. As a source of information for and about the electric utility industry, EEI monitors developments in all aspects of energy-related technology. Publications: *Electric Perspectives*, bimonthly; special reports on a wide range of utility topics.

**Electric Power Research Institute (EPRI)**

Contact: Earl Davis, Manager, Wind Power Integration  
P.O. Box 10412  
Palo Alto, CA 94303-0813  
Phone: (415) 855-2000

Founded: 1972. EPRI was founded by the nation's electric utilities to develop and manage a technology program for improving electric power production, distribution, and utilization. EPRI is a nonprofit research institute funded by and operated for the U.S. electric utility industry, which has sponsored extensive research in the application of wind energy to utility power generation. Publications: *EPRI Journal*, eight times per year; technical reports on research projects funded by EPRI.

**Interstate Renewable Energy Council (IREC)**

Contact: Vicki Mastaitis, Chair  
P.O. Box 1156  
Latham, NY 12110-1156  
Phone: (518) 459-2601 / Fax: (518) 459-2601

Founded: 1980. IREC is a consortium of state renewable energy program managers that provides a national forum for developing compatibility, coordination, uniformity, and efficiency among state renewable energy programs. IREC has worked with such issues as Federal Energy Regulatory Commission guidelines, incorporating renewable energy options in utility least-cost planning, codes and standards, and advertising guidelines. An IREC column is included in some issues of *Solar Today*.

**National Center for Appropriate Technology (NCAT)**

Contact: George Turman, Executive Officer  
P.O. Box 3838  
Butte, MT 59702  
Phone: (406) 494-4572 / (800) 428-2525 / Fax: (406) 494-4572

Founded: 1976. NCAT seeks to develop, apply, research, and transfer technologies appropriate to the energy-related needs of individuals, organizations, communities, and low-income individuals. As a contractor to the U.S. Department of Energy and the U.S. Department of Agriculture, NCAT conducts research in the areas of renewable energy sources, resource conservation, reuse, and recovery, housing and community facilities, integrated community development, and policy development and analysis. The center publishes and disseminates information and provides training and technical assistance for appropriate technology projects. It also maintains a library of 4000 volumes and 200 periodicals and publishes bibliographies, monographs, consumer booklets, and research reports.

**National Association of Regulatory Utility Commissioners (NARUC)**

Contact: Paul Rodgers, Administrative Director  
1102 Interstate Commerce Commission Building  
12th Street and Constitution Avenue, NW  
Washington, DC 20044-0864  
Phone: (202) 898-2200 / Fax: (202) 898-2213

Founded: 1899. NARUC serves consumers by improving the quality and effectiveness of public regulation in the United States. As a nonprofit organization, NARUC is composed of government agencies engaged in the regulation of public utilities and carriers. Publications: *The Bulletin*, weekly; *The Annual Proceedings*; *The Annual Report on Utility and Carrier Regulation*.

**National Climatic Data Center (NCDC)**

Contact: Kenneth C. Hadeen, Director  
151 Patton Avenue, Room 120  
Asheville, NC 28801  
Phone: (704) 271-4800 / Fax: (704) 271-4876

Founded: 1951. NCDC is the national collection center and custodian of U.S. weather records. Data are gathered from the National Weather Service, operated by the National Oceanic and Atmospheric Administration, as well as the weather services of the Air Force, the Navy, the Federal Aviation Administration, the Coast Guard, and other cooperative observers on land, at sea, and in the air. The center also uses cloud photography and other data obtained from environmental satellites. NCDC provides centralized data services for the international community. Principal areas of research are climate, including temperature, pressure, precipitation, and wind; meteorology; solar radiation; and other atmospheric phenomena. Publications: *Local Climatological Data*, monthly; *Storm Data*, monthly; *Climatic Data for the World*, monthly; *Comparative Climatic Data*, annually; and the *Historical Climatological Series*. NCDC maintains a library in meteorology.

**Utility Wind Interest Group, Inc. (UWIG)**

Contact: Robert G. Putnam, Jr., Executive Director  
2111 Wilson Boulevard, Suite 323  
Arlington, VA 22201  
Phone: (703) 351-4492 / Fax: (703) 351-4495

Founded: 1989. UWIG is a nonprofit corporation originally established by the Electric Power Research Institute and a number of utilities, with DOE support, to serve as an informal source of wind power information for utilities. UWIG expanded its scope in 1994 to also promote utilities' interests in wind energy at the national level. It serves as a vehicle for government/utility cost-sharing programs, and provides wind energy planning and implementation support to utilities. The UWIG mission is to accelerate the appropriate integration of wind power for utility applications to benefit utilities, their customers, and society.

**Internationally Based Associations**

**Association of Danish Windmill Manufacturers**

Lykkesvej 18  
Herning DK-7400  
Denmark

**British Wind Energy Association (BWEA)**

42 Kingsway  
London WC2B 6RH  
United Kingdom

**Canadian Wind Energy Association (CanWEA)**

3553 31st Street, NW, Suite 100  
Calgary, Alberta  
T2L 2K7  
Canada  
(403) 289-7713

**European Wind Energy Association (EWEA)**

Via Bormida 2  
Rome I-100198  
Italy

**Finnish Wind Energy Association (FinWEA)**

Lotsg. 16A 10

Helsingfors 00160

Finland

**German Wind Energy Association (GWEA)**

Fohrenring 17

Markt Schwaben 8015

Germany

**International Energy Agency (IEA)**

Contact: Helga Steeg, Executive Director

2, Rue Andre Pascal

F-75775 Paris Cedex 16, France

Phone: +33 1 4524 8200 / Fax: +33 1 4524 9988

Founded: 1974. IEA is a multinational organization of 22 industrialized, oil-consuming countries that carry out an international energy program designed to build and sustain strong energy economies. Objectives are to improve energy supply and demand balance; to develop oil-alternative energy sources; to coordinate international oil market information; to maintain emergency oil-sharing system; and to compile statistics. Publications: *IEA Wind Energy Annual Report*, annually; *Wind Energy Newsletter*, semiannually; *Oil Market Report*, monthly; *Energy Policies and Programmes of IEA Countries*, annually; also publishes energy statistics and reviews of coal and other energy sources.

## Bibliographies

This section lists bibliographies that focus on wind energy or contain sections on wind energy. Although these sources list wind energy publications, some of the listings are drawn from computerized databases that are updated regularly. Often the best way to find recent publications is to search these databases or find the most recently published searches from them. Each entry here contains a bibliographic citation and an abstract. The most recent entries are listed first.

*Wind Energy Technology* (current). Current Awareness publication series. U.S. Department of Energy. Available from: Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831.

This publication, issued bimonthly, announces worldwide information on wind turbine concepts and design, including wind resource identification, wind turbine project planning and development, legal/institutional implications of wind energy conversion systems, and environmental aspects of wind turbines. The citations and abstracts come from U.S. Department of Energy (DOE) databases.

*Wind Energy Bibliography*. (1995). NREL/TP-440-6642. Golden, CO: National Renewable Energy Laboratory.

This bibliography lists technical references on wind energy by subject area including potential of wind power; economics of using wind energy; wind energy resource; wind turbine design, development, and testing; applications; environmental issues; institutional issues and standards; and wind energy systems development. The bibliography contains the same references (unannotated) as this *Information Guide*.

*Wind Turbines: Latest Citations from the U.S. Patent Bibliographic File With Exemplary Claims*. (January 1994). PB94-863404/XAB. Springfield, VA: National Technical Information Service.

The bibliography contains citations of selected patents concerning the design and implementation of wind turbines used for thermal and electrical power generation. Pitch-control apparatus, damping mechanisms, and associated control systems are described. Topics also include specific blade and rotor designs. Contains more than 186 citations and includes a subject term index and title list.

*Wind Turbine Design, Development, Construction, and Performance: Latest citations from Fluidex*. (January 1994). PB94-862398/XAB. Springfield, VA: National Technical Information Service.

The bibliography contains citations concerning the design, development, construction, and performance of windmills and associated systems, subsystems, and components. Both aerodynamic and structural performance characteristics

are discussed. Included are references to siting characteristics, power production and windmill efficiency, and specific system descriptions. Contains 250 citations and includes a subject term index and title list.

*Wind Turbines and Generators for Wind Power Plants: Latest citations from the INSPEC (Information Services for the Physics and Engineering Communities Database).* (September 1993). PB93-890416/XAB. Springfield, VA: National Technical Information Service.

The bibliography contains citations concerning the design, development, testing, controlling, and performance characteristics of a variety of wind turbines and generators used in conjunction with wind power plants. Some consideration is given to economic issues, hybrid systems, and power grid integration studies. Contains 250 citations and includes a subject term index and title list.

*Wind Energy for Agriculture, January 1985–March 1993.* (1993). Beltsville, MD: National Agricultural Library; 32 pp. Available from the USDA, National Agricultural Library, Reference Section, Room 111, Beltsville, MD 20705.

This bibliography lists wind energy citations drawn from AGRICOLA, an on-line database of publications on agriculture. The list includes an author index and a list of land-grant university libraries that provide the U.S. Department of Agriculture's document service.

Electric Power Research Institute (EPRI). *EPRI Guide: Technical Reports Published 1972–1981; EPRI Guide: Technical Reports Published January 1981–August 1987; EPRI Guide: Technical Reports Published January 1987–December 1990.* Palo Alto, CA: EPRI Research Reports Center. EPRI Distribution Center, Box 23205, Pleasant Hill, CA 94523.

These bibliographies include annotated listings of the reports generated by EPRI's research projects for the electric utility industry. Each citation is listed with a short abstract. Topics include wind, wind power, wind power generation, wind power plants, and wind turbines. Other publications from all other EPRI research programs are also listed. After 1990, these citations are only available on-line from the Electric Power Data Base (see Databases).

*Wind Energy Technical Reading List.* (1988). SERI/SP-273-2911. Golden, CO: Solar Energy Research Institute; 20 pp. (NTIS no. DE86010704).

This list cites technical publications produced by DOE's national laboratories and their subcontractors in the area of wind energy research and development. The reading list includes journal articles, conference papers, and technical reports. Publications are grouped in the following categories: general, international, aerodynamics, structural dynamics, controls and support systems, design and testing, environmental compatibility and safety, resource assessment and siting, applications and systems analysis, and economics.

*Wind Energy Utilization: A Bibliography with Abstracts.* (April 1975). DOE/NASA/1010-77/4. Cleveland, OH: NASA Lewis Research Center; 496 pp. Work performed by Technology Applications Center, University of New Mexico, Albuquerque, NM.

This bibliography contains cumulative citations from 1944 to 1974 on the following areas: wind energy utilization, wind power plants, wind power generators, wind machines, wind data and properties, energy storage, and related design topics. The citations are also indexed by author, corporate source, title, and key word.

## Conferences

Conferences, workshops, and expositions are often the best way to find the latest developments in the field. Workshops and conferences provide a forum for researchers and others to present their latest findings and note industry trends. Conferences are a good way to meet the people active in the field and hear the latest developments. The conferences listed here are held regularly. Contact the sponsoring organization for future meeting dates and locations.

*British Wind Energy Association Conference.* Sponsored by the British Wind Energy Association. Issues of *Wind Energy Conversion*, proceedings of this conference, are published in London by Mechanical Engineering Publications Limited. Available from British Wind Energy Association, 42 Kingsway, London, WC2B 6RH, England.

- 1996. Exeter, England. September 25–27.
- 1995. Warwick, England. July 19–21. *Seventeenth Proceedings*; 427 pp.
- 1994. Sterling, Scotland. June 15–17. *Sixteenth Proceedings*; 338 pp.

1993. York, England. October 6-8. *Fifteenth Proceedings*; 432 pp.  
1992. Nottingham, England. March 25-27. *Fourteenth Proceedings*; 384 pp.

*Canadian Wind Energy Conference & Exhibition.* Since 1985, the Canadian Wind Energy Association has sponsored an annual conference on wind energy. The proceedings are available from the Canadian Wind Energy Association, 3553 31st Street, NW, Suite 100, Calgary, Alberta, T2L 2K7, Canada.

1996. Kananaskis, Alberta, Canada. October 6-9.  
1995. Kincardine, Ontario, Canada. October 2-4.  
1994. Regina, Saskatchewan, Canada. October 17-19.

*European Union Wind Energy Conference.* Sponsored by the Commission of the European Communities, Directorate General (XII) for Science, Research and Development; (XVII) for Energy. Topics of papers range from fundamental research to practical application.

1996. Göteborg, Sweden; May 20-24.  
1993. Lübeck-Travemünde, Germany; March 8-12.

*European Wind Energy Conference.* Sponsored by the European Wind Energy Association (EWEA) and local cosponsors. Proceedings are available from EWEA, Via Bormida 2, Rome I-100198, Italy.

1997. Dublin, Ireland; October 6-9.  
1995. Helsinki, Finland; September 5-7. Special Topics Conference: The Economics of Wind Energy.  
1994. Thessaloniki, Greece; October 10-14.

*Wind Energy Symposium.* Sponsored by the Solar Energy Division of the American Society of Mechanical Engineers. Presented annually at the Energy-sources Technology Conference and Exhibition. *Proceedings* available from the American Society of Mechanical Engineers, 345 East 47th Street, New York, NY, 10017.

1997. Reno, Nevada, January 6-9.  
1996. Houston, Texas, January 29-February 2. Book VIII, Vol. I; 213 pp.  
1995. Houston, Texas, January 29-February 1. SED Vol. 16; 291 pp.  
1994. New Orleans, Louisiana, January 23-26. SED Vol. 15; 279 pp.  
1993. Houston, Texas, January 31-February 4. SED Vol. 14; 213 pp.  
1992. Houston, Texas. January 26-30. SED Vol. 12; 155 pp.

*Windpower Conference.* Sponsored by the American Wind Energy Association and local cosponsors. *Proceedings* available from the American Wind Energy Association, 122 C Street, NW, Fourth Floor, Washington, DC 20001.

1997. Austin, Texas. June 15-18.  
1996. Denver, Colorado. June 23-27.  
1995. Washington, DC. March 27-30.  
1994. Minneapolis, Minnesota. May 9-13.  
1993. San Francisco, California. July 12-16.  
1992. Seattle, Washington. October 19-23.

## Databases

This section describes bibliographic and numeric databases that are available to the public and are significant sources of wind energy information. Bibliographic databases provide an efficient method of finding recent publications. Numerical databases provide access to data compilations and facilitate analysis of the data. Most of the databases are available from commercial vendors. A list of these vendors appears in this section. Libraries or other organizations subscribing to these vendors will search them for a fee. In addition, several of the database publishers provide in-house search services. Publications produced from the database, and disks containing the database (CD-ROMs) might also be available. Databases and database vendors are listed in alphabetical order.

## Database Vendors

**CDP Technologies, Inc.**  
333 7th Avenue, 4th Floor  
New York, NY 10001  
(212) 536-3006  
(800) 950-2035

**DATA-STAR**  
Data-Star, Inc.  
Suite 116  
485 Devon Park Drive  
Wayne, PA 19087  
(215) 687-6777  
(800) 221-7754

**DIALOG Information Services**  
A Knight-Ridder Company  
Marketing Department  
3460 Hillview Avenue  
Palo Alto, CA 94303-0993  
(415) 858-3785  
(800) 334-2564

**ESA-QUEST**  
European Space Agency  
Information Retrieval Service  
Esrin, Via Galileo Galelei, C.P. 64  
1-00044 Frascati (Rome)  
Italy  
+39 06 941801

**ORBIT • QUESTEL**  
8000 Westpark Drive  
McLean, VA 22102  
(800) 456-7248

**STN International**  
c/o Chemical Abstracts Service  
2540 Olentangy River Road  
P.O. Box 3012  
Columbus, OH 43210-0012  
(800) 848-6533

## Data Bases and Their Producers

**Aerospace Database**  
American Institute of Aeronautics and Astronautics  
Technical Information Service  
555 West 57th Street  
New York, NY 10019  
Phone: (212) 247-6500

Coverage: 1962 to present. Provides references, abstracts, and controlled-vocabulary indexing of key scientific and technical documents, as well as books, reports, and conferences, covering aerospace research and development in more than 40 countries. This database supports basic and applied research in aeronautics, astronautics, and space sciences. It lists technology development and applications in fields such as chemistry, geosciences, physics, communications, and electronics. In one database, the Aerospace Database combines two publications: Scientific and Technical Aerospace Reports, produced by the National Aeronautics and Space Administration (NASA) and International Aerospace Abstracts, produced by the American Institute of Aeronautics and Astronautics under contract to NASA. The file contains more than 1.5 million citations and is updated twice every month. Available on-line from DIALOG Information Retrieval Service.

**COMPENDEX**  
Engineering Information, Inc.  
345 East 47th Street  
New York, NY 10017  
Phone: (212) 705-7600

Coverage: 1970 to present. COMPENDEX stands for the COMPuterized ENgineering inDEX database. Engineering Information, Inc. (EI), is a nonprofit organization that abstracts and indexes the world's engineering literature. EI maintains COMPENDEX, which contains abstracts and extensive indexing. All engineering fields, including related areas of applied science, management, and energy, are within the scope of COMPENDEX. The EI collection contains more than 2 million bibliographic references and abstracts gathered since 1884. About 1.7 million citations with abstracts are available on COMPENDEX. Abstracts are added to the file at a rate of more than 100,000 per year. EI makes information available in hard copy, microform, and computer-readable forms. Its major publication is *Engineering Index Monthly*. Also published

from the database are *Energy Abstracts* and *Bioengineering Abstracts*. COMPENDEX is widely distributed on-line through North American and European vendors, including DIALOG Information Services, Inc; ORBIT Search Service; Bibliographic Retrieval Services (BRS); ESA-QUEST (European Space Agency); STN International; and DATA-STAR. EI also provides search services and magnetic tape subscriptions from the database.

#### **Derwent World Patents Index**

Derwent Publications, Ltd.  
Suite 401 Dolley Madison Boulevard  
McLean, VA 22101  
Phone: (703) 790-0400

Coverage: 1963 to present. Files contain data from nearly 3 million inventions represented in more than 6 million patent documents from 33 patent-issuing authorities around the world. In addition to bibliographic information, the basic patent record includes the full abstract (for new patents issued from 1981 on), informative title, International Patent Classification codes, and subject codes. It is available from DIALOG and STN.

#### **ENERGYLINE®**

R.R. Bowker Company  
A Reed Reference Publishing Company  
121 Chanlon Road  
New Providence, NJ 07974  
Phone: (908) 464-6800 x7727

Coverage: 1971 to present. ENERGYLINE is a primary source for information relating specifically to energy. Its data are drawn from many conventional discipline-oriented fields, such as chemistry or engineering, but are incorporated in ENERGYLINE only as they relate to energy issues and problems. Coverage includes books, journals, congressional committee prints, conference proceedings, speeches, and statistics. The database, updated monthly, contains more than 80,000 records. ENERGYLINE is the on-line version of *Energy Information Abstracts*. R.R. Bowker Company provides a microfiche service for the full-text articles cited in ENERGYLINE. It is accessible on-line through DIALOG Information Services, Inc.; ESA QUEST (European Space Agency); and ORBIT Search Service. Copies of ENERGYLINE are available from R.R. Bowker.

#### **Energy Technology Data Exchange (ETDE)/DOE Energy Science and Technology**

U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831  
Phone: (615) 576-1188

Coverage: 1974 to present. This database includes more than 3 million energy-related records. This information is compiled from DOE and its contractors, other governments, and professional societies. Sources include the International Energy Agency's multilateral information program, ETDE, and the International Atomic Energy's International Nuclear Information Systems. It includes bibliographic citations to the energy-related literature published in the 14 ETDE member countries, including the United States. The abstracted and indexed records are in English, with original-language titles and notes about the language of origin. Nearly half of the references are from non-U.S. sources. Updated quarterly, the database covers journal articles, report literature, conference papers, books, patents, dissertations, and translations. The following energy topics are included: wind, fossil, nuclear, geothermal, tidal, and solar. Related topics such as environmental aspects of energy production and use and energy policy include full coverage of global climate change. On-line searching is available through DIALOG (as Energy Science and Technology: file 103), and on STN International as Energy. It is available on compact disc (CD-ROM) from SilverPlatter Information. In addition, ETDE member countries provide the database locally through in-house on-line systems, printed publications of research summaries, and other special services.

**EPRINET**

Electric Power Research Institute  
3412 Hillview Avenue  
Palo Alto, CA 94303  
Phone: (415) 855-1000

Coverage: 1972 to present. The Electric Power Research Institute (EPRI), a not-for-profit research institution supported by the electric power industry in the United States, maintains this on-line information service. The database contains summaries of ongoing and completed research in the electric power industry. The service includes access to research related to issues in electric power, including wind turbine generators, hydroelectric power, fossil fuels, nuclear power, solar power, customer use, transmission and distribution economics, advanced power systems, and environmental assessment. The records provide work descriptions, start and completion dates, dollars allocated, results, project reports, publications, and contact persons. Such projects are conducted largely by companies under contract to EPRI or to other utilities.

**FLUIDEX: Fluid Engineering Abstracts**

Elsevier Science Publishers  
Regency House  
34 Duke Street  
Norwich NR3 3AP, United Kingdom  
Phone: +44 603 626327

Coverage: 1973 to present. FLUIDEX, updated monthly, provides indexing and abstracting for literature on every aspect of fluid engineering, from theoretical research to the latest technology and applications. Database coverage includes aerodynamics, wind energy, fluid dynamics, aspects of noise, and more. Nearly 1000 technical journals are indexed, as well as books, conference proceedings, standards, some British patents, and research reports from relevant institutions worldwide. It is available through DIALOG and other database vendors.

**IFI Uniterm Database of U.S. Patents (IFIUDB)**

IFI/Plenum Corporation  
3202 Kirkwood Highway  
Wilmington, DE 19808  
Phone: (302) 998-0478 / (800) 331-4955

Coverage: 1950 to date. This database contains records for all granted U.S. utility patents, reissue patents, and defensive publications. It includes mechanical and electrical patents from 1963 to the present and design patents from 1980 to the present. The source for IFIUDB is the U.S. Patent and Trademark Office *Official Gazette*. It is updated monthly and is available on STN.

**INSPEC (Information Services for the Physics and Engineering Communities Database)**

Institution of Electrical Engineers  
INSPEC Marketing Department  
445 Hoes Lane  
P.O. Box 1331  
Piscataway, NJ 08855-1331  
Phone: (908) 562-5549

Coverage: 1969 to present. INSPEC corresponds to three Science Abstracts print publications: *Physics Abstract*, *Electrical and Electronics Abstracts*, and *Computer and Control Abstracts*. Approximately 16% of the source publications of the databases are in languages other than English, but all articles are abstracted and indexed in English. INSPEC is available on-line from DIALOG.

**ISMEC: Mechanical Engineering Abstracts**

Cambridge Scientific Abstracts

7200 Wisconsin Avenue  
Bethesda, MD 20814  
Phone: (301) 961-6750

ISMEC (Information Service in Mechanical Engineering) indexes significant articles on all aspects of mechanical engineering, production engineering, and engineering management from approximately 750 journals published throughout the world. In addition, books, reports, and conference proceedings are indexed. The primary emphasis is coverage of leading international journals and conferences on mechanical engineering subjects. Principal areas covered include mechanical and electrical engineering, energy and power, and applications of mechanical engineering. ISMEC is available on-line from DIALOG.

**NTIS Bibliographic Database**  
National Technical Information Service  
NTIS Bibliographic Database  
5285 Port Royal Road  
Springfield, VA 22161  
Phone: (703) 487-4600

Coverage: 1964 to present. The National Technical Information Service (NTIS) Bibliographic Database contains approximately 1.2 million citations, most with abstracts, to unrestricted government reports sponsored by the United States and other governments. The U.S. reports are prepared by federal, state, and local agencies and their contractors or grantees. Major subject areas include the biological, social, and physical sciences; mathematics; engineering; and business. NTIS includes announcements of computer-readable software and data files, U.S.-government-owned inventions, selected reprints, federally sponsored translations, and some non-English-language reports. The database corresponds to the biweekly publication, *Government Reports Announcements & Index*, and in part to the weekly *Abstract Newsletters*. The service is available on-line from CDP Technologies, Inc.; DATA-STAR; DIALOG Information Services, Inc.; ORBIT Search Service; and STN International.

**Wind Energy Resource Information System (WERIS)**  
National Climatic Data Center  
Information Services Division  
151 Patton Avenue  
Asheville, NC 28801  
Phone: (704) 271-4800

Includes data and atlas maps from the 12 regional wind energy resource assessments produced for DOE (cited in Chapter 3). The following data files make up the database: station descriptions, mean and frequency distributions, intra- and inter-annual mean and standard deviations, climatic means and weather events, persistence of speed and direction, and wind data grid. Much of the data comes from a Pacific Northwest Laboratory analysis of 973 stations in the National Climatic Data Center (NCDC) TD1440 tape set. Data contained in the database are available on microfiche and magnetic tape from the NCDC. The WERIS user's manual, TD-9793, is also available.

## Directories

This section lists directories and similar reference publications that can direct inquirers to wind energy information, products, services, and organizations (for a list of software directories, see the section entitled "Software Directories and Depositories" at the end of this chapter). Each entry includes a bibliographic citation and an abstract. The most recent publications are listed first.

**SYNERGY, A Directory of Energy Alternatives.** New York: SYNERGY.

SYNERGY contains information about renewable energy and energy storage presented in U.S. and foreign sources, including publications, major articles (in English), conferences, research associations, manufacturers, and facilities. Under the wind power heading, books, patents, government publications, articles, manufacturers' research organizations, and wind turbine

facilities are listed. *SYNERGY* is updated semiannually; summer/fall issues are cumulative for 1 year only.

*American Wind Energy Association's Directory of Industry Members.* (1996). Washington, DC: American Wind Energy Association; 48 pp.

This American Wind Energy Association directory contains domestic and international member companies, including wind turbine and accessory parts manufacturers, wind power plant developers and operators, consultants, repair and maintenance companies, electric utilities, and research centers.

*Energy Information Directory.* (March 1994). DOE/EIA-0205(94).

Washington, DC: National Energy Information Center, U.S. Department of Energy.

This directory lists energy personnel at federal agencies and offices (primarily in DOE but also in other federal agencies) by subject area. Entries include name, title, abbreviated office address, DOE routing symbol, telephone number, and description of program or services related to energy concerns. An index of building locations provides complete addresses. The directory supersedes and enlarges the *Conservation and Renewable Energy Resource Directory*.

Appendices list state energy offices, DOE research and development field facilities, and state energy extension service contacts. Subject and name indexes are also included.

*European Directory of Renewable Energy Suppliers and Services.* (1994).

United Kingdom: James & James Science Publishers, Ltd.

This publication lists nearly 5000 companies in Europe that provide products and services for renewable energy sources, including wind energy. Most of the directory is compiled from an annual questionnaire. In future years, companies outside Europe will also be included.

*International Directory of New and Renewable Energy Information Sources and Research Centers, Third Edition.* (1993).

Paris: United Nations Educational, Scientific and Cultural Organization (UNESCO); 661 pp. London: James & James Science Publishers, Ltd.

This edition contains a total of 3596 entries representing 156 countries. International, national, and regional organizations and publications are included, covering governmental, private, or academic affiliations. The directory includes such renewable energy interest areas as wind energy, biomass, hydropower, geothermal, and others. Only major organizations and publications are included. The directory has five sections: listings by country, organization index, subject index, publication index, and acronym list. In addition, there are two appendices, one detailing the number and type of entries for each country, and the other listing the references used by UNESCO to compile the directory.

*Resource Directory of DOE Information Organizations.* (January 1991).

DOE/OSTI-4616-Rev.4. Oak Ridge, TN: U.S. Department of Energy,

Office of Scientific and Technical Information; 312 pp.

(NTIS order no. DE91001641/XAB).

Covers nearly 200 major information analysis centers, libraries, and information offices operated by DOE or its contractors. Entries include the center name, address, telephone number, name of director, and annotation covering scope, sponsors, services, and qualified users. Entries are arranged by organization, and organization and personal name indexes are included. The directory was formerly called the *Directory of Libraries and Information Specialists in DOE and Its Contractor Organizations*. It supersedes the *Directory of ERDA Information Centers*.

## Internet

The Internet's World Wide Web is an excellent source of updated information. Good sources of wind energy information include the American Wind Energy Association's web site (<http://www.igc.apc.org/awea/>), the National Renewable

Energy Laboratory's wind energy web site (<http://nwtc.nrel.gov>), and DOE's Energy Efficiency and Renewable Energy Network (<http://www.eren.doe.gov>). These home pages include links to wind-related home pages of government research programs, universities, associations, and wind turbine manufacturers. Subject-oriented search databases such as Lycos (<http://www.lycos.cs.cmu.edu/>) and Yahoo (<http://www.yahoo.com/>) can help locate wind energy information.

## Periodicals

This section lists currently available periodicals that are devoted to wind energy or that regularly feature articles on wind energy. These periodicals are a primary source of current news and state-of-the-art developments in wind energy. Each entry provides the title, frequency of publication, publisher name and address, and a description of the periodical. The description includes information on the year first published, purpose or audience, topics covered, types of feature articles and departments, availability of microform or reprints, indexing and abstracting services, and variant titles. Periodicals are listed in alphabetical order.

### *Boundary-Layer Meteorology*

Kluwer Academic Publishers Group  
P.O Box 358, Accord Station  
Hingham, MA 02048-0358

Frequency: Monthly with double issues in January, April, July, and October. First published in 1970, *Boundary-Layer Meteorology* is an interdisciplinary journal concerned with the physical and biological processes in the lowest 1000 meters of the atmosphere. It is an important medium for publishing theoretical, numerical, and experimental studies of the surface and planetary boundary layers. Occasional special issues are published. Subject areas covered in the journal include agriculture and forestry, air pollution, hydrology, micrometeorological instruments, planetary and surface boundary layers, remote sensing, and urban meteorology. Microfilm is available from University Microfilms International. Indexed by: *Applied Mechanics Review*; *Biological Abstracts*; *Current Contents*; *Excerpta Medica*; *Geographical Abstracts*; *Oceanic Abstracts*; *Pollution Abstracts*; *Science Abstracts*; *Science Citation Index*; *Current Titles in Ocean, Coastal, Lake & Waterway Sciences*; *FLUIDEX*; *Environmental Periodicals Bibliography*; *Forestry Abstracts*; *Bibliography and Index of Geology*; *Herbage Abstracts*; *International Aerospace Abstracts*; *Index to Scientific Reviews*; *Meteorological and Geoastrophysical Abstracts*; *Physics Briefs*; and *Soils and Fertilizers*.

### *EPRI Journal*

Electric Power Research Institute  
P.O. Box 10412  
Palo Alto, CA 94303

Frequency: Eight times each year. EPRI was founded in 1972 by the nation's electric utilities to develop and manage a technology program for improving electric power production, distribution, and utilization. The *EPRI Journal* contains a feature article about one aspect of EPRI's research program. Wind energy is featured regularly. In addition, the journal contains a list of recent contracts let and abstracts from recently published technical reports, including those to develop wind turbine generators and integrate them into utility generating systems.

### *Home Power*

Home Power, Inc.  
P.O. Box 520  
Ashland, OR 97520

Frequency: Bimonthly. First published in 1987, this journal assembles realistic technical information about using renewable energy for homes and businesses. It includes information on wind power, photovoltaics, micro-hydro, batteries, transportation, efficient appliances, and more.

*IEEE Transactions on Energy Conversion*  
Institute of Electrical and Electronics Engineers  
345 East 47th Street  
New York, NY 10017-2394

Frequency: Quarterly. First published in 1986 as *IEEE Transactions on Power Apparatus and Systems*, it was replaced by three new transactions: Energy Conversion, Power Delivery, and Power Systems. *IEEE Transactions on Energy Conversion* includes articles on wind power technology and covers virtually all aspects of the research, development, design, application, construction, installation, and operation of electric power generation facilities. In general, papers are preprinted and presented at a technical meeting of the Institute before being published in the appropriate transactions. Discussions by qualified specialists are sought and published along with a closure by the author. All contributions are reviewed by an appropriate technical committee of the Power Engineering Society.

*Independent Energy*  
Marier Communications, Inc.  
620 Central Avenue North  
Milaca, MN 56353

Frequency: Ten times per year. First published in 1971 as *Alternative Sources of Energy*, the magazine is directed to those concerned with the development and use of renewable forms of independent electric power generation. Information regularly appears on products and services, people in the industry, Federal Energy Regulatory Commission certification applications, industry news, and conference reports. Regular departments include events calendar; editorial; investor information; classified advertisements; and legislative, regulatory, and association updates. Directories to manufacturers and products are listed once each year. Indexed by: *Alternative Press Index; Applied Science and Technology Index; Science Abstracts; Energy Index; Fuel & Energy Abstract; Gas Abstract; and Index to Scientific Reviews*.

*International Journal of Ambient Energy*  
Ambient Press Ltd.  
P.O. Box 25  
Lutterworth, Leics LE17 4FF  
United Kingdom

Frequency: Quarterly. First published in 1980, this journal serves as a forum for the worldwide dissemination of new information on self-regenerating sources of energy and their potential use in serving the needs of humanity. Research and applications of wind, solar, wave, tidal, and geothermal energies are documented by the journal. The largest single use of energy in many countries is for environmental control in buildings, and the application of ambient energy for this purpose receives particular emphasis. The design and construction of buildings and complexes to use natural energy sources, as well as technical information on design and performance of heating, hot water, and air-conditioning systems, is covered. Papers include original research, development of new technology, and practical applications of ambient energy, case studies, and state-of-the-art reviews. A book review section examines new books from all parts of the world. Indexed by: *Excerpta Medica, Science Abstracts, Fluidex, and International Aerospace Abstracts*.

*International Journal of Energy Research*  
John Wiley & Sons Ltd.  
Baffins Lane  
Chichester, Sussex PO19 1UD  
United Kingdom

Frequency: Quarterly. First published in 1977, this journal deals with the development and exploitation of both traditional and new fuels and other sources of energy. An interdisciplinary approach to topics including solar power, nuclear power, heat pumps, buildings, wave power, transport, industrial technologies, storage, wind, conservation, synthetic fuels, and district

heating is encouraged. The editors publish original material in the areas of economic, environmental, scientific, or technological development or feasibility. Other features include reviews on important development areas, letters, book reviews, and a list of coming conferences. Reprints are available from University Microfilms International and the Institute for Scientific Information. Indexed by: *Chemical Abstracts; Current Contents; Science Abstracts; Science Citation Index; FLUIDEX; Geographical Abstracts; and International Aerospace Abstracts.*

*International Journal of Solar Energy*

Harwood Academic Publishers  
P.O. Box 786, Cooper Station  
New York, NY 10276

Frequency: Twenty-four times per year. First published in 1982, this journal publishes experimental, theoretical, and applied results in both the science and engineering of solar energy (for example, wind generators, photovoltaic power, biofuels, solar heating, thermal power plants, and radiation data). The journal provides up-to-date information from Europe, North America, Japan, and the developing nations. It publishes papers on development achievements and original research, as well as review articles, news items, and technical notes. Indexed by: *Chemical Abstracts, Science Abstracts, and International Aerospace Abstracts.*

*International Solar Energy Intelligence Report*

Business Publishers, Inc.  
951 Pershing Drive  
Silver Spring, MD 20910-4464

Frequency: Weekly. First published in 1975, this newsletter reports news and developments for all aspects of solar energy technology, legislation, budget, and business. Feature stories and short news items make up the body of the periodical. Each issue also lists publications available from NTIS, including *Solar Industry Bulletin, World Solar Markets, Solar Energy Digest, Practical Solar, Solar Energy Business & Marketing Report, Solar Outlook, Solar Energy Washington Letter, and Solar Energy Industry Report.*

*Journal of Solar Energy Engineering*  
American Society of Mechanical Engineers  
United Engineering Center  
345 East 47th Street  
New York, NY 10017

Frequency: Quarterly. First published in 1980, this journal publishes peer-reviewed papers dealing with basic research, design, and engineering applications of solar energy technologies, including wind. It includes book reviews and an events calendar. A special edition devoted to wind energy papers is published from time to time.

*Journal of Wind Engineering and Industrial Aerodynamics*  
Elsevier Science Publishers B.V.  
655 Avenue of the Americas  
New York, NY 10010

Frequency: Nine times per year. First published in 1975, this publication reports on those aspects of wind engineering that are included in the activities of the International Association for Wind Engineering. These aspects include wind power generation, social and economic impacts of wind effects, wind characteristics and structure, local wind environments, wind loads and structural responses, wind effects on building heat loss and ventilation, wind effects on transport systems, and wind effects codification. Papers on these subjects describe full-scale measurements, wind-tunnel simulation studies, or theoretical methods. There are papers dealing with the development of techniques and apparatus for wind engineering experiments. Indexed by: *Applied Mechanics Review, Current Contents, Engineering Index, Science Abstracts,*

*Science Citation Index, Agricultural Engineering Abstracts, FLUIDEX, Geographical Abstracts, INSPEC, and Index to Scientific Reviews.*

*Solar and Wind Technology*

Pergamon Press, Inc., Journals Division  
Maxwell House, Fairview Park  
Elmsford, NY 10523

Frequency: Quarterly. First published in 1985, this journal covers all forms of solar and wind energy and encompasses technical, environmental, social, and economic issues, with particular emphasis on the practical applications of solar energy. It also provides an international forum for the science and technology of solar and wind energy application. Submissions from developing countries and the Arab world are especially welcome. Microform is available from Microforms International Marketing and University Microfilms International. Indexed by: *Current Contents and Science Abstracts.*

*Solar Energy*

Elsevier Science, Inc.  
660 White Plains Road  
Tarrytown, NY 10591-5153

Frequency: Monthly. First published in 1957, *Solar Energy* covers all forms of solar energy applications over a range of technical, economic, environmental, social, and legal issues. *Solar Energy* is the official journal of the International Solar Energy Society. Microform is available from University Microfilms International. Indexed by: *Applied Mechanics Review, Applied Science and Technology Index, Biological Abstracts, Chemical Abstracts, Current Contents, Engineering Index, Science Abstracts, Automatic Subject Citation Alert, and Fuel and Energy Abstracts.*

*Solar Today*

American Solar Energy Society, Inc.  
2400 Central Avenue  
Unit G-1  
Boulder, CO 80301-2843

Frequency: Bimonthly. First published in 1987, *Solar Today* provides news of the latest in solar technology development. As the official publication of the American Solar Energy Society (ASES), *Solar Today* serves as a means of communication to ASES members. Each issue includes feature articles, industry news, an events calendar, an editorial from the chairman, International Solar Energy Society news, and ASES news.

*Sun World*

Franklin Company Consultants Ltd.  
192 Franklin Road  
Birmingham B30 2HE  
United Kingdom

Frequency: Quarterly. The journal of the International Solar Energy Society (ISES), *Sun World* includes articles by members on all topics relating to solar energy with special emphasis on country-specific applications. It includes editorials, lists of organizations in each field of solar energy, ISES news, book reviews, and a calendar of upcoming events.

*Wind Energy Weekly*

American Wind Energy Association  
122 C Street, NW, Fourth Floor  
Washington, DC 20001

Frequency: Weekly. This publication provides information on wind energy developments worldwide. Subjects covered include business opportunities, legislation and regulation, international issues, wind farm projects, wind and renewable energy events, research and

technical findings, and market projections. In addition, *Wind Energy Weekly* reports on such areas as trade news, economics, new products, and new announcements. *Wind Energy Weekly* is a newsletter of the American Wind Energy Association.

*Wind Engineering*  
Multi-Science Publishing Company, Ltd.  
107 High Street  
Brentwood, Essex CM14 4RX  
United Kingdom

Frequency: Quarterly. First published in 1977, *Wind Engineering* covers all aspects of wind energy systems, including measurement methods and related economic and environmental topics. In addition to technical papers, the journal contains abstracts of relevant papers from other journals, news items, book reviews, and news of upcoming conferences. Indexed by: *Science Abstracts*, *Fluidex*, *Geographical Abstracts*, and *International Aerospace Abstracts*.

*Wind Engineering Abstracts*  
Multi-Science Publishing Company, Ltd.  
107 High Street  
Brentwood, Essex CM14 4RX  
United Kingdom

Frequency: Four issues per year. *Wind Engineering Abstracts* offers several hundred summaries in each volume of contributions to the advancement of wind energy, drawn from a wide range of journals, government agency reports, and conference proceedings.

*Windirections*  
British Wind Energy Association  
4 Hamilton Place  
London W1V 0BQ  
United Kingdom

The official newsletter of the British and European Wind Energy Associations includes an events calendar, abstracts of recent books, commission of the European Communities news, industry developments, United Kingdom news, European news, features on wind machines, international notes (including the United States), and news from the developing world.

*Windletter*  
American Wind Energy Association  
1730 North Lynn Street, Suite 610  
Arlington, VA 22209

Frequency: Eight issues per year. The newsletter of the American Wind Energy Association, this periodical covers major issues concerning wind and other alternative energy sources, including legislation and regulatory reporting, national and international news, and items relating to wind farms and residential systems.

*Windpower Monthly News Magazine*  
U.S. Office of Forlaget Vistoft A-S  
P.O. Box 496007, Street 217  
Redding, CA 96049

Frequency: Monthly. The magazine was first published in 1985. It includes feature articles, an opinion column, news from around the world, a company profile, statistics, letters, and an events calendar.

*Windstats Newsletter*  
U.S. Office of Forlaget Vistoft A-S  
P.O. Box 496007, Suite 217  
Redding, CA 96049

Frequency: Monthly. This newsletter presents statistics relating to wind machines, wind energy, and the wind energy industry. A quarterly Wind Power Economy Index gathers data on the cost of electricity produced by wind turbines and compares the results with the cost of conventionally produced energy. A monthly statistics overview provides operation and production information on more than 1000 wind turbines. Other articles report on technical developments, brief news items, book reviews, and opinion.

## Research Centers

This section lists some of the organizations currently engaged in some form of wind energy research. Research centers are listed alphabetically.

The private sector of the wind industry conducts research as well. For a list of the companies and consulting firms involved in wind energy research, consult the American Wind Energy Association's *Membership Directory*, available from the American Wind Energy Association, 122 C Street, NW, Fourth Floor, Washington, DC 20001.

### U.S. Research Centers

#### **Colorado State University (CSU), Department of Civil Engineering**

Fort Collins, CO 80523

Phone: (303) 491-5048

Key Personnel: Robert Meroney; David Neff

CSU professors and students have performed studies for the U.S. Department of Energy on siting wind machines (especially large units), including topographical studies and the use of a wind tunnel to model terrain effects on the wind. Studies have included agricultural applications of wind energy, the aerodynamics of turbulence and wind flow around wind turbine blades, and the effect of vegetation on wind energy availability in hilly terrain.

#### **Electric Power Research Institute (EPRI)**

P.O. Box 10412

Palo Alto, CA 94303-0813

Phone: (415) 855-2000

Key Personnel: Earl Davis, Manager, Wind Power Integration

EPRI manages a broad-based research, development, and demonstration program in areas of importance to electric utilities in the United States. Renewable energy technologies, including wind energy, are developed and demonstrated in subcontracted research. EPRI has published studies on wind turbine siting, performance, and testing; wind energy markets; and utility interface issues. In addition, EPRI manages a consortium that is developing a variable-speed wind turbine. Together with the U.S. Department of Energy, EPRI is supporting work to introduce utilities to the use of wind power through demonstration projects and the Utility Wind Interest Group. It maintains a database containing summaries of ongoing and completed research in the electric power industry.

#### **Iowa State University, Aerospace Engineering Department**

404 Town Engineering Building

Ames, Iowa 50011

Phone: (515) 294-6796 / Fax: (515) 294-3262

Key Personnel: R.G. Rajagopalan

Performed work under contract to DOE on turbulence-induced aerodynamic loads, including wind power plant siting and array effects.

**Michigan State University, Department of Electrical Engineering**

East Lansing, MI 48824-1226

Phone: (517) 355-5066 / Fax: (517) 353-1980

Key Personnel: Robert A. Schlueter; Gerald L. Park

Studies wind-electric planning, integration, and testing. Michigan State is a land-grant university that has received federal and utility support for these studies since 1973. Activities have included measuring multiple-level, short-term wind velocities at the former candidate wind turbine generator (WTG) site at Ludington, Michigan; evaluating improved dispatching models for utilities with high WTG penetration; and completing smaller WTG testing in Michigan.

**Michigan Technological University, Mechanical Engineering Department**

Houghton, MI 49931

Key Personnel: S. Yang

Conducted research under contract to DOE to define the structural characteristics for advanced composite blades to achieve competitive cost.

**Minnesota Department of Public Service, Energy Division**

121 7th Place East, Suite 200

St. Paul, MN 55101-2145

Phone: (612) 296-5120 / Fax: (612) 297-1959

Key Personnel: Narv Somdahl, Alternative Energy Engineering; Rory Artig, WRAP

The department has operated the Wind Resource Assessment Program (WRAP) for the past 8 years. Data from 28 locations include velocity distribution, hourly average wind speed, and wind direction. WRAP data from 18 additional utility and private sites will be added to these databases. The department is developing the capability to cross-reference WRAP data with the electric demands of a given area. The goal is to assist utilities and independent wind farm developers in the process of harvesting the electric generation potential of Minnesota's winds. As part of the state-mandated integrated resource planning requirement, the department is encouraging and aggressively working with utilities to include wind power as a significant part of their plans to meet future electrical demand.

**Montana State University, Department of Chemical Engineering**

302 Cableigh Hall

Bozeman, MT 59730

Phone: (406) 994-4543 / Fax: (406) 994-5308

Key Personnel: John Mandell

Performs work under contract to DOE to investigate the fatigue behavior of composite substructures typical of wind turbine blades.

**National Oceanic and Atmospheric Administration (NOAA), Atmospheric Turbulence and Diffusion Division**

P.O. Box 2456

Oak Ridge, TN 37831-2456

Phone: (615) 576-1233 / Fax: (615) 576-1327

Key Personnel: Rayford P. Hosker, Jr.; Carmen J. Nappo; K. Shankar Rao; Richard M. Eckman; William R. Pendergrass

The division serves as the meteorological authority for the DOE Oak Ridge Operations Office and conducts research in support of DOE and NOAA goals. Part of the research is directed toward atmospheric dispersion; wind field information is a basic component of this. Studies are conducted of flow over terrain of varying complexity, and numerical models are constructed and tested against field data.

**National Renewable Energy Laboratory (NREL)**

1617 Cole Boulevard

Golden, CO 80401

Phone: (303) 275-4090 / Fax: (303) 275-4091

NREL, located in Golden, Colorado, is the world's largest scientific institution dedicated to developing renewable energy technologies. As the primary national laboratory for the DOE Wind Energy Program, NREL manages the National Wind Technology Center, located near Golden. NREL's wind program manages a variety of cooperative government and industry activities, and conducts research in structures and fatigue testing, wind characteristics, resource assessment, site evaluation, aerodynamics, and advanced components and systems.

**National Wind Technology Center (NWTC)**

1617 Cole Boulevard

Golden, CO 80401

Phone: (303) 384-6900 / Fax: (303) 384-6999

Key Personnel: Robert Thresher, Center Director; Susan Hock, Technology Program Manager

A national center for wind turbine research and development operated by the National Renewable Energy Laboratory, the NWTC is spread out over 280 acres of land near Golden, Colorado. Research scientists work side by side with wind turbine manufacturers, wind power plant developers, wind plant operators, and utilities to advance the technology and understanding of wind energy systems. An Industrial User Facility will enable industry engineers to work with researchers to study and test their wind turbine systems and components. Computer models, a large blade-testing bay, research expertise, and 10,000 square feet of laboratory space are available to industry in this secure building; adjacent facilities include machine and wood shops, indoor test bays, and a complete electronics laboratory. The Advanced Research Turbines on site serve as test beds for new components such as blades or control systems.

**Ohio State University (OSU), Aeronautical and Astronautical Department**

2300 West Case Road

Columbus, OH 43220

Phone: (614) 292-5491 / Fax: (614) 292-5552

Key Personnel: G.M. Gregorek; M. Hoffman; R. Reuss Ramsay

Under contract to DOE, researchers are developing an empirical database of airfoil performance data, including steady-state and unsteady conditions with clean and contaminated surfaces for various airfoils. They will use the results to develop analytical techniques for predicting rotor performance in real-world conditions. OSU researchers have conducted tests of vortex generation of advanced airfoils.

**Oregon State University, Mechanical Engineering Department**

Corvallis, OR 97331

Phone: (503) 737-2218 / Fax: (503) 737-3462

Key Personnel: Robert Wilson; Stel Walker

Researchers at Oregon State are developing analytical codes for dynamic response of wind turbines to calculate loads caused by such factors as gravity, wind shear, dynamic stall, and tower shadow.

**Pacific International Center for High Technology Research (PICHTR)**

2800 Woodlawn Drive, Suite 180

Honolulu, HI 96822-1843

Phone: (808) 539-3900 / Fax: (808) 539-3899

Key Personnel: Andrew R. Trenka, Program Manager, Energy Applications

PICHTR is an independent, not-for-profit, applied research and development center incorporated in Hawaii with an international board of directors from the United States, Asia, and the Pacific region. PICHTR works with government and industry to advance sustainable development in the Asia-Pacific region. In addition to its ocean energy and biomass energy projects, PICHTR's Energy Applications projects include the design and testing of wind/pumped-hydro integration and other hybrid wind energy applications. Tests and model validation are conducted at the Renewable Energy Storage Test facility.

**Sandia National Laboratories**  
Wind Energy Technology Department 6214  
MS 0708  
P.O. Box 5800  
Albuquerque, NM 87185-0708  
Phone: (505) 844-5253 / Fax: (505) 845-9500  
Key Personnel: Henry Dodd

Sandia, located in Albuquerque, New Mexico, and Livermore, California, has been involved in renewable energy technologies for more than 20 years, with wind energy as one of its original programs. The current wind program focuses on both industry/utility issues and applied research. As part of the industry-driven Turbine Development Program, Sandia is leading an Advanced Manufacturing initiative to reduce turbine costs through innovative component manufacturing. In addition, applied research activities emphasize the development, validation, and transfer to industry of analytical and experimental tools in the areas of aerodynamics, structural dynamics, fatigue, reliability, materials, and controls.

**Southern University, Department of Mechanical Engineering**  
Department of Mechanical Engineering  
Baton Rouge, LA 70813  
Key Personnel: I. Graham

Researchers work on structural dynamics and fatigue in wind turbines.

**Stanford University, Aeronautics and Astronautics**  
Stanford, CA 94305-4035  
Phone: (415) 725-3305 / Fax: (415) 725-3377  
Key Personnel: Stephen Tsai; Sanwook Sihn

Researchers developed a user-friendly finite-element analysis model of blades for everyday use by designers.

**Tennessee State University, Department of Electrical and Computer Engineering**  
3500 John Merritt Boulevard  
Nashville, TN 37209-1561  
Phone: (615) 320-3268 / Fax: (615) 320-3554  
Key Personnel: Satinderpal Singh Devgan

Graduate and undergraduate courses are offered in wind turbine design. Under contract to DOE, researchers study issues of interconnecting wind turbine generators to the utility grid.

**Texas Technology University, Mechanical Engineering Department**  
P.O Box 4289  
Lubbock, TX 79409  
Key Personnel: J.W. Oler

Researchers work on turbulence-induced aerodynamic loads assessment.

**University of Alaska, Alaska State Climate Center**  
707 A Street  
Anchorage, AK 99501  
Phone: (907) 279-2741, 257-2737 / (Fax:) (907) 276-6847  
Key Personnel: Dwight D. Pollard, State Climatologist (wind resource assessment)

The Climate Center conducts climate-related research, including wind measurements. The university also participates in DOE's wind resource assessments for Alaska.

**University of Arizona, Aerospace and Mechanical Engineering Department**

Building 16

Tucson, AZ 85721

Phone: (602) 621-2235 / Fax: (602) 621-8191

Key Personnel: L.B. Scott, Jr.

Researchers perform wind energy research in feasibility assessment for remote sites (such as McMurdo Station, Antarctica) and wind turbine blade optimization, using numerical penalty function codes. The Department, which is accredited by the Accreditation Board for Engineering and Technology, offers B.S., M.S., and Ph.D. degrees in aerospace engineering and mechanical engineering. Goals in the wind energy area are teaching and computer-aided design.

**University of Colorado, Aerospace Engineering Sciences**

Campus Box 429

Boulder, CO 80309-0429

Phone: (303) 492-6416

Key Personnel: Donald Kennedy

The Department of Aerospace Engineering Sciences performs research in unsteady aerodynamics.

**University of Colorado, Electrical and Computer Engineering Department**

Campus Box 425

Boulder, CO 80309-0429

Phone: (303) 492-7010

Key Personnel: Ewald Fuchs

Researchers from the Electrical and Computer Engineering Department work under contract to DOE to design and build a variable-speed, constant-frequency wind turbine with direct-drive transmission.

**University of Detroit, Mercy Department of Electrical Engineering**

4001 West McNichols Road

Detroit, MI 48219-3599

Phone: (313) 993-3365

Key Personnel: D.L. Sengupta

Researchers study the electromagnetic interference effects of wind turbines.

**University of Illinois at Urbana-Champaign, Department of Aeronautical and Astronautical Engineering**

306 Talbot Laboratory

104 South Wright Street

Urbana, IL 61801-2935

Phone: (217) 244-5757 / Fax: (217) 244-0720

Key Personnel: Michael S. Selig

Research is conducted on aerodynamic performance prediction for horizontal-axis wind turbines.

**University of Massachusetts, Renewable Energy Research Laboratory**

College of Engineering

Engineering Laboratory Building

Amherst, MA 01003

Phone: (413) 545-4359 / Fax: (413) 545-0724

Key Personnel: James F. Manwell; R. Kirchoff

The research program offers graduate students the opportunity to pursue master's and doctorate degrees in mechanical or electrical engineering. Recent research topics include wind/diesel systems simulation design, energy storage, nonlinear aerodynamics, wind-tunnel testing, wind farm siting, wind resource characteristics, dynamics and control of wind turbines,

power electronics, data acquisition and analysis, photovoltaic systems, desalination, and offshore wind systems. Facilities include a large wind turbine, wind-diesel system simulation, open-jet wind tunnel, and machine shop.

**University of Michigan, Department of Electrical Engineering and Computer Science**  
1301 Beal Avenue  
Ann Arbor, MI 48109-2122  
Phone: (313) 764-0500 / Fax: (313) 747-2106  
Key Personnel: T.B.A. Senior; V.V. Liepa

Michigan researchers study electromagnetic wave interference caused by large and small wind turbines, including television, FM, microwave link, and navigation systems. The radiation laboratory carries out theoretical and experimental research in all areas of electromagnetics, particularly scattering, remote sensing, antennas, and interference. Involvement in wind energy research began in 1976 with the study of interference of wind turbines with the electromagnetic environment, particularly TV reception and microwave systems. Theories predicting interference have been developed for all existing large horizontal- and vertical-axis wind turbines and have been verified with on-site measurements. These have also been used in preparing environmental impact statements for large installations.

**University of New Mexico, New Mexico Engineering Research Institute (NMERI)**  
901 University Boulevard SE  
Albuquerque, NM 87106  
Phone: (505) 272-7220  
Key Personnel: Dan Burwinkle; Ron Linker; Tracy Wilson

NMERI provides technical services to both government and private enterprise in wind turbine system and component design. NMERI specializes in stress analysis and fatigue research, data acquisition and analysis system design, code development, control system design, research planning and reliability analysis, strain gauge design, and installation.

**University of Texas at El Paso, Mechanical and Industrial Engineering Department**  
101 Engineering Science Complex  
El Paso, TX 79968-0521  
Key Personnel: Andy Swift; Lionel Craver; Juan Herrera; Chris Wu; Emil Moroz  
Phone: (915) 747-5450 / Fax: (915) 747-5019

The department provides wind engineering training to students of various engineering disciplines by means of in-class teaching and research activities. Under contract to DOE, research is performed on teetered-rotor wind turbines.

**University of Utah, Mechanical Engineering Department**  
MEB 3106  
Salt Lake City, UT 84112  
Phone: (801) 581-4145 / Fax: (801) 581-8692  
Key Personnel: A. Craig Hansen

Researchers analyze the aerodynamics and dynamics of wind turbines. Current research involves developing aerodynamics analyses for use with structural dynamics and performance models. YawDyn, a computer program to assist in the design of yaw-control systems, and aerodynamics for the general-purpose structural dynamics program, ADAMS, are both being developed and validated.

**U.S. Department of Agriculture (USDA), Agricultural Research Service**  
Conservation and Production Research Laboratory  
P.O. Drawer 10  
Bushland, TX 79012  
Phone: (806) 356-5734 / Fax: (806) 356-5750  
Key Personnel: R. Nolan Clark; Ronald G. Davis

The Agricultural Research Service is a government-funded research laboratory where the use of wind energy for water pumping and irrigation is studied. Since 1976, researchers at the USDA Conservation and Production Research Laboratory in Bushland, Texas, have conducted field experiments on wind-powered irrigation pumping systems from 10 to 500 kW in size. Stand-alone electrical and mechanical water-pumping systems have also been developed and tested. Current work explores system design and operation for wind/hybrid electrical generation for rural areas. The Sandia/DOE/USDA 34-m vertical-axis wind turbine test bed is located at Bushland.

**U.S. Department of Energy (DOE)**  
Office of Renewable Energy Conversion  
Wind/Hydro/Ocean Division, EE-121  
1000 Independence Avenue, SW  
Washington, DC 20585

Key Personnel: Peter Goldman, Acting Director, Wind/Hydro/Ocean Division

The DOE Wind/Hydro/Ocean Division manages the federal Wind Energy Program. In addition to policy management, the division coordinates wind research and development activities at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories. The federal Wind Energy Program also funds operation of the National Wind Technology Center by NREL. The goal of these research activities is to establish wind energy technology as a viable energy supply option, primarily by improving the technology base and by supporting industry in its effort to develop safer, more reliable, and more cost-effective wind systems.

**West Texas State University, Alternative Energy Institute**  
P.O. Box 248  
Canyon, TX 79016  
Phone: (806) 656-2295 / Fax: (806) 656-2733  
Key Personnel: Vaughn Nelson, Director; Earl Gilmore; Forrest Stoddard

Researchers evaluate wind turbines at the 28-acre Wind Test Center. They investigate wind energy systems for agricultural uses. These turbines can also be used for homes or industry. Researchers measure the wind resource at sites around the state and study wind characteristics as they apply to turbine design.

**Wichita State University, Aerospace Engineering Department**  
Campus Box 44  
Wichita, KS 62760-0044  
Phone: (316) 689-3410 / Fax: (316) 689-3853  
Key Personnel: L. Scott Miller; Steve Huang

The Aerospace Engineering Department works under contract to DOE to develop and test aerodynamic controls for wind turbine blades.

**Wichita State University, Center for Energy Studies**  
Campus Box 44  
Wichita, KS 67260-0044  
Phone: (316) 689-3415 / Fax: (316) 689-3853  
Key Personnel: Robert Egbert; Ward Jewell; Asrat Teshome

The Center For Energy Studies conducts energy research, with special emphasis on applications to the state of Kansas. Wind energy research projects have included using small wind generators in a Kansas electric utility, evaluating wind power plant sites and aileron and spoiler-control sections for large wind machines, designing new airfoil sections for large wind machines, and analyzing the Kansas wind resource.

## International Research Centers

### Center for Renewable Energy Sources

19th km Marathonos Avenue  
Pikermi, Attiki, 19009  
Greece

Phone: +30 1 6039900 / Fax: +30 1 6039904/5

### Deutches Windenergie-Institut (DEWI)

EbertstraBe 96  
Wilhelmshaven, 26382  
Germany

Phone: +49 4421-4808-0-15 / Fax: +49 4421-4808-43

### Institut de Recherche d' Hydro-Quebec

1800 Montee Ste-Julie  
Varennes, Quebec  
JOL 2 P.O.  
Canada

### National Engineering Laboratory

National Wind Turbine Centre  
Environmental Technology Group  
East Kilbride  
Glasgow, G75 0QU  
United Kingdom

Phone: +44 13552 20222 / Fax: +44 13552 72333

### Netherlands Energy Research Foundation, ECN

P.O. Box 1  
Petten, 1755 ZG  
The Netherlands

Phone: +31 2246 4025 / Fax: +31 2246 3214

### RISØ

Risø National Laboratory  
Test Center for Wind Turbines  
4000 Roskilde  
Denmark

Phone: +45 46775035 / Fax: +45 42372965

### WINDTEST Kaiser-Wilhelm-Koog

GmbH  
Sommerdeich 14b  
Kaiser-Wilhelm-Koog, D-25709  
Germany

Phone: +49 4856 901 12 / Fax: +49 4856 901 49

## Software Directories and Depositories

This section lists additional sources of information on the latest codes, design tools, and models related to wind energy. Specific models are mentioned in the first eight chapters of this book under the topic they address. New models are being developed daily, and the sources listed here will contain the latest models that are publicly available and well documented. Many other sources of information about software are available, such as recent reports listed under Databases, Conferences, Research Centers, and Associations.

### DATAPRO Software Directory

DATAPRO Information Services Group  
600 Delran Parkway  
Delran, NJ 08075  
Phone: (800) 328-2776 or (609) 764-0100

This catalog, which is updated monthly, describes more than 3200 programs for major microcomputers and minicomputers. It includes major subject and application categories such as scientific and professional industries, including architecture, energy, and public utilities. The software section includes complete information about vendors and programs. Entries are indexed by computer system, operating system, programming language, microprocessor, subject and application, keyword, and program name. Available on-line from DIALOG.

### Energy Information Administration (EIA)

National Energy Information Center, EI-231  
Forrestal Building, Room 1F-048  
Washington, DC 20585  
Phone: (202) 586-8800

The EIA publishes the *Directory of Energy Information Administration Models*, which contains descriptions of each model used by the EIA including title, acronym, and purpose. A more detailed description follows that includes characteristics, uses, and requirements of the models used. In the 1994 version, 37 EIA models active as of February 1, 1994, are described.

**Energy, Science, and Technology Software Center**

Oak Ridge National Laboratory

P.O. Box 62

Oak Ridge, TN 37831

Phone: (615) 576-2606

The Center maintains a library of computer programs, models, systems routines, and data compilations developed by DOE and its contractors in carrying out the agency's research and development activities.

**Federal Computer Products Center**

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

Phone: (703) 487-4650

The Center maintains a steady flow of new and updated software and data files from various federal agencies. It is managed by the National Technical Information Service (NTIS) of the U.S. Department of Commerce. A wide variety of computer products pertinent to business and scientific interests are available for sale. The collection contains more than 3500 software and data files from more than 100 federal agencies and covers a wide range of subjects. The center publishes the *Directory of U.S. Government Software for Mainframes and Microcomputers*, the *Directory of Computer Datafiles*, and the *Computers, Control & Information Theory NTIS Alert*.

**University of Arizona, Solar Energy Research Facility**

The Solar Energy Research Facility conducts periodic national conferences on the use of computer models and databases. Cosponsors include the U.S. Department of Energy, the Western Area Power Administration, the National Renewable Energy Laboratory, and the American Solar Energy Society. *Proceedings: the Fourth National Conference on Microcomputer Applications in Energy, April 25-27, 1990, Tucson, Arizona.* (1990). Edited by Donald E. Osborn, University of Arizona.

# Appendix A

## List of Abbreviations and Acronyms

ac	alternating current
ARS	Agricultural Research Service
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AWEA	American Wind Energy Association
CO <sub>2</sub>	Carbon dioxide
COE	cost of energy
dc	direct current
DOE	Department of Energy
EPRI	Electric Power Research Institute
EWEC	European Wind Energy Conference
FAROW	Fatigue and Reliability of Wind Turbines
FAST	Fatigue, Aerodynamics, Structural, Turbulence
FLAP	Force and Loads Analysis Program
ft	feet
HAWT	horizontal-axis wind turbine
IEA	International Energy Agency
IEA R&D Wind	Implementing Agreement for Cooperation in the Research and Development of Wind Turbine Systems
ILL	Interlibrary loan
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
m	meter
mph	mile per hour
mps	meter per second
MW	megawatt
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NREL	National Renewable Energy Laboratory
NWTC	National Wind Technology Center
NTIS	National Technical Information Service
O&M	operation and maintenance
ORNL	Oak Ridge National Laboratory
PNL	Pacific Northwest Laboratory
PURPA	Public Utility Regulatory Policies Act
PV	photovoltaics
R&D	research and development
s	second
SERI	Solar Energy Research Institute
SWECS	small wind energy conversion systems
TAG	Technical Assessment Guide
US/ECRE	U.S. Export Council for Renewable Energy
UWIG	Utility Wind Interest Group
VAWT	vertical-axis wind turbine
WECS	wind energy conversion system
WERIS	Wind Energy Resource Information System
YawDyn	Yaw Dynamics of Horizontal-Axis Wind Turbines

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