NASA/DOE Second- and Third-Generation HAWTs

The Mod-2 Program

Even before the first-generation Mod-1 HAWT began its test program, development was started at NASA Lewis on a second-generation large-scale machine, to be named the *Mod-2 HAWT*, which would represent a major advance from earlier systems. *Boeing Aerospace Corporation* received the development contract, and a site was selected at Goodnoe Hills, near the Columbia River Gorge and the town of Goldendale, Washington. The Bonneville Power Administration was the cooperating utility, with the power to be fed into the grid of the Klickitat County Public Utility District.

The state of knowledge of structural dynamics of wind turbines had then reached the stage where a "soft" structural design could be attempted on a large turbine. An upwind rotor configuration was selected to reduce the possibility of noise and cyclic loads from tower shadow. As shown in Figure 3-37, the two-bladed rotor concept of the Mod-0 and Mod-1 was retained. Instead of full-span pitch control, however, partial-span tip control was selected, which allowed a teetered hub that was less expensive and structurally superior.

Economic optimization from the utility viewpoint, coupled with the federal role of pursuing technology levels that were beyond the risk limits acceptable to a private company, led to the selection of a power rating of 2.5 MW at a rated wind speed of 12.3 m/s (at the hub) and a rotor diameter of 91.4 m. The 900-kN (100-ton) rotor was fabricated from welded steel plates in five separate sections: a hub, two mid-blades, and two pitchable tips. These were bolted together at the site and lifted into place in one piece [Boeing 1982].

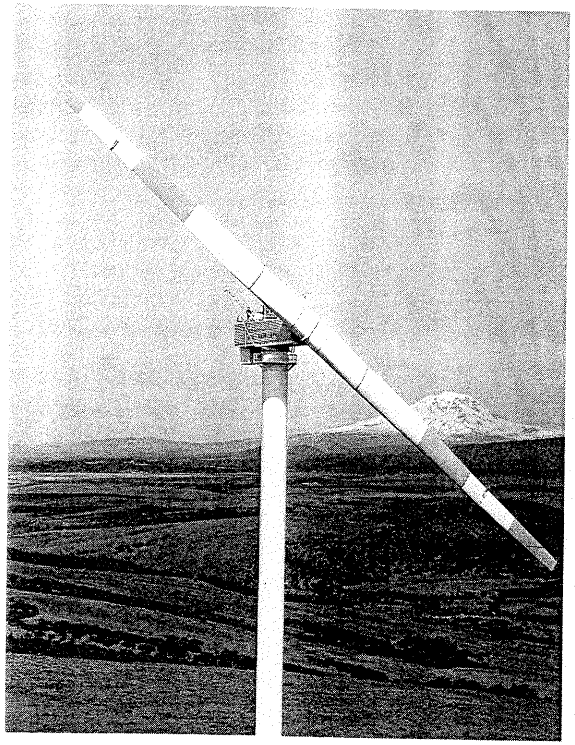


Figure 3-37. The 2.5-MW Mod-2 HAWT, the second-generation turbine in the large-scale segment of the Federal Wind Energy Program. Its welded-steel, teetered rotor was 91.4 m from tip to tip, with pitchable tips. *(Courtesy of NASA Lewis Research Center)*

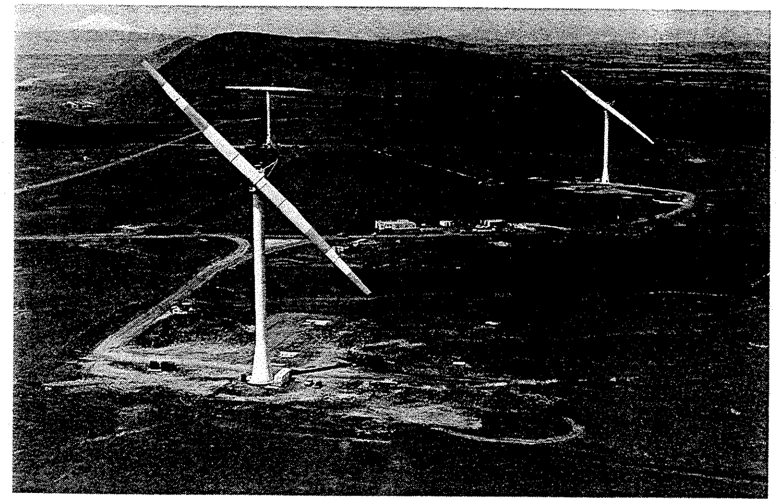


Figure 3-38. Arrangement of the three Mod-2 HAWTs on the Goodnoe Hills site near Goldendale, Washington. The triangular pattern permitted research on wake interference effects at different downwind distances. *(Courtesy of Boeing Aerospace Corporation)*

Three Mod-2 turbines were built and tested at the Goodnoe Hills site in order to investigate initial problems associated with large-scale wind power stations and interactions and interferences between multiple large wind turbines. The three turbines were placed in a triangular pattern 5, 7, and 10 diameters apart such that wake interactions could be examined under different spacings as changing wind directions placed the various units behind one another (Fig. 3-38). Extensive use of anemometers as well as kites, smoke, balloons, and other techniques were used to characterize the local wind flow over the site in detail.

As in any high-risk technological advance, a number of problems were encountered, particularly during the first two years of operation. These included fatigue cracks in the turbine shafts originating at component mounting holes, contaminated hydraulic oil, and leaking grease seals causing premature failure of blade tip support bearings. While these difficulties caused significant delays and costs because of the size of the components and the necessity to special-order or fabricate each part, the turbines themselves operated according to design. Investigations continued into operating strategies and control algorithms, to increase energy capture and reduce structural loads.

Other modifications were made to improve the Mod-2 system, based on experience gained during the program. For example, lines of small vortex generators were installed on the low pressure side of the blade, which delayed flow separation, enhanced control stability, and significantly increased energy capture. As a result, the turbine produced more power than its design predictions, in spite of the tips operating at higher angles of attack than expected.

One problem that was directly associated with the design of the wind turbine was that rotor cyclic loads were higher than calculated. While no structural failures occurred, the Mod-2 rotor as built would probably have had an approximately 10-year fatigue life, rather than the 30-year design value. It was felt that the rotor could be redesigned for a 30-year life, based on continued research which has shown the foundations of the problem. The structural loading estimates of that time used overly-simplified models of the wind. The effects of atmospheric turbulence on unsteady local lift forces, then on loads and stresses, and finally upon fatigue life were not adequately represented in design models. Based on the Mod-2 test results, major improvements in these models have been made in recent years. However, achieving long fatigue life in the presence of small-scale turbulence remains a principal technical challenge to the development of advanced wind turbines that are still reliable and cost-effective.

After modifications and repairs associated with initial mechanical problems, the Mod-2 test program and the turbines themselves went on to accomplish major test and performance objectives. The three Mod-2 HAWTs at Goodnoe Hills together accumulated over 16,000 hours of operating time and supplied over 10 million kWh to the local grid, over 60 percent of that amount in the final year of testing. A major test objective that was achieved was proving conclusively that groups of modern wind turbines could operate in a totally automatic, unattended mode. Another was establishing a data base on rotor wake structures and wake effects on downwind turbines that has led to the development of improved wake models being applied now to wind power stations (see Chapter 6).

Two additional Mod-2 turbines were built by Boeing for utility companies who wished to examine the performance of large-scale wind turbines directly from their perspective. One, purchased by the Pacific Gas and Electric Company, was installed on a test site in Solano County, northeast of San Francisco. A second, for the Bureau of Reclamation, was installed near the WTS-4 HAWT at Medicine Bow, Wyoming, for comparative testing. While all five of these machines achieved significant (and sometimes spectacular) test and operating results, large wind turbines were not yet at the stage where they could compete successfully for utility company operating funds, nor was there an industry willing to take the financial risks associated with their commercial development. All Mod-2 turbines were later dismantled, while the technology continued to be developed and commercial use awaited a change in energy economics.

The Mod-5 Program

Plans had already been laid in the late 1970s for the development of third-generation wind turbines. First, conceptual studies of advanced large- and medium-scale turbines (designated as Mod-3 and Mod-4) were conducted, but these were never carried beyond the preparatory stage. Later, consideration was given to two hardware-development programs: A large-scale *Mod-5 HAWT* program and a medium-scale *Mod-6 HAWT and VAWT* program. Two contractors were chosen to design and develop what became known as the *General Electric Mod-5A* and the *Boeing Mod-5B* HAWTs. At that point energy and fuel costs peaked and then turned downward, and energy was no longer a major national priority. As a result, the Mod-6 program (whose contractors had not yet been selected) was canceled, and General Electric chose not to proceed past the design stage. Thus, only one third-generation turbine, the Mod-5B, was completed under the Federal Wind Energy Program. NASA-Lewis engineers managed the project and *Hawaiian Electric Industries* became Boeing's utility partner.

The Mod-5B (Fig. 2-1 and 4-5), installed at the Kahuku wind power station on Oahu, has an overall configuration similar to that of the Mod-2, with a two-bladed, partial-span controlled, teetered, and upwind rotor atop a steel shell tower [Boeing 1988]. The pitchable tip sections were extended 3 m longer than those on the Mod-2 rotor, leading to a rotor diameter of 97.5 m. This makes the Mod-5B HAWT currently the largest wind turbine in the world. Its rated power is 3.2 MW, up 28 percent from the Mod-2 rating.

The major advancement in technology achieved by the Mod-5B is that it is the first large-scale wind turbine to operate successfully at *variable speed.* The speed varies from 13 to 17.3 rpm depending on wind speed, thus improving energy capture as well as

reducing structural loads. Maintaining constant 60-cycle power is accomplished through the use of a *doubly-wound generator*, associated *cycloconverter* power electronic equipment, and advanced control algorithms. *Vortex generators* (shown being installed in Fig. 5-24) and *trailing-edge tabs* improve the aerodynamic performance of the rotor. Most importantly, the Mod-5B was designed using advanced structural-dynamic computer codes like *Dylosat* [Finger 1985] and incorporating experience from the Mod-2 test program [Bovarnick and Engle 1985]. Thus it appears to be the first large-scale turbine with a reasonable expectation of a 30-year structural lifetime.

Final assembly commenced in January, 1987, at the site on the north shore of the island of Oahu, not far from where the fourth Mod-0A 200-kW wind turbine had been located. The turbine nacelle and rotor had been shipped by barge to Oahu from the mainland in subassemblies, together with the very large *ringer crane* needed for final assembly. The hub and mid-blade subassemblies of the 1.4-MN rotor, also of all-steel construction, were welded together on-site, rather than having bolted joints, as was the case with the Mod-2.

First wind-powered rotation of the Mod-5B HAWT occurred on July 1, 1987. The test program began in earnest in August, 1987, and consisted of two 500-hour phases. The first phase accomplished checkout of the turbine through its operating envelope and adjustment of controls and the variable-speed generating system. The second phase consisted of testing under a utility acceptance test scenario, the purchase price to the utility being a function of both *performance* and *availability* during a test period of at least 500 hours. The turbine achieved an energy capture performance of 106% of the basic contract requirement, producing 988 MWh during 660 hours of testing. It also achieved an availability of 95 percent, 5 percent over the basic requirement, an unparalleled level for that early a stage of testing of a new, advanced, and very large wind turbine.

In January of 1988, the Mod-5B was sold to the project's utility partner to operate as an integral part of the power generation mix on Oahu. During its first 55 months of service as a commercial power plant, the Mod-5B operated for 18,920 hours and produced 24,533 MWh of electricity, for an average power output of 1.32 MW [Spera and Miller 1992].

Currently, the Kahuku wind power station, consisting of the Mod-5B and 15 *Westinghouse WWG-0600* turbines rated at 600 kW (Fig. 3-39), is owned and operated by the Makani Uwila Power Corporation. The design of these Westinghouse machines combines successful technology from the Mod-0A program (wood/epoxy blades, nacelle structure, yaw drive by hydraulic actuators) with that from the Mod-2 (upwind/teetered rotor, shell tower, and dynamic flexibility).

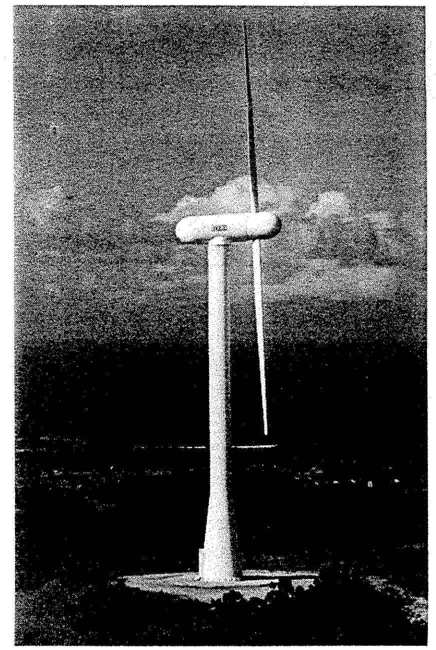


Figure 3-39. A 600-kW Westinghouse WWG-0600 HAWT, 43.3-m in diameter. This design applies technology from both the Mod-0A and Mod-2 wind turbines. (*Courtesy of Hawaiian Electric Industries*)

Advanced Wind Turbine Development

The development of technologically-advanced, higher-efficiency wind turbines continues to be a high priority of the wind industry worldwide. In the U.S., the Department of Energy is sponsoring a range of programs with the goal of developing wind power plants that can compete with conventional electric generation, producing energy at a cost of \$0.04/kWh by the year 2000 at sites with average wind speeds of 5.8 m/s (at a 10-m elevation). One of these, the "Advanced Wind Turbine Program" managed by the National Renewable Energy Laboratory [Laxon *et al.* 1992], is assisting U.S. industry to apply the latest technology to (1) improve existing wind turbine configurations, designs, and manufacturing methods, and (2) to initiate conceptual design studies of advanced wind power systems. Table 3-3 lists the participants and turbines in this cost-sharing program.

Table 3-3. Participants in the DOE/NREL Advanced Wind Turbine Program

Manufacturer	HAWT Model	Rotor Type [1]	Rotor Diameter (m)	Rated Power (kW)	Reference
Atlantic Orient Corp.	AOC 15/50	3/D/R	15	50	[Hughes *et al.* 1991]
Carter Wind Turbines	CWT-300	2/D/T	24	300	[Carter 1993]
Northern Power Systems	NW 250	2/U/T	21.3	150	[Coleman 1991]
R. Lynette & Associates	AWT-26	2/D/T	26.2	275	[Lynette 1991]

[1] Number of blades/Upwind or Downwind of Tower/Rigid or Teetered Hub

Many of the recent advances in technology and analytical capability have yet to be applied to commercial wind turbines. This is expected to occur over the next several years, particularly with the resurgence of interest in alternate sources of energy in the early 1990s. Passage of the Energy Policy Act of 1992 re-introduced tax credits in the U.S., in the form of production credits. This is believed by many to be more effective than the earlier tax credits based on capital investment. Increased emphasis on reducing power-plant emissions and on global climate changes are also providing a spur to non-polluting energy sources. An excellent discussion of current trends in wind turbine performance and cost and an exploration of future turbine configurations is given by Thresher *et al.* [1993].

Concluding Remarks

Whether commercial machines in the future grow in size to that of the Mod-5B HAWT only time, the international marketplace, and the vagaries of energy cost and availability will determine. Meanwhile, several other advanced medium-scale and large-scale systems with rated powers from 500 kW to 2 MW and rotor diameters from 30 m to 60 m are under development in Europe. Commercial development of small- and medium-scale wind turbines continues, albeit this development was slowed somewhat by the slackening of the energy market and changes in energy incentives and tax policy. Most of all, research and advanced technology development continue, in both the private and public sectors, in a quest for higher-performance coupled with more reliability.

Stepping back from individual details, one can assess the significant changes in the technology of wind turbines over the two decades by examining their overall performance. *Specific annual energy production* (kilowatt-hours per square meter of swept area) has

increased approximately 40 percent from the mid-1970s to the mid-1980s because of improved aerodynamic performance. *On-line availability* has improved from the 60% range to over 95% (for the better systems) during the same period. In California in 1992, these two factors plus improvements in operating and maintenance strategies have significantly increased specific annual energy production to an average of almost 900 kWh/m^2 for machines rated above 200 kW. The average rated power of commercial wind turbines installed in the U. S. has increased from less than 50 kW in 1981 to well over 100 kW today. *Installed costs* have declined from over \$3,000 per square meter in the mid-1970s to the \$500 level available today.

While significant progress has been made, additional improvements are both necessary and possible. Cost-effective wind turbines are required for the much-more prevalent sites with medium wind speeds, in order to expand the geographic distribution of wind power stations. This still remains the principal challenge to the developing technology of wind power. In the short term, improvements in the structural lifetime of components, particularly of rotor blades, is required.

Predicting the longer term future is more difficult. One can anticipate a continuing increase in performance and energy capture from improved airfoils, control systems (including increased adoption of variable-speed designs), operating strategies, and siting techniques. One also anticipates decreased structural weight and complexity from improved understanding of the interaction between wind turbulence, air loads, and structural response. Just which turbine configurations, component designs, and innovative ideas will be adopted in the future cannot be predicted.

While there remain many areas in which research and development will continue, the evolution of modern wind turbines since World War II (and particularly during the past two decades) have brought us to a stage where the large-scale use of wind power with minimal technical risk is a probability. The success of commercial wind power stations, after overcoming early difficulties, has established the technical and economic potential of wind power. More energy is being produced today by wind turbines than has ever been produced in the history of wind power.

References

ASME, 1989, *Performance Test Codes - Wind Turbines*, ASME/ANSI PTC 42-1988, New York, New York: American Society of Mechanical Engineers.

Balombin, J. R., 1980, *An Exploratory Survey of Noise Levels Associated with a 100 kW Wind Turbine*, NASA TM-81486, Cleveland, Ohio: NASA Lewis Research Center.

Barchet, W. R., A. Bass, S. R. Andersen, *et al*, 1980-81, *Wind Energy Resource Atlas, Vols. 1 - 12*, PNL-3195-WERA-1 to -12, Richland, Washington: Battelle Pacific Northwest Laboratories.

Berg, D. E., P. C. Klimas, and W. A. Stephenson, 1990, "Aerodynamic Design and Initial Performance Measurements for the Sandia 34-m Diameter Vertical-Axis Wind Turbine," *Proceedings, Ninth ASME Wind Energy Symposium,* D. E. Berg, ed., New York: American Society of Mechanical Engineers, pp. 93-99.

Boeing Engineering and Construction Company, 1982, *Mod-2 Wind Turbine System Development Final Report - Vol. I, Executive Summary*, NASA CR-168006, DOE/NASA/0002-1, Cleveland, Ohio: NASA Lewis Research Center.

Boeing Aerospace Company, 1988, *Mod-5B Wind Turbine System Development Final Report - Vol. I, Executive Summary*, NASA CR-180896, DOE/NASA/0200-3, Cleveland, Ohio: NASA Lewis Research Center.

Bongers, P. M. M., G. E. van Baars, and S. Dijkstra, 1993, "DUWECS: A Wind Turbine Design Tool," *Proceedings, Windpower '93 Conference*, Washington, DC: American Wind Energy Association, pp. 305-312.

Bonnefille, R., 1974, "French Contribution to Wind Power Development - by EDF 1958 - 1966," *Proceedings, Advanced Wind Energy Systems*, Vol. 1, (published 1976), O. Ljungström, ed., Stockholm: Swedish Board for Technical Development and Swedish State Power Board, pp. 1-17 to 1-22.

Bovarnick, M. L., and W. W. Engle, 1985, "The Evolution of the Mod-2 and Mod-5B Wind Turbine Systems," *Proceedings, Windpower '85*, SERI/CP-217-2902, Washington, DC: American Wind Energy Association, pp. 158-163.

Carter, J. W., Jr., 1993, "Development and Performance of the Lightweight Carter Wind Turbine," *Proceedings, Windpower '93 Conference*, Washington, DC: American Wind Energy Association, pp. 142-151.

Clark, R. N., 1983, "Agricultural Wind Energy Research -- An Overview," *Proceedings, Sixth Biennial Wind Energy Conference and Workshop*, B. H. Glenn, ed., Boulder, Colorado: American Solar Energy Society, pp. 31-34.

Coleman, C., 1991, "Northern Power's Advanced Wind Turbine Development Program," *Proceedings, Windpower '91*, Washington, DC: American Wind Energy Association, pp. 185-192.

Collins, J. L., R. K. Shaltens, R. H. Poor, and R. S. Barton, April 1982, *Experience and Assessment of the DOE-NASA Mod-1 2000-kW Wind Turbine Generator at Boone, North Carolina*, NASA TM-82721, DOE/NASA/23066-2, Cleveland, Ohio: NASA Lewis Research Center and The General Electric Company.

Dieter, G. E., J. Chapman, H. T. Hahn, D. H. Hodges, C. W. Rogers, L. Valavani, and M. D. Zuteck, 1981, *Assessment of Research Needs for Wind Turbine Rotor Materials Technology*, National Research Council Report NAT S-324, Washington, DC: National Academy Press.

Elliott, D. L., C. G. Holloday, W. R. Barchet, H. P. Foote, and W. F. Sandusky, 1987, *Wind Energy Resource Atlas of the United States*, DOE/CH-10094-4, Golden, Colorado: National Renewable Energy Laboratory; also available from American Wind Energy Association, Washington, DC.

Ferber, R., 1977, "Public Reactions to Wind Energy and Windmill Designs," *Proceedings, Third Biennial Conference and Workshop on Wind Energy Conversion Systems*, CONF 770921, Washington, DC: JBF Scientific Corporation, pp. 413-419.

Foreman, K. M., and G. L. Gilbert, 1979, "Technical Development of the Diffuser Augmented Wind Turbine (DAWT) Concept," *Wind Engineering*, Vol. 3, No. 4: pp. 153-166.

Frandsen, S. (ed.), 1990, *Recommended Practices for Wind Turbine Testing and Evaluation - Vol. 1: Power Performance Testing*, Second Edition, Lyngby, Denmark: Department of Fluid Mechanics, Technical University of Denmark.

Frederick, G. R., and J. M. Savino, 1986, *Summary of Tower Designs for Large Horizontal Axis Wind Turbines*, NASA TM-87166, DOE/NASA/20320-68, Cleveland, Ohio: NASA Lewis Research Center.

Golding, E. W., 1955, *The Generation of Electricity by Wind Power*, London: E. & F.N. Spon Ltd.; reprinted with an additional chapter by R. I. Harris, 1976, New York: Halsted Press, Division of John Wiley & Sons, Inc.

Godtfredsen, F., P. H. Jensen, and P. E. Morthorst, 1993, "Wind Energy in Denmark: Development in Wind Turbine Technology and Economics Since 1980," *Proceedings, Windpower '93 Conference*, Washington, DC: American Wind Energy Association, pp. 110-117.

Honnef, H., 1932, *Windkraftwerke*, Braunschweig: F. Vieweg & Sohn Verlag.

Hughes, P. S., R. W. Sherwin, and H. M. Clews, 1991, "Development of Atlantic Orient's 15/50 Wind Turbine," *Proceedings, Windpower '91 Conference*, Washington, DC: American Wind Energy Association, pp. 193-199.

Hütter, U., 1973a, *The Development of Wind Power Installations for Electrical Power Generation in Germany*, NASA Technical Translation TT F-15,050 (L. Kanner Associates), Washington, D.C.: National Aeronautics and Space Administration.

Hütter, U., 1973b, *A Wind Turbine with a 34-m Rotor Diameter*, NASA Technical Translation TT F-14,879 (L. Kanner Associates), Washington, D.C.: National Aeronautics and Space Administration.

Hütter, U., 1974, "Review of Development in West-Germany," *Proceedings, Workshop on Advanced Wind Energy Systems*, Vol. 1, 1974 (published 1976), O. Ljungström, ed., Stockholm: Swedish Board for Technical Development and Swedish State Power Board, pp. 1-51 to 1-72.

IEA, 1993, *IEA Wind Energy Annual Report 1992*, B. Pershagen, ed., Stockholm: NUTEK.

Juul, J., 1964, "Design of Wind Power Plants in Denmark," *Wind Power, Proceedings of United Nations Conference on New Sources of Energy*, Vol. 7, New York: The United Nations, pp. 229-240.

Klimas, P. C., and M. H. Worstell, 1986, "Performance Testing of the Sandia National Laboratories 17-m Diameter Research Turbine with Natural Laminar Flow Blade Elements," *Proceedings, Fifth ASME Wind Energy Symposium*, New York: American Society of Mechanical Engineers.

Lauffer, J. P., T. G. Carne, and T. D. Ashwill, 1987, "Modal Testing in the Design Evaluation of Wind Turbines," *Proceedings, Windpower '87 Conference*, SERI/CP-217-3315, Golden, Colorado: National Renewable Energy Laboratory, pp. 79-87.

Laxson, A. S., S. M. Hock, W. D. Musial, and P. R. Goldman, 1992, "An Overview of DOE's Wind Turbine Development Program," *Proceedings, Windpower '92 Conference*, Washington, DC: American Wind Energy Association, pp. 426-430.

Loeffler, A. L., Jr., 1981, "Flow Field Analysis and Performance of Wind Turbines Employing Slotted Diffusers," *Transactions ASME, Journal of Solar Engineering*, Vol. 103: pp. 17-22.

Linscott, B. S., P. Perkins, and J. T. Dennett, 1984, *Large, Horizontal-Axis Wind Turbines*, NASA TM-83546, DOE/NASA/20320-58, Cleveland, Ohio: NASA Lewis Research Center.

Lissaman, P. B. S., A. D. Zalay, and B. Hibbs, 1980, "Development of the Dynamic Inducer Wind Turbine," *Proceedings, Second Wind Energy Innovative Systems Conference*, Vol. II, SERI/CP-635-1061, Golden, Colorado: National Renewable Energy Laboratory, pp. 113-132.

Lundsager, P., S. Frandsen, and C. J. Christensen, 1980, *Analysis of Data from the Gedser Wind Turbine, 1977-1979*, Risø-M-2242, Roskilde, Denmark: Risø National Laboratory Station for Wind Turbines.

Lynette, R., 1991, "Advanced 275 kW Wind Turbine," *Proceedings, Windpower '91 Conference*, Washington, DC: American Wind Energy Association, pp. 200-205.

Muraca, R. J., Stephen, S., V. Maria, and R. J. Dagenhart, 1975, *Theoretical Performance of Vertical Axis Windmills*, NASA TMX-72662, Hampton, VA: NASA Langley Research Center.

Musgrove, P. J., and R. Clare, 1987, "Development of the U.K. Vertical Axis Wind Turbine," *Proceedings, Windpower '87 Conference*, SERI/CP-217-3315, Washington, DC: American Wind Energy Association, pp. 28-34.

Milborrow, D. J., and J. F. Ainslie, 1992, *Intensified Study of Wake Effects Behind Single Turbines and in Wind Turbine Parks*, Leatherhead, U.K.: National Wind Power.

Miller, A., and R. L. Simon, September 1980, *Wind Resource Potential in California*, California Energy Commission Report P-500-82-052, San Jose, California: San Jose State University.

Miller, R. H., et al, 1978, *Wind Energy Conversion - Vol. 2: Aerodynamics of Horizontal Axis Wind Turbines*, C00-4131-T1, Cambridge, Massachusetts: Massachusetts Institute of Technology.

Page, D. I., and L. A. W. Bedford, 1987, "A Progress Report on the UK Department of Energy's Wind Energy Programme," *Proceedings, Windpower '87 Conference*, SERI/CP-217-3315, Washington, DC: American Wind Energy Association, pp. 246-252.

PNL, 1980, *Siting Handbook for Small Wind Energy Conversion Systems*, PNL-2521, Richland, Washington: Battelle Pacific Northwest Laboratories.

PNL, 1981, *Meteorological Aspects of Siting Large Wind Turbines*, PNL-2522, Richland, Washington: Battelle Pacific Northwest Laboratories.

Puthoff, R. L., and P. J. Sirocky, 1974, *Preliminary Design of a 100-kW Wind Turbine Generator*, NASA TMX-71585, ERDA/NASA/1004-77/6, Cleveland, Ohio: NASA Lewis Research Center.

Putnam, P. C., 1948, *Power from the Wind*, New York: Van Nostrand Reinhold Company.

Richards, B., 1987, "Initial Operation of Project Eolé 4 MW Vertical Axis Wind Turbine Generator," *Proceedings, Windpower '87 Conference*, Washington, DC: American Wind Energy Association, pp. 22-27.

Rogers, S. E., B. W. Cornaby, P. R. Sticksel, and D. A. Tolle, 1977, *Environmental Studies Related to the Operation of Wind Energy Systems*, COO-0092-77/2, BCL-0092, Columbus, Ohio: Battelle Memorial Institute.

Rybak, S. C., 1981, "Description of the 3 MW SWT-3 Wind Turbine at San Gorgonio Pass California," *Proceedings, Fifth Biennial Wind Energy Conference and Workshop*, Vol. I, I. E. Vas, ed., Washington, DC: American Wind Energy Association, pp. 193-206.

Senior, T. B. A., D. L. Sengupta, and J. E. Ferris, 1977, *TV and FM Interference by Windmills*, DOE/TIC-11348, Ann Arbor, Michigan: University of Michigan.

Shaltens, R. K., and A. G. Birchenough, 1983, *Operational Results for the Experimental DOE/NASA Mod-0A Wind Turbine Project*, NASA TM-83517,DOE/NASA/20320-55, Cleveland, Ohio: NASA Lewis Research Center.

South, P., and R. S. Rangi, 1972, *A Wind Tunnel Investigation of a 14-ft Diameter Vertical Axis Windmill*, NRC Laboratory Technical Report LTR-LA-105, Toronto: National Research Council of Canada.

Spera, D. A., 1977, *Comparison of Computer Codes for Calculating Dynamic Loads in Wind Turbines*, NASA TM-73773, DOE/NASA/1028-78/16, Cleveland, Ohio: NASA Lewis Research Center.

Spera, D. A., J. B. Esgar, M. Gougeon, and M. D. Zuteck, 1990, *Structural Properties of Laminated Douglas Fir/Epoxy Composite Material*, NASA Reference Publication 1236, DOE/NASA/20320-76, Cleveland, Ohio: NASA Lewis Research Center.

Spera, D. A., and M. W. Miller, 1992, "Performance of the 3.2-MW Mod-5B Horizontal-Axis Wind Turbine During 55 Months of Commercial Operation in Hawaii," *Proceedings, Windpower '92 Conference,* Washington, DC: American Wind Energy Association, pp. 231-238.

Stahl, W., and R. Windheim, 1987, "Wind Energy Utilization: Status of Research and Development in the Federal Republic of Germany," *Proceedings, Windpower '87*, SERI/CP-217-3315, Washington, DC: American Wind Energy Association, pp. 240-245.

Stodhart, A. H., 1974, "Review of the UK Wind Power Programme 1948-1960," *Proceedings, Workshop on Advanced Wind Energy Systems,* Vol. 1, (published 1976), O. Ljungström, ed., Stockholm: Swedish Board for Technical Development and Swedish State Power Board, pp. 1-23 to 1-34.

Thomas, P. H., 1946, *Electric Power from the Wind,* Federal Power Commission Report.

Thomas, P. H., 1949, "Harnessing the Wind for Electric Power," *Proceedings, United Nations Scientific Conference on the Conservation and Utilization of Resources,* Vol. III, New York: The United Nations, pp. 310.

Thomas, R. L., 1982, *DOE/NASA Lewis Large Wind Turbine Program,* NASA TM-82991, Cleveland, Ohio: NASA Lewis Research Center.

Thresher, R. W., S. M. Hock, H. M. Dodd, and J. M. Cohen, 1993, "Advanced Technology for the Year 2000: Utility Application," *Proceedings, Windpower '93 Conference,* Washington, DC: American Wind Energy Association, pp. 61-70.

USDA, 1979, *Wind Energy Applications in Agriculture,* Report No. 1109-20401/79/2, Washington, D.C.: U. S. Department of Agriculture.

Vas, I. E., and R. L. Mitchell, 1979, "A Review of the Wind Energy Innovative Systems Program," *Proceedings, Fourth Biennial Conference and Workshop on Wind Energy Conversion Systems,* CONF-791097, Washington, DC: JBF Sci. Corp., pp. 349-418.

Weingart, O., 1981, *Design, Evaluation, and Fabrication of Low-Cost Composite Blades for Intermediate-Size Wind Turbines,* NASA CR-165342, DOE/NASA/0100-1, Cleveland, Ohio: NASA Lewis Research Center.

Wilson, R. E., and P. B. S. Lissaman, 1974, *Applied Aerodynamics of Wind Power Machines,* Corvallis, OR: Oregon State University.

Wilson, R. E., P. B. S. Lissaman, and S. N. Walker, 1976, *Aerodynamic Performance of Wind Turbines,* ERDA/NSF/04014-76/1, Corvallis, OR: Oregon State University.

Windheim, R., 1983, "The Wind Energy Program of the Federal Republic of Germany and State of Wind Energy Projects," *Proceedings, Sixth Biennial Wind Energy Conference and Workshop,* B. H. Glenn, ed., Boulder, Colorado: American Solar Energy Society, pp. 75-85.

Wright, A. D., M. L. Buhl, and R. W. Thresher, 1988, *FLAP Code Development and Validation,* SERI/TR-217-3125, Golden, Colorado: National Renewable Energy Laboratory.

Wright, A. D., M. L. Buhl, and A. S. Elliott, 1993, "Development of a Wind Turbine Systems Dynamics Model for a Two-Bladed Teetering Hub Turbine Using the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) Software," *Proceedings, Windpower '93 Conference,* Washington, DC: American Wind Energy Association, pp. 299-304.

WMO, 1981, *Meteorological Aspects of the Utilization of Wind as an Energy Source,* WMO Report No. 575, Geneva, Switzerland: World Meteorological Organization.

4

Commercial Wind Turbine Systems and Applications

Robert Lynette
R. Lynette and Associates, Inc.
Redmond, Washington

and

Paul Gipe
Paul Gipe and Associates
Tehachapi, California

Introduction

This chapter describes commercial wind turbine systems in the U.S. and abroad, including windmills for water pumping and wind turbines for generating electrical energy. Commercial wind systems, as defined here, include production turbines, pre-production turbines that could be manufactured commercially within the next five years, and prototype (one-of-a-kind) turbines that are privately owned and producing electricity for sale. Although the history of wind system development was discussed in the previous chapters, some historical details will be introduced here as well, when they help place commercial wind power systems in the proper historical or technological context. This discussion of commercial systems and applications considers small-, medium-, and large-scale horizontal-axis wind turbines (HAWTs), and medium-scale vertical axis wind turbines (VAWTs).

Wind power applications described include *wind power stations* on utility grids, *distributed (dispersed) turbines* on utility grids, turbines on *isolated and/or small electrical systems*, and *stand-alone units* for mechanical and electrical power. *Operation and maintenance* (O&M) requirements for current systems are discussed that reflect the past 15 years of commercial experience, including typical maintenance scenarios, associated costs, and trends within the industry.

The development of current wind systems did not occur in a vacuum. This chapter concludes with material that describes the *social, business, and regulatory environment* that led to the development of the current wind power industry and provides the past, current, and future *cost goals* for commercial wind turbines. These non-technical forces strongly affect the present wind power industry and the development of future wind turbines and applications.

The wind turbine has evolved into a highly specialized device whose configuration, size, and technological sophistication are application-dependent. For pumping small amounts of water in flat terrain, no substitute has been found for the classic, multi-bladed *American windmill* driving a mechanical pump. However, when the turbine must be located away from the water source, modern *electrical water pumpers* are a better choice. For remote, unattended locations, *battery chargers* employing highly-reliable rotor control methods are selected. If power is required to supplement the needs of homes or small businesses, *small AC units* with outputs up to 25 kW are the machines of choice.

Small wind turbines can also be interconnected with utility networks in clusters to provide larger amounts of power. But developers have found that *medium-scale* systems ranging from 100 kW up to 600 kW are more desirable for such applications. Finally, several government programs have built and tested huge, experimental *multi-megawatt* machines with rotor diameters up to 100 m.

The horizontal-axis orientation continues to be dominant in wind power production, as it has been for most of the modern era. Because the interconnection of wind turbines to utilities became their principal application during the 1980s and continues to be so into the 1990s, the average size of wind turbines has grown. In the U.S., many small machine designs have simply disappeared as manufacturers have scaled them up into the medium size range. The very question of *size classifications* has been raised, as well, in recent years. For purposes of this chapter, wind turbines are classified as shown in Table 4-1, according to their diameters and/or their rated powers. This table follows the terminology used in the early U.S. Federal Wind Energy Program (described in Chapter 3), but with some variation in numbers:

Table 4-1. Scale Classifications of Wind Turbines

Scale	Rotor Diameter	Power Rating
Small	Less than 12 m	Less than 40 kW
Medium	12 m to 45 m	40 kW to 999 kW
Large	46 m and larger	1.0 MW and larger

Commercial Installations in the U.S. in the Mid-1980s

To illustrate the wide variety of small-, medium-, and large-scale turbines that have been operated commercially, sketches of most of the wind turbines installed in major U.S. wind power stations in the mid-1980s are shown in Appendix C, together with pertinent technical data [Johnson and Young 1985; SCE and U.S. Windpower Inc. 1986a; SCE and U.S. Windpower Inc. 1986b; PG&E and U.S. Windpower, Inc. 1986 and 1988; Suehiro and Miller 1988]. The number of units installed of a given configuration is the total for all regions during this time period.

Wind power stations have been installed on a wide variety of terrains, as shown by the general views in Figures 4-1 to 4-5. In California, these include the rolling inland terrain of Altamont Pass (Fig. 4-1), the rugged terrain of the Tehachapi Mountains (Fig. 4-2), and the flat desert areas in San Gorgonio Pass (Fig. 4-3). Two other types of terrain with wind turbines are represented by the coastal hills on Oahu in the Hawaiian Islands (Fig. 4-4), and the flat high-plains area near Medicine Bow, Wyoming (Fig. 4-5).

While many of the wind turbine models described in Appendix C are no longer being manufactured, this set of designs defines the scope of commercial wind power development in the U.S. in the mid-1980s. Since that time, some small-scale turbines have been retired and, in most cases, replaced by larger units. Plant operators have modified many of the medium-scale machines to upgrade their durability and performance. Retrofitting of rotors, power trains, and yaw drives has been common, and some power ratings have had to be lowered. The large-scale Mod-5B and WTS-4 HAWTs, built for technology development under U.S. government sponsorship, are now privately owned and are operated as commercial power plants. No further production of these two machines is planned.

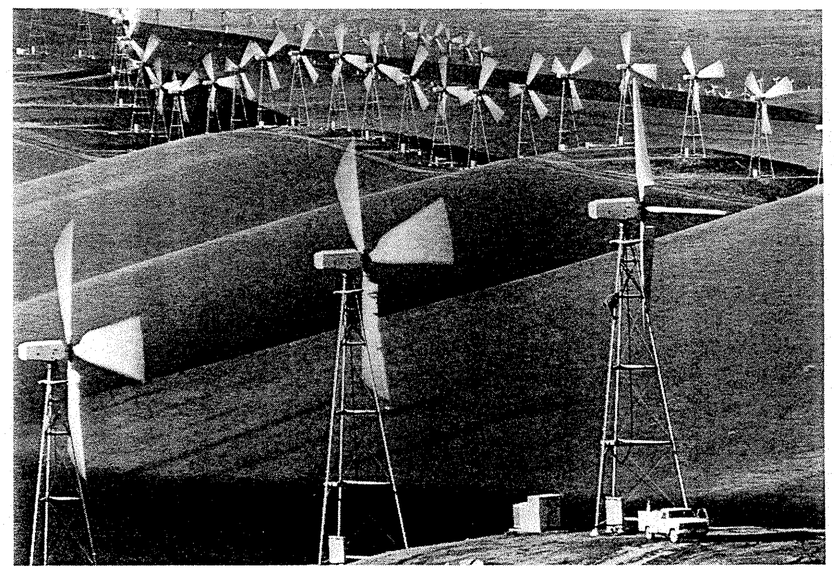


Figure 4-1. Rolling terrain in the Altamont Pass region of California. Lines of *USW 56-100* HAWTs are normal to the prevailing wind, with spacings larger in the windwise and smaller in the crosswind directions. (*Courtesy of Kenetech/U. S. Windpower, Inc.*)

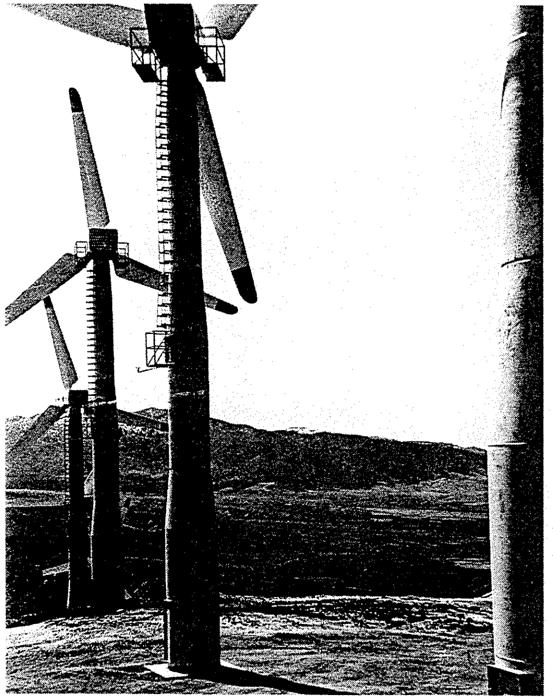


Figure 4-2. Rugged terrain in the Tehachapi Mountains of California. These 120-kW *Bonus 120/20* HAWTs are typical of the three-bladed, upwind-rotor turbines manufactured in Denmark. (*Courtesy of Arbutus Energy Company*)

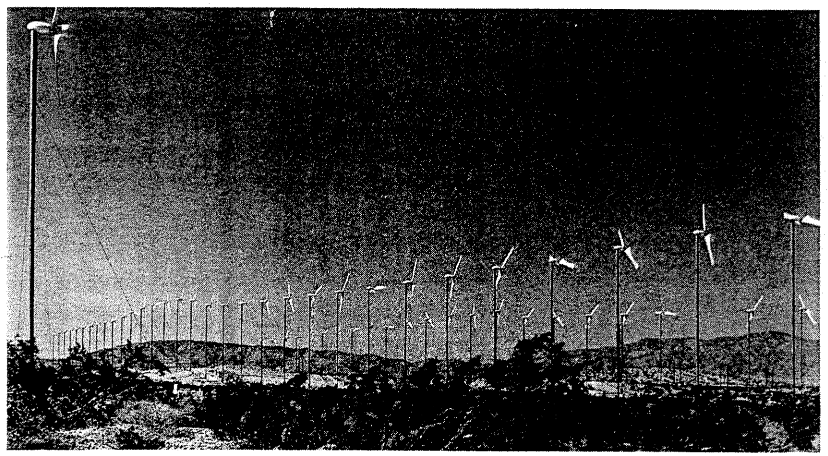


Figure 4-3. Flat desert terrain in the San Gorgonio Pass near Palm Springs, California. The two-bladed, downwind-rotor turbines shown are 25-kW *Carter 25* HAWTs. (*Courtesy of NASA Langley Research Center*)

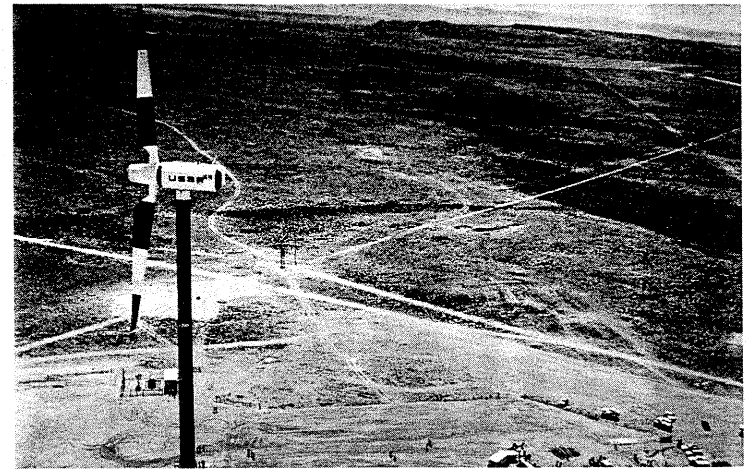


Figure 4-4. Flat high-plains terrain in Wyoming. The 4.0-MW *WTS-4* HAWT shown here is a former research prototype of the U. S. Bureau of Reclamation, now in commercial service. (*Courtesy of the Medicine Bow Energy Company*)

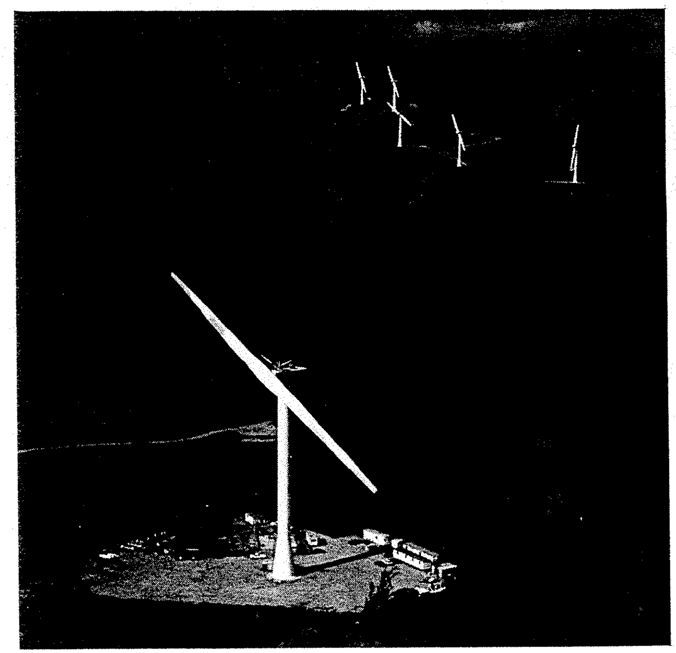


Figure 4-5. Coastal hills on Oahu in the Hawaiian Islands. In the foreground is the 2.5-MW *Mod-5B* HAWT, and 600-kW *WWG-0600* machines are in the background. (*Courtesy of Hawaiian Electric Industries*)

A comprehensive documentation of the commercial development of wind turbines world-wide in the late 1980s is given by Jaras [1987]. In addition to extensive statistics on the world market for wind turbines (*e.g.* by region, rotor diameter, and type of application), descriptions are included of 160 manufacturers of small- and medium-scale machines, with sketches, specifications, and estimated numbers of the wind turbine models produced.

Small Windmills Used for Water Pumping

Pumping water requires the rotor to deliver higher torque than that required by an electrical generator of the same power. Torque requirements were particularly high prior to the 19th Century when one revolution of the rotor completed one pump cycle, prior to the development of *back gearing (gear reduction)*. Because the demand for water is most critical during the dry or summer season, the water pumping windmill must function when the winds are usually light. Most designers of water-pumping windmills solved this problem by using rotors with *multiple blades* of flat panels or paddles around either a vertical or a conventional horizontal axis. Uses include land *irrigation*, human or livestock *water supply*, and *drainage*.

American Windmills

In the United States during the early 19th century, many improvised turbines were built on the Great Plains. The result was the appearance of the machine known as the classic *American windmill* (Fig. 1-17), developed during the late 19th Century. This much-copied design is now found throughout the world. The abundance of non-U.S. manufacturers, especially Australian, has led some outside the U.S. to describe the design today as a *classical windmill* rather than American. These machines drive a piston-type pump in a well that normally ranges from 1 m to more than 150 m in depth. The major components of water pumping windmills are the *rotor*, the *crank* mechanism, the *tracking* mechanism, the *pump*, and the *tower*. Attempts have been made to improve upon these multi-blade turbines by using articulating paddles or blades in vertical-axis designs, but with little success.

Rotor

The "mathematical" windmill, as the first American rotors were called, substituted curved metal sheets for the wooden slats previously used for blades. This design nearly doubled performance to about 15 percent efficiency, and dominated the market until the 1980s. Most of the rotors are of *high solidity*, with 10 to 20 radial blades. These rotors rotate at slower speeds and have higher starting torques than two- or three-bladed, low-solidity rotors. A high starting torque is desirable for those wind machines that pump water from deep wells. The deeper the well, the longer and heavier the pump rod and the higher the water has to be lifted, so more force is required. Rotor diameters range from about 2 m to 7 m. Wind tracking is generally achieved by the use of a *tail vane*.

Crank Mechanism

The crank mechanism (Fig. 4-6) converts rotational motion into *vertical reciprocating* motion. A slight *gear reduction* (about 3:1) is often used between the turbine shaft and the crank shaft. This reduction decreases crankshaft speed and increases available torque.

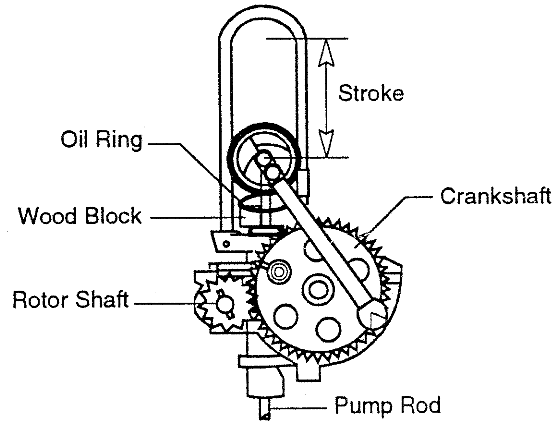


Figure 4-6. Gear reduction and crank mechanism of a water-pumping windmill.

Pump and Tower

The most common type of pump being used is the *single-action piston pump*, where water is pumped on the upward stroke. Cylinder diameter sizes range from about 25 mm for deep wells to about 250 mm for shallow wells. Most towers are of *truss design*.

Modern Windmills and Wind Turbines for Water Pumping

Designs of water-pumping windmills must reflect their application, since their performance is dependent on the *flow required*, the type of *well*, and the *head* (the distance from the well water to the outlet). In the United States, most of these machines are intended for *low flow* (approximately 1 m^3/h) and *medium head* (from 15 m to 45 m). In the developing world, the flow desired may be similar, but the head is often less. The windmill may be driving a *piston*, *air-lift*, or *diaphragm pump*.

Developing Countries

Because of the renewed interest in water pumping applications, organizations such as the *Intermediate Technology Development Group* (ITDG) in the United Kingdom have produced water pumper designs using fewer blades. These designs deliver higher efficiencies than the American design. About 1,500 water pumping windmills incorporating these features are in use around the world. For applications in developing countries, water-pumping windmills must be easily built (preferably from local materials by semi-skilled labor), and easily maintained (preferably requiring little or no service).

Construction in such applications is characterized by the use of sheet metal, wood, or fabric blades and few machined parts. Fabric-covered blades have made a comeback in developing-country use because of their low cost, ease of construction, and readily-available materials. However, the ITDG and other groups have returned to the historically-optimized American windmill because of its proven low manufacturing costs and low maintenance requirements.

Wind-Assisted Irrigation

For a century, conventional windmills have been used successfully to drive mechanical pumps at ground level. However, for large-volume irrigation needs (100 m^3/h) from deep wells (50 m to 100 m), the American water-pumping windmill is not appropriate. When the U.S. Department of Agriculture (USDA) addressed this problem, there were few modern wind machines large enough to meet these flow and head requirements, and many were ill-suited for delivering mechanical power at ground level for easier maintenance. USDA picked the Darrieus configuration to demonstrate *wind-assisted irrigation* because it was large enough to drive the pump and its drive train was close to the ground.

As shown in Figure 4-7 [Clark *et al.*, 1981], the well pump is connected to both an electric motor and a drive shaft to a VAWT through a combination drive. The motor is connected to the utility line and drives the pump when winds are low. With a *speed-increasing* transmission on the VAWT shaft, wind power can be used to drive a deep-well pump directly through an *over-running clutch* when wind speeds are in the operating range of the turbine. This is a desirable feature in the Southwest U.S. where gasoline or diesel engines drive numerous irrigation pumps mechanically. HAWTs of comparable size are not as well suited to this application, as shown by unsuccessful attempts with a *Jacobs* turbine.

Wind-Assisted Drainage

The American water-pumping windmill is not designed for the high-volume, low-head pumping required for draining land in lowland countries such as those in Northern Europe or in Ireland's peat bogs [Hurley 1986]. The Germans, Danes, and Dutch have developed *wind-pumps* for such applications. They use fewer blades (often four) rotating at higher speeds. These small turbines (generally less than 4 meters in diameter) drive *diaphragm* or *centrifugal* pumps. Conventional wind turbines driving induction generators also can be used in this application to off-load the demand for electricity to run a high-volume, low-head drainage pump.

Wind-Powered Irrigation

Another approach for irrigation is to use conventional HAWTs or VAWTs to power an electric deep-well pump. This method allows flexibility when the turbine is at a different location than the pump. In 1987, the U.S. Department of Energy sponsored a test of an wind-electric system utilizing a *Bergey Excel* 10-kW HAWT. In a recent study [Clark and Mulh 1992] the calculated annual output of a modern windmill (a 2.44-m diameter *Aermotor*) and its mechanical pump was compared to that of a small-scale wind turbine (a *Bergey 1500* 1.5 kW HAWT) powering a submersible electric motor and pump. The basis for these calculations was short-term performance test data and long-term wind data. For approximately the same installed cost, the wind-electric system was predicted to pump about 68% more water per year for the same lift. However, a consideration of the total system costs (*i.e.*, cost per cubic meter of water delivered with the same lift) may show more balance between the two approaches [Moroz 1993].

Most electrical configurations will employ an *induction generator* connected to the grid for *excitation*. However, USDA researchers have demonstrated that stand-alone wind turbines with alternators producing *variable-frequency variable-voltage* electricity can also be used to drive well motors [Clark and Pinkerton 1988]. This is an important consideration when designing pumping systems for remote applications where utility service is nonexistent. In a variable-speed system it is necessary to match the performance characteristics of the turbine, motor, and pump components over the speed range expected.

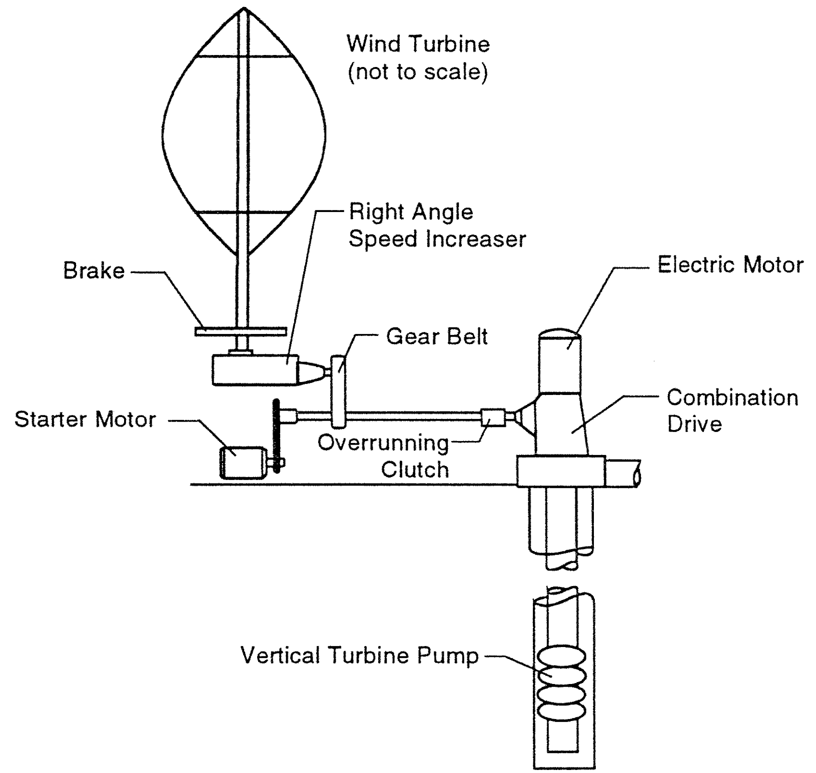


Figure 4-7. Diagram of a VAWT mechanical drive system for wind-assisted irrigation. [Clark *et. al.* 1981]

Another system for pumping water solely with wind power is illustrated in Figure 4-8, in which two different wind turbines are used in tandem. The well pump is driven mechanically by a multi-bladed windmill, lifting water first to a ground-level storage tank. An electrical *booster pump* powered by a small-scale wind turbine is then used to distribute the water to higher elevations. Shown here is a commercially-available system that uses this approach, combining a 6.4-m diameter *Wind Baron Softwind 21* windmill, which drives a reciprocating well pump, with a 1.5-m diameter, 600-W *Wind Baron NEO* HAWT for powering the booster pump.

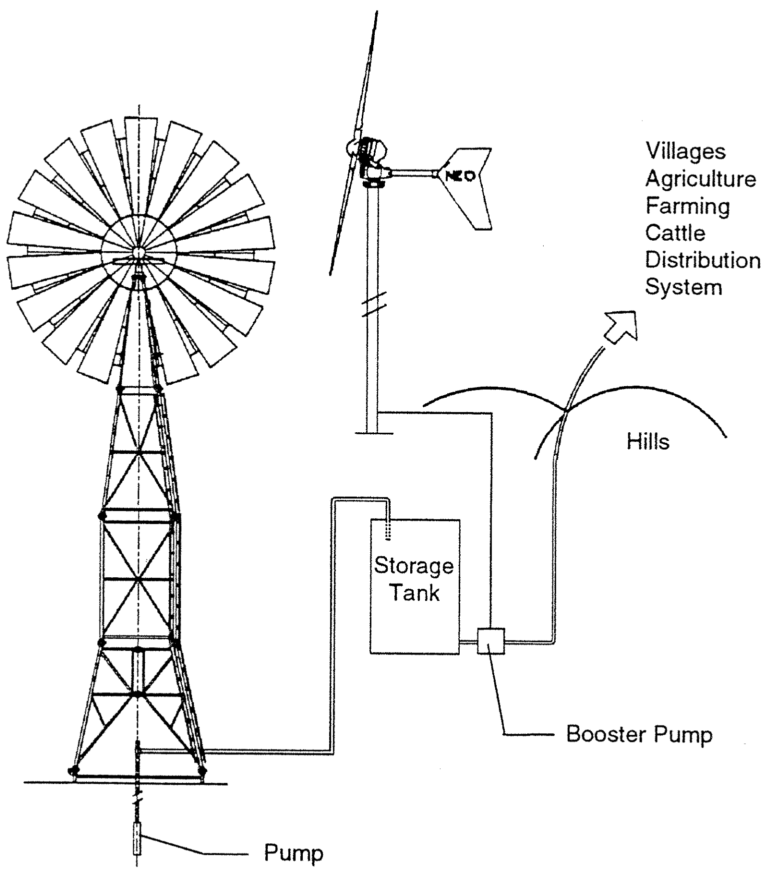


Figure 4-8. Diagram of a tandem wind-powered system for pumping water. A windmill drives the well pump, while a wind turbine powers an electric booster pump for the distribution system. (*Courtesy of Wind Baron Corporation*)

Recent Technical Developments in Water-Pumping Windmills

Until the last 10 years, there were few fundamental changes in the design of the windmill or water pump. One of the objectives in recent improved designs is to reduce the required *starting torque*. This improvement would allow the machine to start pumping water at lower wind speeds, as well as increase the flow rate at higher wind speeds. The most direct approach is to balance most of the weight of the pump rod and water column by the use of *counterweights* and/or *springs*. Another approach used is a *quick-return cam mechanism* that directs more of the available energy (per cycle) into the upward or pumping stroke and less energy into the downstroke.

The most promising new design is called an *automatic stroke control* device that can be attached to a conventional windmill. This device varies the pump stroke proportionally to the wind speed. At lower wind speeds the stroke is shorter, which results in a mechanical advantage that decreases the torque required to start pumping water. As the wind speed increases, the stroke automatically increases at a predetermined rate. This design produces a better match between the pump load and the available power from the wind than is found in any other system. The highest known windmill/pump efficiency was obtained by using this mechanism. With an automatic stroke control system, it will be possible to use high-speed, low-solidity rotors to achieve higher efficiencies in pumping and lower rotor weights.

Improvements in the basic pump designs include the use of *double-acting pumps* rather than single-acting, *long-life cylinders*, *larger flapper valves*, and *air lift pumps*. Many different power transmission schemes are being tried. These include mechanical (direct or indirect), electrical, pneumatic, and hydraulic.

Small-Scale Wind Turbines for Generating Electricity

From the early days of electricity, wind turbines have been used to drive generators. Until the late 1970s, small wind generators were designed for stand-alone *battery-charging* applications. Since then, wind turbines under 12 m in diameter also have been designed for generating *utility-grade electricity* suitable for interconnection with the local network. In many respects, small-scale wind turbines resemble their larger counterparts, which are described later. One aspect of small HAWTs that makes them different from larger ones is their frequent reliance on *tail vanes* for orienting the rotor into the wind. Most commercial small wind turbines are conventional, horizontal-axis machines and are oriented upwind of the tower. Although a number of downwind designs were produced during the 1970s (*e.g.* the *Grumman, Kedco, and Enertech HAWTs*), few remain on the market today.

Small VAWTs have not been able to penetrate the market. Development by *Alcoa* of an 8-kW Darrieus wind turbine was canceled by the U.S. Department of Energy because the machine could not compete with the cost of small horizontal-axis designs. One British firm briefly marketed a small *H-configuration VAWT*. Few small vertical axis turbines are currently produced, though several companies manufacture large ones.

Rotor Designs

Over the years, designers have used a wide variety of rotor configurations on small machines. During the 1930s, and even into the mid-1980s, small battery-charging turbines (from 50 to 500 watts) used a one-piece, two-bladed rotor. During the 1930s, one manufacturer used four blades on a 1.5 kW, 4.3-m wind charger. Most now use three blades. Three blades give more dynamic stability than one, two, or even four blades. However, one German firm and one Italian firm have marketed small turbines driven by a one-bladed rotor.

Rotor Blades

With the exception of extruded or pultruded shapes, most blades on small turbines are *tapered* and *twisted*. Most extruded shapes have been used on vertical-axis designs where the inability of this process to produce variable chords and twist are less of a disadvantage. But some conventional turbines have also used extruded shapes. One 1930s-era wind charger used four *extruded aluminum* blades, and one Australian turbine produced through the 1970s used three extruded aluminum blades. Extruded aluminum is usually used on small Darrieus rotors. One design, sponsored by the U.S. Department of Energy, pioneered the use of *pultruded fiberglass* blades that were later scaled up to larger diameters and employed in several California wind power stations. In 1988, *Bergey Windpower Company* was using pultruded blades on its 1-kW and 10-kW HAWTs.

Blades on small wind turbines are often made of *wood* and *wood-epoxy laminates* which are readily available, inexpensive, strong, and resistant to fatigue. They can be molded or carved into complex shapes. *Cloth* has been used on an experimental small turbine (*Princeton Sail Wing*), but the concept has never been commercialized. Fiberglass blades were tried on a DOE-sponsored Darrieus design, without much success. One DOE-sponsored 10-meter wind turbine designed by the *Windworks Company* avoided some of aluminum's limitations by using a fiberglass tip on the outer third of the blade. Thus, in the area where the most lift is produced, the Windworks design used a more optimum airfoil and blade geometry than that of the inboard aluminum extrusion. This 10-meter turbine also used a novel approach to lessen the fatigue stress on the aluminum by fastening the blades to the hub with steel cables.

Mechanical Brakes for Rotor Speed Control

Most small turbines operate at variable rotor speeds, depending upon the wind speed, and only limit maximum rotor speed. As with large turbines, one of the most critical design characteristics for small machines is rotor control in *high winds* and during a *loss of load*, when the turbine must have some mechanism for dumping excess power. Some manufacturers of small turbines use *mechanical brakes* to stop the rotor, usually placing them on the *generator drive shaft* or aft of the generator because of the lower torque required. There is general agreement within the industry that if mechanical brakes are the primary means of stopping the rotor, the turbine must either provide aerodynamic braking to augment them or provide fail-safe protection (such as redundant brakes) should the primary brakes fail.

Tip Brakes, Buckets, and Pitchable Blade Tips

Two types of tip devices for stopping a wind turbine with fixed-pitch blades are illustrated in Figure 4-9. *Tip brakes*, Figure 4-9(a), are flat metal or fiberglass plates attached to the end of each blade and are normally parallel to the blade's path. During an emergency they operate centrifugally to deploy perpendicular to the blade's path, slowing the rotor by drag. They are simple and effective, and have saved many small fixed-pitch rotors from destruction. However, tip brakes are not aerodynamically part of the blade and, when deployed, do not reduce the blade's lift. When not deployed they add significant

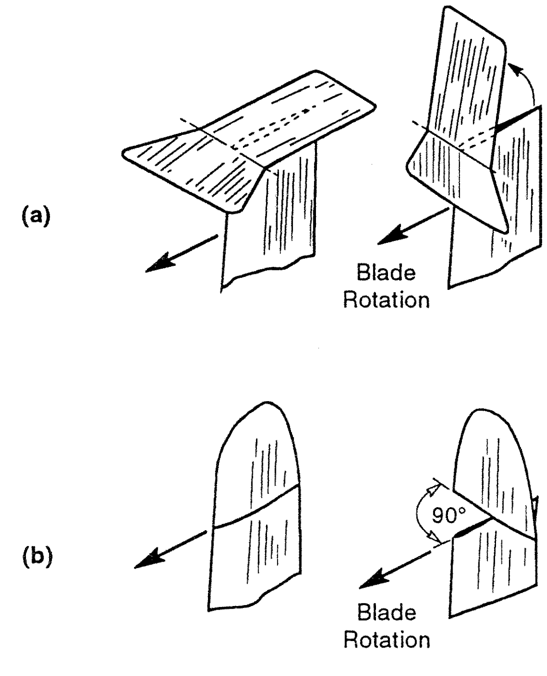


Figure 4-9. Tip devices for stopping a fixed-pitch rotor, in the undeployed (left) and deployed (right) positions. (a) Aerodynamic tip brakes (b) Pitchable tips

drag, lessening the efficiency of the rotor. No small-scale turbines using tip brakes were being built in the late 1980s. *Buckets* are semi-circular metal plates which, like tip brakes, are centrifugally deployed to create drag and slow the rotor. One manufacturer of 200-W to 500-W turbines still uses buckets today.

Pitchable tips, Figure 4-9(b), differ from tip brakes in that they are an integral part of the blade airfoil. When deployed, they rotate from within the plane of the blade to an out-of-plane position. This not only creates drag near the tip but also takes about 10 percent of each blade out of operation. Since the outer third of the blade creates most of the lift, the deployed tips dramatically reduce rotor torque, when operating properly. In the past, Danish turbines have characteristically used movable blade tips, even in small machines. However, no small turbines are being built today with pitchable tips, although they remain popular for medium-scale turbines 15 m to 37 m in diameter. No U.S.-built small turbine has ever employed this technique, because of their typically high rotor speeds and slender, flexible blades.

Variable Blade Pitch

One of the more popular means for limiting rotor power is changing the *pitch angle* of the blades. Nearly all small turbines using this approach employ a *governor* activated by centrifugal forces. The classic "fly-ball" governor on the *Jacobs* wind generator used weights that mechanically changed blade pitch towards feather. A later version used the weight of the blade itself to activate the governor. All mechanical governors require periodic service, and most have demonstrated only modest reliability.

The *blade-activated governor* was reintroduced in the 1970s by firms manufacturing 1930s-era machine designs (*e.g., Dakota Wind & Sun*), and by those building modified versions of these designs (*Aeropower*). More than 600 small (7-m to 9-m diameter) turbines with blade-activated governors have operated in commercial wind power stations near Palm Springs, California. One of the most popular product lines of small-scale wind turbines, from *Bergey Windpower Company*, employs a patented "Powerflex" rotor system that uses weights near the rotor blade tips. Aerodynamic and centrifugal forces act together to twist the blades toward their optimum running position, once the turbine is operating. This form of pitch control does not limit power, but aids in starting the rotor in low winds.

Since the 1960s, a small French firm (*Aerowatt*) has used pitch weights to drive the blades toward *stall* rather than toward feather, to control power. Another technique used by several turbine manufacturers for speed and power control is *furling*, in which the rotor is turned partially out of the wind by yawing to one side (called *horizontal furling*) or pitching upward (*vertical furling*). It is possible to accomplish this through the application of aerodynamic thrust balanced by spring or gravity forces.

Spoilers

Spoilers are longitudinal slats, normally below the blade surface, that decrease the airfoil's performance when deployed. Their function is similar to that of pitchable blade tips, namely to induce drag and reduce lift. Like pitchable blade tips, spoilers have been used on small Danish turbines, but not on U.S. turbines, again because U.S. machines have high rotational speeds and flexible rotors. Spoilers have been employed on British-built, 10-m rotors that replaced the original rotors on 80 small U.S. turbines at a commercial wind power station in California. No small turbine rotors are being made today with spoilers.

Yaw Control

Most small wind turbine rotors are oriented upwind of the tower and track the wind by *weather-vaning*, through the action of wind forces acting on a tail vane. The turbine turns on a *yaw bearing*. Downwind rotors under 12 m in diameter have utilized *free* or *damped yaw*, with the rotor and nacelle weather-vaning as a unit. No such small machines were being built in the late 1980s, but there are no data to confirm that such designs are not practical in small sizes.

Towers

Typical wind turbine tower configurations are shown in Figure 4-10. In order to place the rotor at heights where the winds are more energetic, towers for small wind turbines are generally taller in relation to their rotor diameters than those of large turbines. Unlike the predominance of free-standing towers with larger commercial turbines, guyed towers have proven popular for small turbines. *Guyed towers*, particularly guyed-truss towers, are less costly and often easier to install than free-standing towers of the same height. Installation of the guyed-lattice tower requires only simple hand tools and a vehicle or winch. *Truss* or *lattice towers* are similar to those used for larger HAWTs.

Small turbines are often mounted on *pole towers* made from a variety of materials including wood, fiberglass, concrete, and tubular steel. For turbines from 1 kW to 5 kW, wood poles offer an inexpensive tower option. Wood poles are graded for different loads and can be sized to the loads produced by the turbine. The problems of transporting and

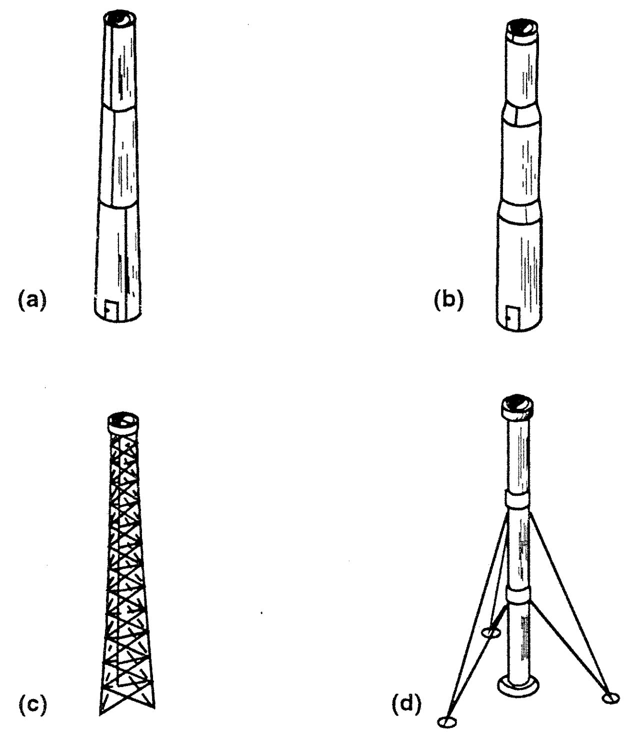


Figure 4-10. Typical HAWT tower configurations. (a) Shell (b) Stepped shell (c) Truss (or lattice) (d) Guyed shell (or, similarly, guyed truss)

installing wood and fiberglass towers are similar. Concrete and fiberglass towers have limited availability in the remote areas which are common in developing countries.

Form of Electrical Generation

The intended use for a small turbine determines the type of generator selected. At remote sites where battery charging is needed, DC generators or rectified AC alternators are employed. Designers often choose induction generators for applications where the wind turbine is to be connected to the utility grid.

DC Generators

During the 1930s, wind turbines charged batteries using *shunt-wound DC generators*, which were relatively massive. These pass current directly from the generator rotor through the brushes, requiring regular brush replacement. Only a few very small turbines (200 W to 500 W) use DC generators today, remaining essentially unchanged since they were first designed 60 years ago.

Alternators

Most small-scale wind turbines now built in the U.S. use *alternators*, which utilize materials more effectively than DC generators and draw current off the *stator*. As a result, the *slip rings* in a typical alternator carry only enough current to magnetize the field. There are no brushes that need replacement. Like the DC generators before them, today's alternators are driven at variable speeds. Their AC output is rectified to DC for charging batteries. In some applications, the variable-frequency, variable-voltage AC is first *rectified* to DC, then *inverted* back to constant-frequency AC for producing utility-grade electricity. This is a so-called *AC-DC-AC* electrical system. Most alternators that have been applied to wind applications use *electromagnets* in the spinning field, but *permanent magnets* also play an important role because they do not require slip rings.

Inverters

To produce constant-frequency, constant-voltage power from a variable-speed alternator, some form of *inverter* is needed. Inverters also convert DC from the storage batteries into utility-grade AC. Inverters often use solid-state switches to approximate the *AC wave form* of a true synchronous generator. Some have used battery-supplied DC to drive a motor-generator set (called *rotary inverters*) to generate their own utility-grade AC. But the rotary inverter is only 60 percent efficient, while the solid-state inverter can be up to 90 percent efficient.

In interconnected applications, a *synchronous* or *line-commutated inverter* is used to convert the alternator's output to line-quality AC. The synchronous inverter uses the utility line wave form as a signal to fire or switch a *thyristor bridge*. The thyristors act as gates which pass current at the proper voltage as necessary to produce an AC wave form following that of the electric utility. Synchronous inverters are susceptible to line transients and lightning and are costly to repair, but they are working reliably in hundreds of installations across the United States.

Induction Generators

Induction generators are common in the wind turbine industry around the world. They serve in many applications and are inexpensive when compared with alternators. Nearly all Danish and several U.S. manufacturers have used induction generators on small wind turbines. This was the most widely used type of generator when the U.S. production of small-scale turbines reached its peak in 1980-1981. However, few remain on the market today, because most induction-generator designs have been scaled up to medium size.

Typical Small-Scale Commercial HAWTs for Generating Electricity

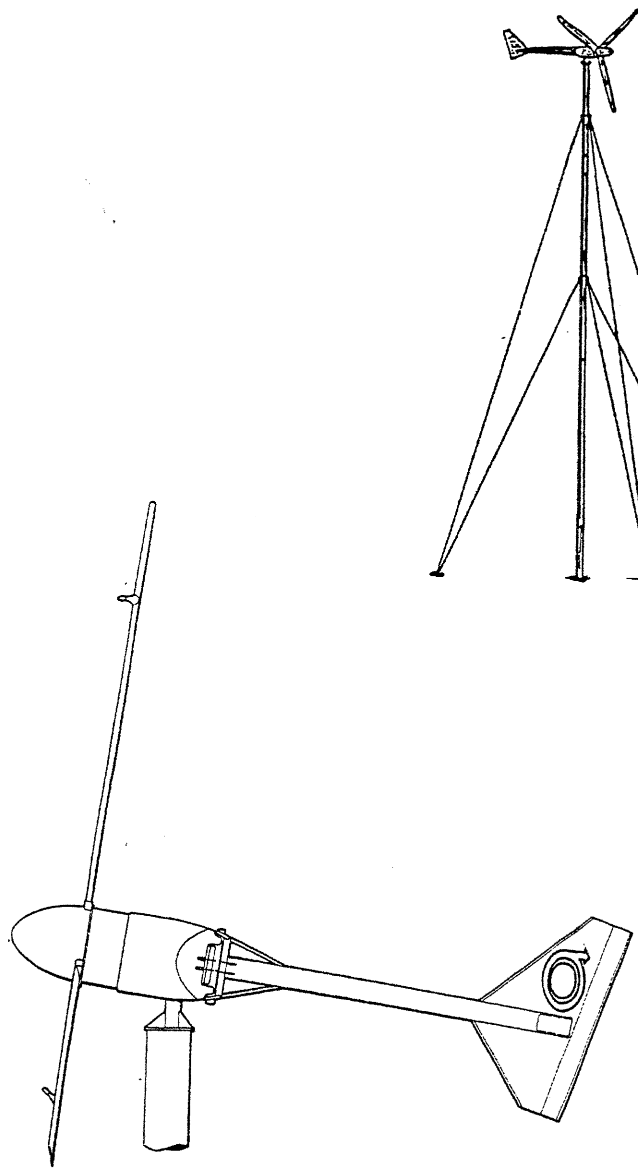
Figures 4-11 show five small-scale HAWTs whose designs are illustrative of the current technology for this class of machine. Table 4-2 summarizes their key specifications. Additional information on *stand-alone power systems* and on the following topics related to the application of small wind power systems is given in [Gipe 1993]:

- permit applications, siting, and zoning;
- wind measurement and atlas of U.S. wind resources;
- power and water-pumping output tables;
- installation and safety;
- economics of new and used wind turbines.

Table 4-2. Specifications for Typical Small-Scale HAWTs

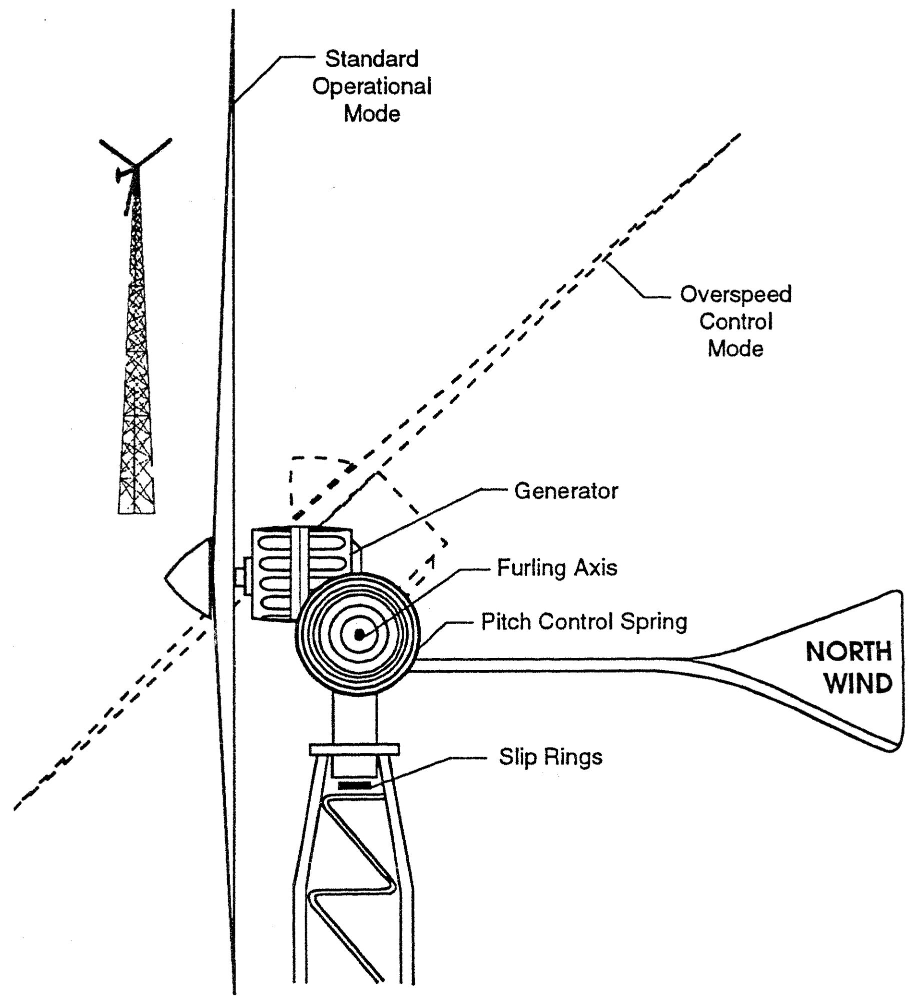
Manufacturer: / Model:	Bergey Wind-Power Co. BWC 1500	Northern Power Sys. North Wind HR3	Wind Turbine Industries EESI-12.5/23	Micon Energy Sys. M 22	Carter Wind Systems Carter 25
Rotor diameter	3.1 m	5.0 m	7.0 m	9.8 m	9.9 m
Rated power	1.5 kW	3 kW	12.5 kW	22 kW	25 kW
Rotor location	Upwind	Upwind	Upwind	Upwind	Downwind
No. of blades	3	3	3	3	2
Blade material	Poly/Glass	Wood/Epoxy	Wood	Poly/Glass	Fiberglass
Pitch control	Flexural	Tilt rotor	Variable	Fixed	Fixed*
Braking					
Normal	None	Vert. furling	Mech. disk	Electromech.	Mech. disk
Overspeed	Horiz. furling	Vert. furling	Aerodynamic	Aerodynamic	Aerodynamic
Gearbox (no. of stages)	None (0)	None (0)	Offset-hypoid	Parallel-shaft (2)	Round helical (1)
Generator					
Type	Alternator	Alternator	Alternator	Induction	Induction
Speed	60-450 rpm	≤ 300 rpm	Variable	1,800 rpm	1,836 rpm
Voltage	Options	Options	Variable	480 VAC	220-440 VAC
Yawing system	Passive	Passive	Passive	Active	Passive
Tower type	Options	Options	Truss	Shell	Guyed Shell

*Except for shutdown



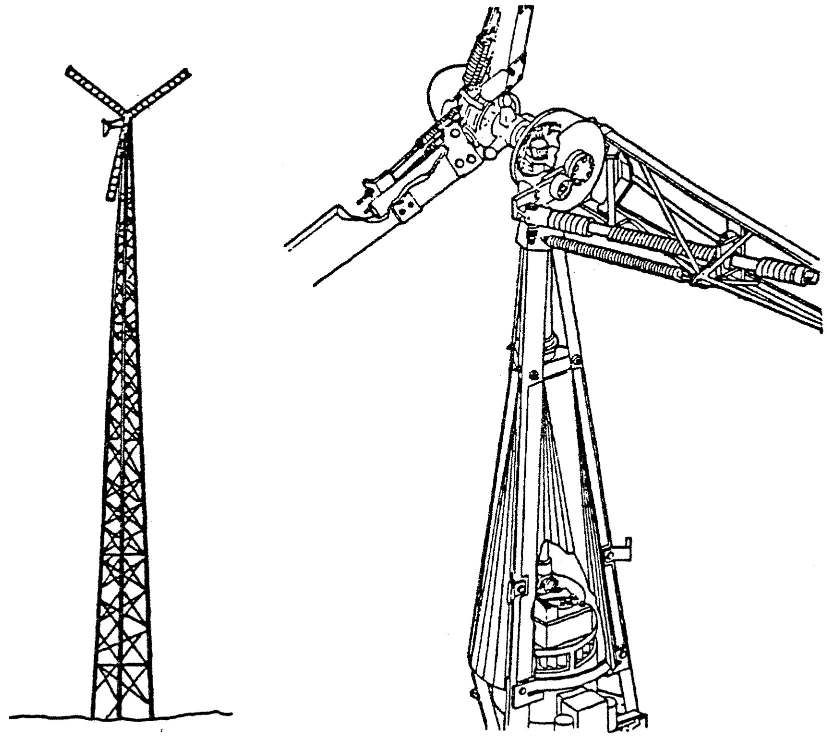
(a) *BWC 1500*. (Manufactured by Bergey Windpower Company)

Figure 4-11. Typical small-scale commercial HAWTs.



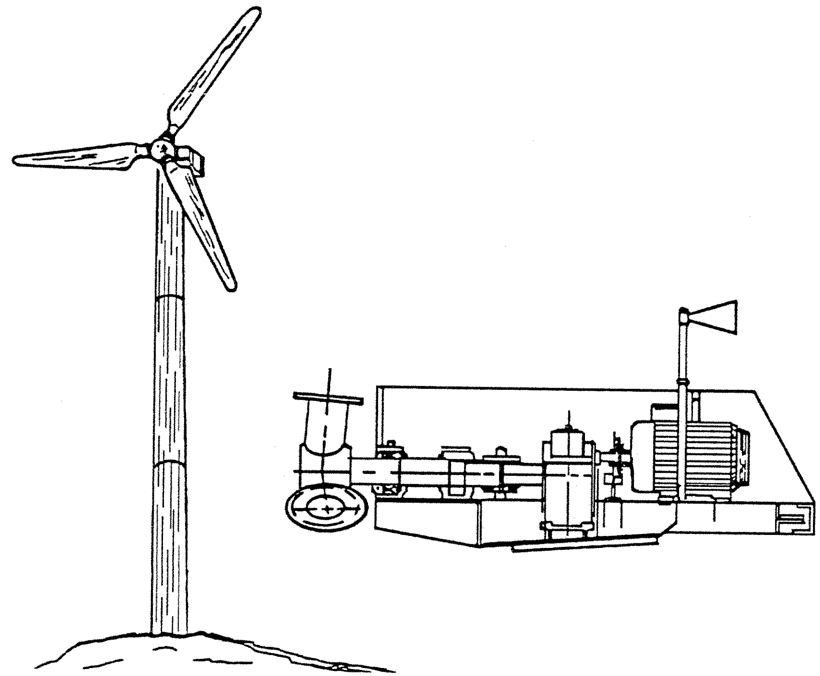
(b) *North Wind HR3*. (Manufactured by Northern Power Systems)

Figure 4-11 (Continued). Typical small-scale commercial HAWTs.



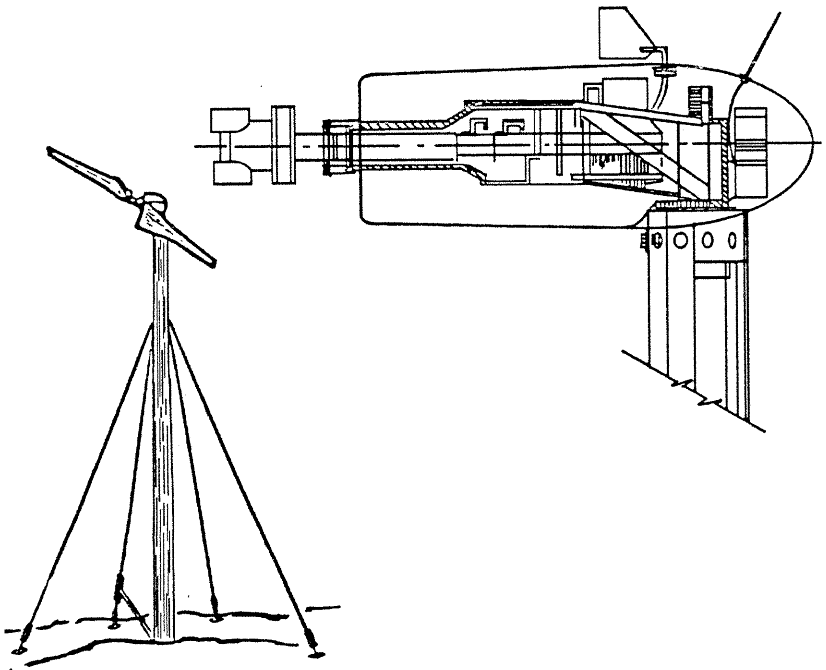
(c) *EESI-12.5/23*. (Manufactured by Wind Turbine Industries, Inc.)

Figure 4-11 (Continued). Typical small-scale commercial HAWTs.



(d) *Micon M 22*. (Manufactured by Micon Energy Systems)

Figure 4-11 (Continued). Typical small-scale commercial HAWTs.



(e) *Carter 25.* (Manufactured by Carter Wind Turbines, Inc.)

Figure 4-11 (Concluded). Typical small-scale commercial HAWTs.

Medium-Scale Horizontal-Axis Wind Turbines

By the guidelines in Table 4-1, medium-scale wind turbines are those with rotor diameters between 12 and 45 m and/or power ratings between 40 and 999 kW. Subsystems of medium-scale HAWTs will be discussed here, expanding on the information given previously for small-scale systems. There are, of course, many similarities between the two sizes, since the dividing line separating them is somewhat arbitrary. Also, they share a common technology base. As shown by the sketches and data in Appendix C, there are significant design variations in the rotors, power trains, yaw drives, and towers within the wind turbine industry.

Rotors

A large variety of rotor configurations have been employed, and no clear "best" configuration has evolved. Table 4-3 contains a summary of the rotor characteristics typical of the commercial wind turbine models with ratings of 25 kW or higher that were available for sale in the mid-1980s. The most prevalent commercial wind turbines then and now are oriented upwind, have three fiberglass blades, and employ rigid hubs. The majority of Danish wind turbines are of this configuration, and Danish wind turbines comprised 41% of the cumulative capacity and 61% of the new capacity of wind turbines in California in 1992 [Loyola 1993]. Although fiberglass is the dominant material used in medium-scale commercial rotor blades, several types of machines use laminated wood-epoxy blades.

Table 4-3. Characteristics of Commercial Medium-Scale Rotors in the Mid-1980s [Strategies Unlimited 1987]

Rotor characteristic	Range, or percent of designs
Diameter	9.8 m to 44.8 m
Rotor location:	
Upwind / Downwind	75% / 25%
Number of blades:	
Three / Two	82% / 18%
Hub configuration:	
Rigid / Teetered	91% / 9%
Pitch control:	
Fixed pitch	86%
Variable pitch	9%
Other	5%
Blade coning angle	0 deg to 10 deg
Axis tilt angle	2 deg to 9 deg
Solidity	3.4% to 14%
Planform shape:	
Tapered and twisted	70%
Twisted only	20%
Tapered only	7%
Other	2%
Blade material:	
Fiberglass / Wood	89% / 11%

The most serious rotor subsystem problems experienced to date in commercial operations have been associated with (1) *dynamic instability* of rotors that employ elastic deformation to change the blade pitch as a function of rotor speed (*i.e., self-twisting* or *torsional root* concepts), (2) inadequate *quality control of fiberglass* during manufacturing, (3) failure of *fiberglass-to-steel blade root joints*, and (4) *unreliable tip brakes* as a result of inadequate mechanical designs. Product improvement activities being pursued include

-- developing *new thick and thin airfoils* to improve energy capture, reduce fatigue loads (through restraint of the maximum lift coefficient in the tip region), and decrease the sensitivity of blades to efficiency losses caused by dirt and insects;
-- using *vortex generators* on the blade root area to delay stall;
-- developing *lighter, lower-cost blades*;
-- developing *more reliable blade root joints*;
-- developing *more reliable tip braking mechanisms*.

Power Trains

As discussed in Chapter 2, the major components within the power trains of medium- and large-scale wind turbines are a *turbine shaft* (often called the *low-speed* shaft), *turbine shaft bearings, couplings*, a *gearbox* (speed increaser), a *brake* (located on either side of the gearbox), a *generator drive shaft* (often called the *high-speed* shaft), and a *generator*. The gearbox increases the turbine speed (generally in the range from 30 to 120 rpm for medium-scale rotors) to 1,200 to 1,800 rpm, the normal speeds required for most generators that produce AC power at a frequency of 60 Hz.

To illustrate the range of power-train configurations that have been used in medium-scale commercial HAWTs, ten have been selected that represent different design approaches as well as power levels from 40 to 600 kW. These are listed in Tables 4-4 and 4-5, and sketches of their power trains are shown in Figures 4-12.

Table 4-4. Representative Medium-Scale HAWTs: 12-m to 24-m Diameter

Manufacturer: / Model:	M.A.N. Neue Tech. Aeroman 12.5	U.S. Wind-power, Inc. USW 56-100	Bonus Wind Turbines 120/20	Carter Wind Turbines Carter 300	Energy Systems, Inc. ESI-80/200
Rotor diameter	12.5 m	17.1 m	19.4 m	24.2 m	24.4 m
Rated power	40 kW	100 kW	120 kW	300 kW	250 kW
Rotor location	Upwind	Downwind	Upwind	Downwind	Downwind
No. of blades	2	3	3	2	2
Blade material	Poly/glass	Poly/glass	Poly/glass	Fibergls/epoxy	Wood/epoxy
Pitch control	Variable	Variable	Fixed	Fixed*	Fixed
Braking	Mech. disk	Aerodynamic	Mech. disk	Mech. disk	Mech.& Aero.
Overspeed	Aerodynamic	Aerodynamic	Aerodynamic	Aerodynamic	Aerodynamic
Gearbox (no. of stages)	Spur gear (3)	Parallel-shaft	Parallel-shaft (2)	Planetary (2)	Planetary
Generator	Induction	Induction	Induction	Induction	Induction
Speed	1,800 rpm	1,200 rpm	1,200 rpm	1,822 rpm	1,800 rpm
Voltage	460 VAC	480 VAC	480 VAC	480 VAC	480 VAC
Yawing system	Active	Passive	Passive	Active/Passive	Passive
Tower type	Shell	Truss	Shell	Guyed Shell	Truss

*Except for shutdown

Table 4-5. Representative Medium-Scale HAWTs: 25-m to 43-m Diameter

Manufacturer: / Model:	WindMaster 300	Mitsubishi Heavy Ind. MWT-250	Wind Energy Group WEG 400	Vestas Wind Systems A/S V39-500	Westinghouse Electric Corp. WWG-0600
Rotor diameter	25.0 m	29.0 m	36.4 m	39.0 m	43.3 m
Rated power	300 kW	300 kW	400 kW	500 kW	600 kW
Rotor location	Upwind	Upwind	Upwind	Upwind	Upwind
No. of blades	3	3	2	3	2
Blade material	Fiberglass	Fiberglass	Wood/epoxy	Fiberglass	Wood/epoxy
Pitch control	Variable	Variable	Variable	Variable	Variable
Braking	Aerodynamic	Aerodynamic	Aerodynamic	Aerodynamic	Aerodynamic
Overspeed	Aero.& Mech.	Aerodynamic	Aero.& Mech.	Aero.& Mech.	Aerodynamic
Gearbox (no. of stages)	Helical (3)	Planetary (2)	Planetary/ parallel	Parallel/ planetary	Planetary/ parallel (3)
Generator	Induction	Induction	PAM Induction	Induction	Synchronous
Speed	1508 rpm	1800 rpm	1500/1000 rpm	1,522 rpm	1,800 rpm
Voltage	380/460 VAC	480 VAC	660 VAC	690 VAC	4,160 VAC
Yawing system	Passive	Active	Active	Active	Active
Tower type	Shell	Shell	Shell	Shell	Shell

(a)

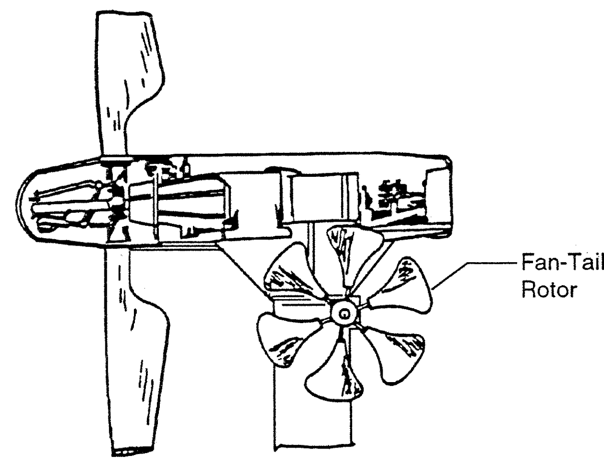
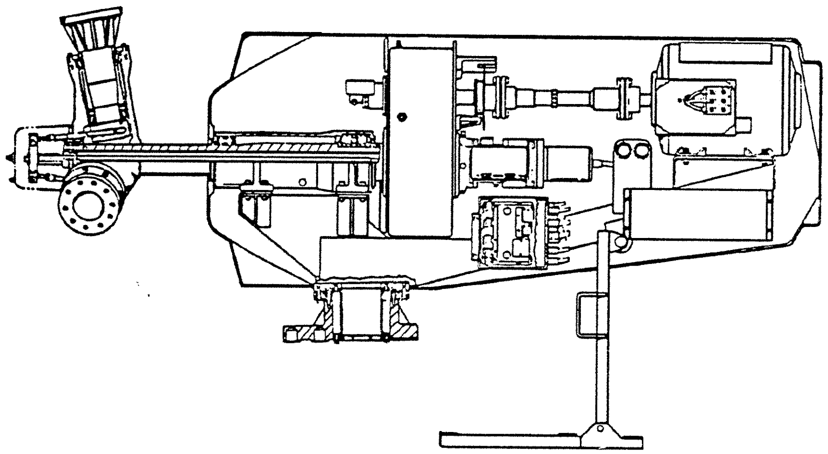
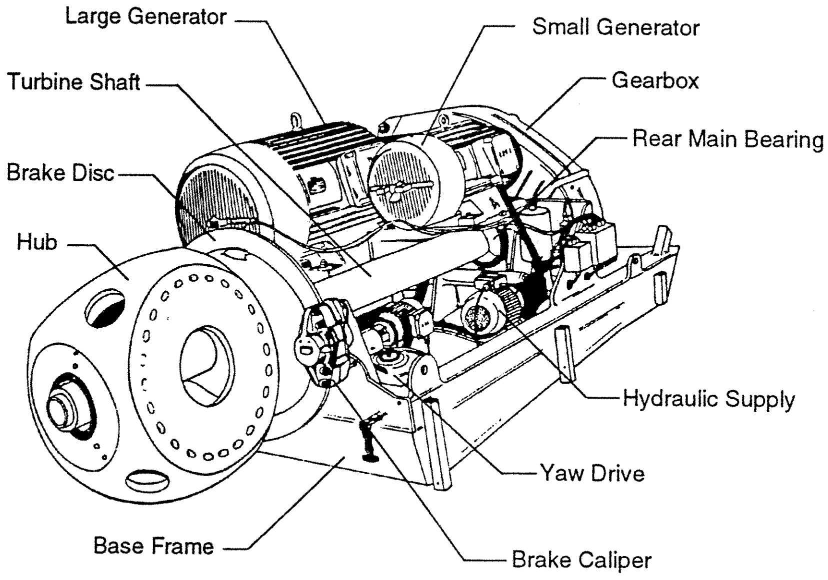


Figure 4-12. Power trains in representative medium-scale HAWTs.
(a) 40-kW *Aeroman 12.5*. (Manufactured by M.A.N. Neue Technologie)

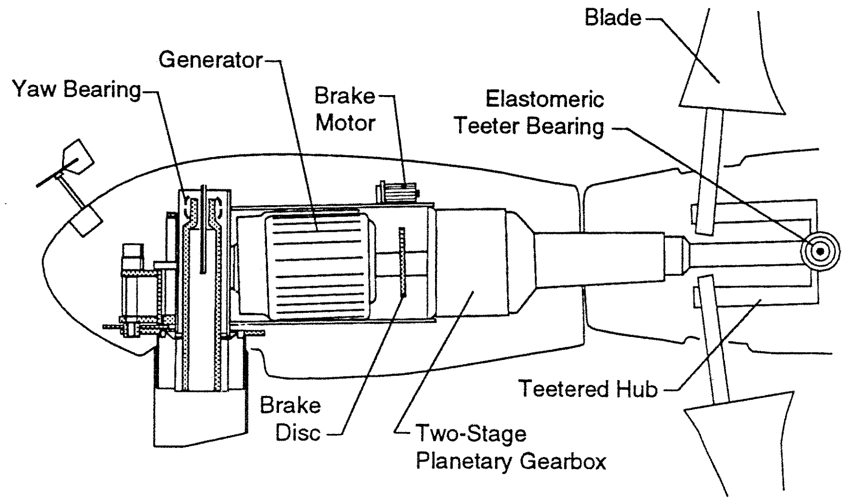


(b)

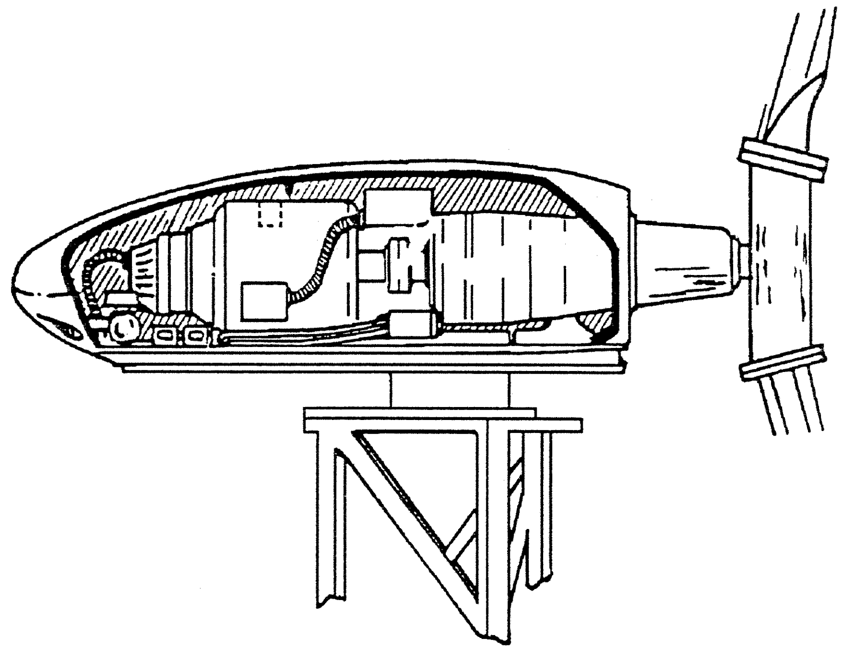


(c)

Figure 4-12. Power trains in representative medium-scale HAWTs (Continued).
(b) 100-kW *USW 56-100* HAWT. (Manufactured by Kenetech/U. S. Windpower, Inc.)
(c) 120-kW *Bonus 120/20* HAWT. (Manufactured by Bonus Wind Turbines, Inc.)



(d)



(e)

Figure 4-12. Power trains in representative medium-scale HAWTs (Continued).
(d) 300-kW *Carter 300* HAWT. (Manufactured by Carter Wind Systems, Inc.)
(e) 250-kW *ESI-80/200* HAWT. (Manufactured by Energy Systems, Inc.)

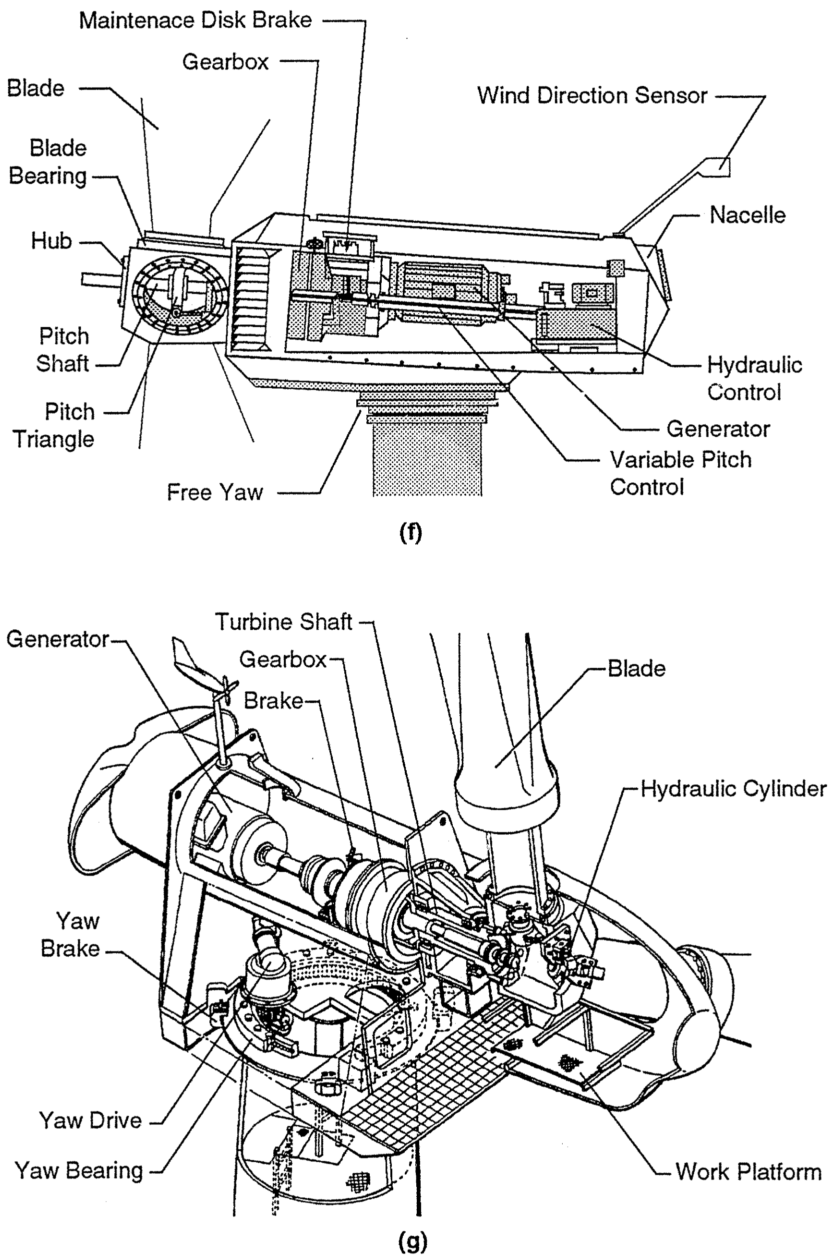


Figure 4-12. Power trains in representative medium-scale HAWTs (Continued).
(f) 300-kW *WindMaster 300* HAWT. (Manufactured by WindMaster U.S.A., Inc.)
(g) 300-kW *MWT 250* HAWT. (Manufactured by Mitsubishi Heavy Industries America)

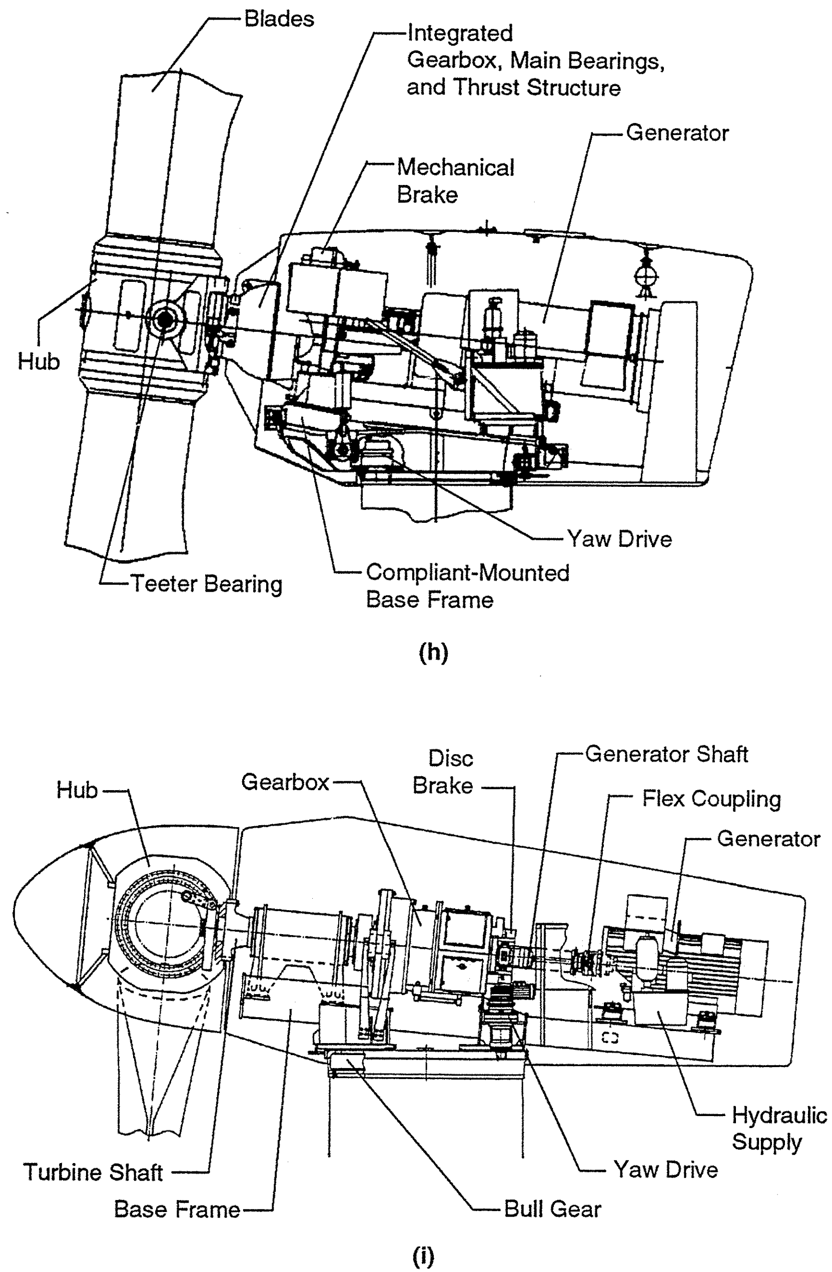
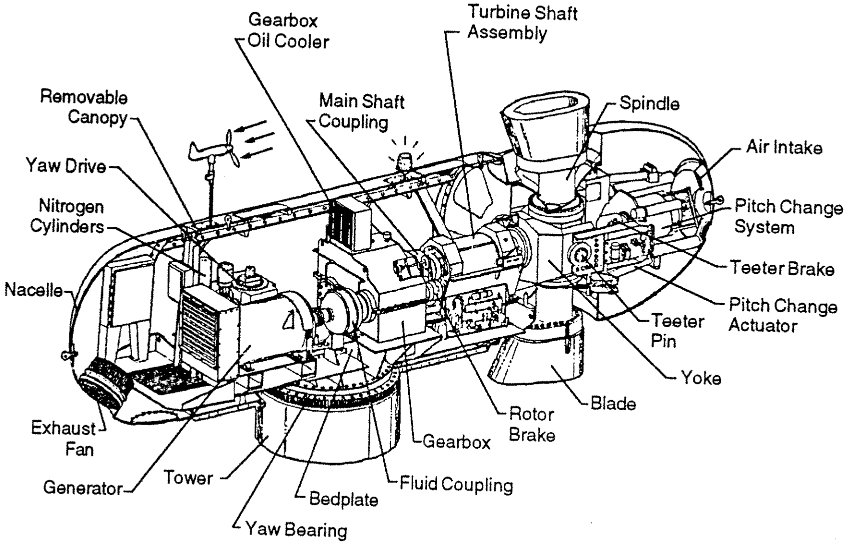


Figure 4-12. Power trains in representative medium-scale HAWTs (Continued).
(h) 400-kW *WEG 400* HAWT. (Manufactured by Wind Energy Group)
(i) 500-kW *V39-500* HAWT. (Manufactured by Vestas Wind Systems A/S)



(j)

Figure 4-12. Power trains in representative medium-scale HAWTs (Concluded). (j) 600-kW *WWG-0600* HAWT. (Manufactured by Westinghouse Electric Corporation)

Current commercial medium-scale HAWTs run at constant speed, with the generator "electrically locked" to the utility grid under normal operation, so the drive train must also serve to partially dampen *torque fluctuations* caused by wind gusts. This is generally accomplished by the use of one or more *flexible couplings* located on either side of the gearbox or by a *quill shaft* (*e.g.* inside the Mod-5B turbine shaft assembly shown in Fig. 2-4), which is a torsionally flexible tube between the hub and the gearbox. Another approach employed by several wind turbine manufacturers to dampen torque fluctuations is to allow the gearbox to rotate through several degrees by use of *shock/spring mounts*. Approximately 60 percent of all commercial wind turbines employ *parallel-axis gearboxes*, and most of the remainder employ *planetary* systems.

Gearbox problems encountered in commercial service have generally been the result of (1) lack of understanding of the *cyclical and random loads* imposed by the rotor, resulting in premature fatigue failures; (2) inadequate *alignment* of the high-speed shafts, resulting in seal degradation; (3) inadequate *servicing* resulting in premature failures from friction and wear; (4) poor quality control resulting in excessive bearing endplay and misalignment; and (5) inadequate control of loads imposed by brakes on the high-speed shaft, resulting in fracture of critical components.

Brakes

In addition to stopping a rotor after a normal shut down and holding it parked, braking systems for wind turbines are needed to prevent overspeed caused by loss of the utility grid or breaks in the drive train. Aerodynamic *tip brakes* and *pitchable tips* (Fig. 4-9) are used on almost all fixed-pitch stall-regulated HAWTs, and are designed to operate when the cen-

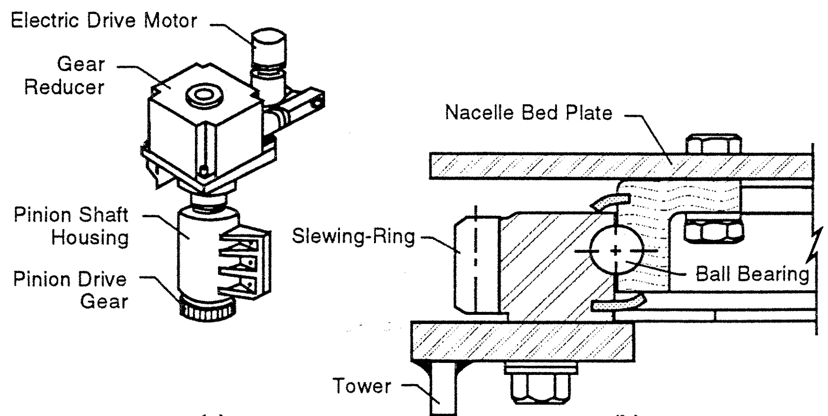
trifugal force at the blade tips exceeds a predetermined limit. Several HAWTs employ mechanical or electrical connections between the two or three tip mechanisms on their rotors (one per blade). Otherwise, there is a high probability that the tip brakes will deploy at different times, resulting in increased loads on the system.

Mechanical brakes are employed for normal stopping and/or holding the wind turbine rotor after it is stopped. Mechanical brakes are activated either electro-mechanically, hydraulically, or pneumatically. The most common brake systems are conventional disc and caliper types. Brake wear has been a problem at some sites. Wear is accelerated by frequent *start-stop cycles* which occur in areas of high, gusty winds (causing frequent high-wind shut downs) and in areas where the utility grid is frequently disabled, resulting in repeated losses of load and a high number of rapid stops. In addition to mechanical brakes, several manufacturers have incorporated circuitry that allows the use of the generator as an *electrical brake* or, as it is commonly termed, a *dynamic brake*.

Yaw Subsystems

All commercial HAWTs are designed to track the wind by orienting the nacelle in *azimuth* so that the rotor plane is normal to the wind. Most U.S.-manufactured wind turbines are oriented downwind, while most foreign units are oriented upwind. Until recently, almost all downwind machines used the *weather vane* concept or *passive yaw* for tracking the wind. However, the downwind *Carter 300* turbine uses a motorized or *active* yaw in order to reduce fatigue loads caused by the relatively large *yaw errors* frequently encountered with passive yaw systems. Larger upwind machines employ an active means of maintaining the rotor normal to the wind because of the structural problems associated with very large tails. For these reasons, only active yaw systems will be described here.

The large majority of yaw drive systems are electro-mechanical, with the remainder being hydraulic or mechanical. Figure 4-13(a) illustrates a common yaw drive system in which a motor turns a small *pinion gear* through a *worm-gear reducer*. These components are mounted on the bedplate of the nacelle. The pinion gear engages a large, stationary *slewing-ring* or *bull gear* mounted rigidly on the tower, as illustrated in Figure 4-13(b). The tower structure provides the stiff vertical support required for the *yaw bearing*.



(a) (b)

Figure 4-13. Schematic diagram of a motor-driven yaw system. (a) Electric or hydraulic motor drive and pinion gear (b) Bull gear and yaw bearing assembly

A mechanical alternative to motorized yaw drives is the *fantail* shown in Figure 4-12(a). Fantails, invented in 1745 (see Chapter 1), have been used most recently on several 40-kW to 55-kW European-built wind turbines installed in California wind power stations. This device consists of one or a pair of small, multi-bladed windmills with directionally-sensitive blades, geared down to drive a yaw worm or pinion gear. This small gear then drives a bull gear fixed to the tower. A fantail rotor is mounted perpendicular to the main wind turbine rotor and jockeys the yaw drive back and forth until its blades are parallel to the wind and no longer turning. This places the main turbine perpendicular to the wind. Fantails are most commonly used on upwind machines, but can also be used on downwind machines to provide additional control or damping.

The problems that have been encountered most frequently with downwind machines are associated with *hunting*, which causes premature wear of yaw drives and bearings. Hunting refers to the tendency of some machines to continuously and slowly oscillate plus or minus 10 to 15 deg around the optimum rotor orientation. Upwind machines have experienced fatigue-related problems of the yaw slew ring and the pinion drives. Most of these result from unbalanced rotors and underestimating wind loads from turbulence and wind shear, both horizontal and vertical. *Yaw damping*, either by the use of sliding *brakes* or "soft" drive mechanisms, has proven beneficial in reducing yaw slewing rates and cyclic loads.

Towers

Referring again to Figure 4-10, commercial medium-scale wind turbines use either *truss* or *shell towers* produced from steel. Although some machines employ *guyed towers*, the large majority (approximately 85%) are not guyed. The industry has recognized that significant increases in energy production can be achieved with the use of taller towers in sites with a positive wind shear. This could lead to the increased use of guyed towers which cost less than tall free-standing towers. Guyed systems, however, require additional maintenance, primarily because thermal cycling causes periodic loosening of guys and turnbuckles at most sites. Some manufacturers employ *tilt-down* towers, which generally require the use of a winch to lower and raise the tower. There is no consensus within the industry regarding the "best" approach, though tilt-down towers have clear advantages in remote areas or for stand-alone applications where crane availability is a problem.

Problems with truss towers are commonly associated with the fasteners, which can become loose, or with fatigue of one or more of the tower legs. Fatigue problems have been caused by improperly transferring the loads from the tower top plates to the tower legs. Tower-to-foundation interface problems have generally been associated with poor foundation installations. Tower problems are accentuated by excessive yaw motion and rotor vibration in highly turbulent wind regimes.

Electrical Systems

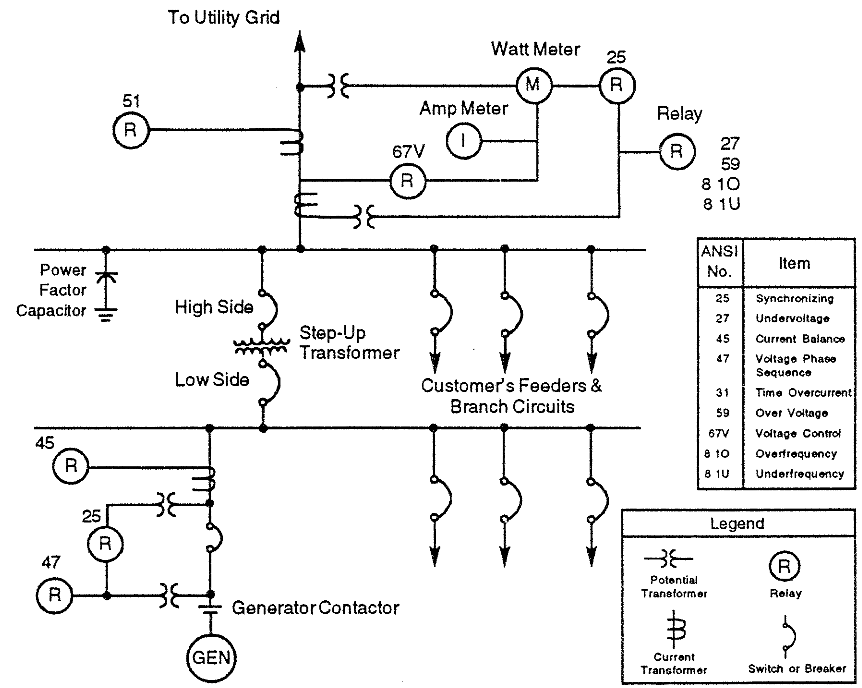
With few exceptions, medium-scale commercial wind turbines employ *three-phase induction generators* with 460/480 VAC output. Synchronous and variable speed generators have been used primarily on large-scale machines. Variable-speed generators are viewed by the wind energy community as potentially beneficial for systems of all sizes. However, in the late 1980s no small- or medium-scale commercial machines used variable-speed generators, because of cost and because of industry uncertainties regarding their benefits for smaller systems. A small Darrieus VAWT was equipped with such a generator and showed some potential to increase energy output. However, two different variable-speed generator systems were tested on the medium-scale Mod-0 HAWT test bed with results that were somewhat less encouraging [Herrera *et al.* 1985].

Figure 4-14 is a *one-line electrical diagram* for a typical wind turbine connected to a utility grid. Standard electrical *protection devices* are employed on commercial wind turbines to detect the following fault characteristics:

-- over- and under-voltage;
-- over- and under-frequency;
-- over-current (current detectors for each phase);
-- line out-of-phase;
-- generator over-temperature.

Lightning protection and capacitors for *power factor correction* are generally used with commercial wind turbines.

Electrical energy from the turbine generator is transferred from the rotating nacelle to the ground by use of *slip rings* or a *droop cable*. Droop cables are fixed at both ends and can "wind up" and be destroyed unless some provision is made to periodically unwind them. Many wind turbines with an active yaw system employ a nacelle *yaw revolution counter* and automatically turn the nacelle to unwind the cable after a predetermined number of nacelle rotations in one direction are reached. Other approaches employ a *pop-out connector* at the base of the tower to prevent droop cable damage from excessive twisting. If there is no active yaw system on the wind turbine, the cable must be manually untwisted periodically, which has proven to be only a minor inconvenience. Because droop cables lower initial costs and maintenance requirements by eliminating the need for slip rings, they are employed in approximately 75 percent of all commercial models.



ANSI No.	Item
25	Synchronizing
27	Undervoltage
45	Current Balance
47	Voltage Phase Sequence
31	Time Overcurrent
59	Over Voltage
67V	Voltage Control
8 1O	Overfrequency
8 1U	Underfrequency

Figure 4-14. Typical one-line electrical diagram for a grid-connected wind turbine.

Most of the problems that have occurred with wind turbine electrical systems have been traced to the use of marginal or substandard components. The use of improper electrical connectors has caused significant machine downtime. Many commercial developers used step-up transformers with marginal ratings, and failures of these components have been a problem at some wind power stations. Generator failures, such as short circuits and overheating, have been common and are usually caused by moisture in the windings. New models generally employ heaters and temperature sensors in the generator windings to prevent these problems.

Control and Performance Monitoring

Approximately 85 percent of all commercial medium-scale wind turbines employ a *microprocessor* to control wind turbine operations and measure performance. Early wind power stations did not connect turbines to a central control station to measure output and other operating parameters. This made it necessary to take meter readings at each machine and to determine operational status by visual means. Most new wind power stations are equipped with central monitoring and control, so that an *on-board microprocessor* in each wind turbine sends performance and machine status information to a *central computer* equipped to constantly monitor and record these data. Automatic alarms that notify an operator of a wind turbine or utility line problem are widely used. Most of the problems encountered with microprocessor controls have been related to the associated *software programs*. The on-board microprocessor generally controls the following functions:

-- *cut-in* and *cut-out* wind speeds (defining the operating range);
-- connection of the generator output lines to the grid;
-- nacelle orientation (active yaw systems);
-- blade pitch angle (active pitch systems);
-- wind turbine normal and emergency shutdowns;
-- diagnostics for fault detection.

Solid-state or conventional mechanical *relays* are used to activate the associated mechanisms. *Time-delay devices* are used to prevent frequent wind turbine starts and stops when the winds loiter around the turbine's cut-in and cut-out speeds. Standard *analog meters* for kilowatt-hour and voltage data are used by some manufacturers, but the trend within the industry is to employ less-expensive *digital readout devices*. In addition to its operational duties, the central microprocessor generally monitors and records the following performance parameters:

-- wind turbine status (on-line or disabled);
-- cumulative wind turbine availability;
-- wind speed and direction;
-- generator output;
-- cumulative energy produced;
-- power-curve performance (*i.e.*, generator output *vs.* wind speed).

Some of the more sophisticated central computers compare the actual performance of each individual wind turbine to its expected performance (*i.e.*, expected power and/or energy output *vs.* wind speed) and provide a *figure of merit* for each machine. This information allows the operator to identify machines that are not producing as expected. Other features that have been incorporated into the central processors are the ability to calculate *time-of-day* and *cumulative revenues* for each wind turbine and for the entire wind power station.

Sensors

In addition to electrical protection, wind turbines employ various other sensors to protect the machinery from damage and to assist in the control of the machine. The following items have been monitored for these purposes:

-- wind speed;
-- wind direction;
-- nacelle orientation;
-- rotor speed;
-- blade pitch angle (for variable pitch wind turbines);
-- equipment vibration levels;
-- gearbox oil level, temperature, and pressure;
-- generator speed;
-- brake pad thickness;
-- hydraulic fluid level, temperature, and pressure;
-- bearing temperatures;
-- structural integrity (*e.g.*, crack detectors and bolt damage sensors).

Trends in Medium-Scale HAWT Design

The transition of the U.S. wind power industry from a domestic one competing with other renewable energy sources to one that must compete with foreign manufacturers in a utility power production environment has led to a number of changes. With the end of federal and state tax credits, a more competitive environment has resulted in a contraction of the number of manufacturers and developers. All aspects of wind turbine design are being examined in an effort to reduce costs and increase productivity. In addition, the machines currently being developed are benefitting from the design and operating experiences on current turbines. This has resulted in a better understanding of wind loads and the aerodynamic and structural dynamic behavior of wind turbines. Potential design trends for medium-scale wind turbines are as follows:

-- use materials other than glass-reinforced polyester for blades longer than 15 m, such as wood-epoxy and advanced composites;
-- use teetered rotors more extensively;
-- select and develop advanced and/or special purpose airfoils;
-- use variable-speed generator systems;
-- increase machine size and rated power;
-- use taller towers, to take advantage of positive wind shear.

Compared to multi-megawatt turbines, medium-scale machines offer potential economies associated with (1) lower rotor costs per unit of swept area, (2) higher-volume buying of components (lower cost), (3) easier transportation and installation (shipped on trucks; no very large cranes), and (4) potentially higher overall reliability for the station (increased modularity). The overriding advantages of intermediate-sized machines that led to their use in current wind power stations are lower development risk, availability of many appropriate mechanical and electrical components from other industries, and availability of a wide variety of tested (if not always proven) designs.

Medium-Scale Vertical-Axis Wind Turbines

Of the several types of vertical-axis turbines, only the *Darrieus* has been developed commercially in the U.S. Figures 3-24 and 4-15 illustrate the general configuration shared by all commercial Darrieus systems. Three manufacturers have deployed approximately 650 VAWTs of the Darrieus configuration in the U.S.: *FloWind Corporation* and *Vawtpower* in the U.S. and *DAF-Indal Technologies* in Canada. As of 1987, two of these companies had discontinued production, but many experimental units are still being developed. All of the commercial Darrieus rotors have emulated the designs developed at the Sandia National Laboratories and at the National Research Council of Canada. Commercial machines use modifications of the Sandia rotor designs that offer greater ease of production and shipping. Typically, each blade is in three sections which are assembled at the site.

Operational problems with Darrieus VAWTs have been associated with their rotor blades and supporting struts. Fatigue-related failures have been encountered at the connections of the blade to the upper and lower hubs, at the blade splices, and at the blade-to-strut connections. Additional problems have occurred because of loosening or fatigue of the guy wires and turnbuckles.

In Great Britain, the *H-type* or *Musgrove rotor VAWT* has been developed by *Vertical Axis Wind Turbines Limited* (Fig. 3-18). Two prototypes were constructed in 1986: a 25-m machine sponsored by the U.K. Department of Energy, and a 14-m system funded by Tema SpA of Italy. Another H-type VAWT is the *HM-Rotor-300* manufactured by *Heidelberg Motor*. A prototype is currently being tested at the *Kaiser-Wilhelm-Koog Wind Test Site*. This turbine has no gearbox, and its low rotor speed is said to reduce noise [IEA 1992].

Trends in Medium-Scale VAWT Design

In less than 15 years, VAWT technology in the U.S. has evolved from a state of limited knowledge to the installation and operation of more than 600 commercial machines. Significant advances have been made in developing analytical tools for aerodynamic and structural-dynamic analyses. Analytical codes now exist that yield good agreement between theory and experiment for mean aerodynamic and structural characteristics of VAWTs. The installation and operation of the 625-kW *34-m Sandia/DOE VAWT* test bed in 1987 (Figure 2-2) represents a significant step in the development of larger and more efficient commercial machines. As commercial Darrieus VAWTs have grown from their initial 100-kW size to 250 kW and larger, installed costs have been reduced to approximately $900 to $1,300 per kilowatt. The most promising improvements for VAWTs appear to be in the areas of improved aerodynamic performance and reduced manufacturing costs.

One attempt to improve the aerodynamic performance of a Darrieus rotor is the use of a combination airfoil that has tapered (or stepped) sections to optimize the shape from the root to the equator. This change alone may reduce the cost of energy from 10 to 20 percent. Another approach to reducing energy cost which is receiving consideration in the industry is the use of either a *multiple constant-speed* or a *continuously-variable speed* design. Either method permits *lower cut-in wind speed* (high cut-in speed is a problem with VAWTs), with *higher energy capture* over the wind speed range at a particular site.

The relative costs for a VAWT may be divided among subsystems approximately as shown in Table 4-6. There may be some margin for cost reduction in each of these areas. Most Darrieus blades are *extruded aluminum*. The cost of this element is relatively high, and extrusion does not offer the opportunity to vary the shape of the airfoil over the length of the blade. Future blade designs may be fabricated from fiber-reinforced plastics or other composites, and may involve a box-spar construction or another fabrication technique that is less expensive than extrusion.

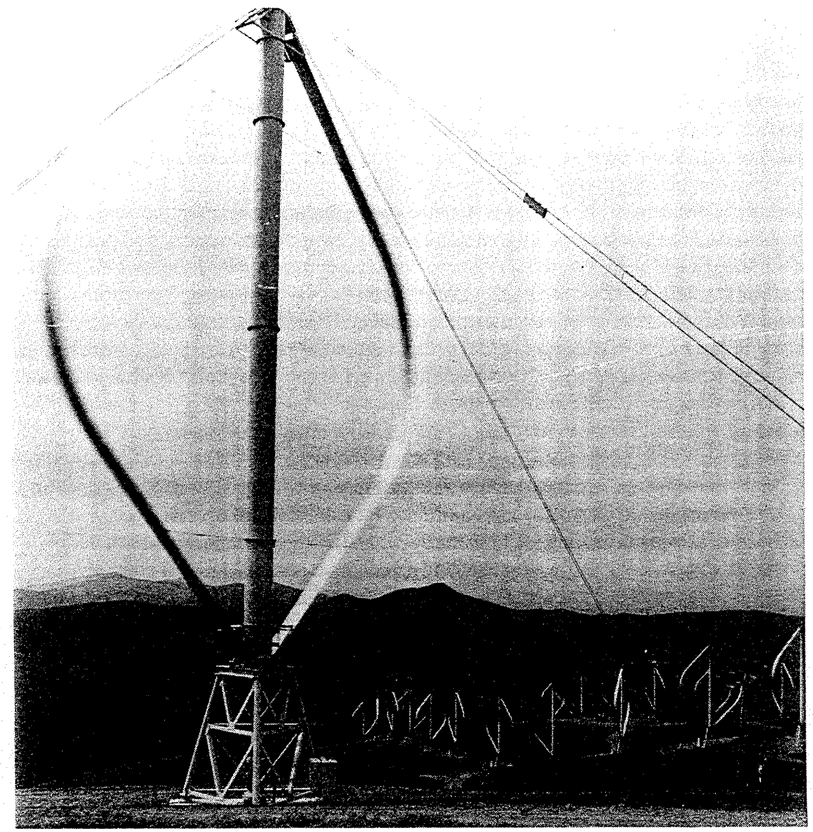


Figure 4-15. Darrieus VAWTs deployed in the Altamont Pass region of California. Power-train equipment at ground level is ready accessible for maintenance. Turbines are 170-kW *FloWind 17* VAWTs. (*Courtesy of NASA Lewis Research Center*)

Table 4-6. Typical Relative Costs of VAWT Subsystems

Subsystem	Cost share
Blade support system: (Struts, root connections, central column, upper bearing, guys)	25%
Power Train:	20%
Control System:	20%
Base Structure:	20%
Blades:	15%

Large-Scale Horizontal-Axis Wind Turbines

Since 1977, U.S. and foreign government agencies and private corporations have funded research on and development of a number of prototype multi-megawatt HAWTs. Earlier NASA/DOE experimental machines (*e.g.* the 100-kW Mod-0, 200-kW Mod-0A, 2.0-MW Mod-1, and 2.5-MW Mod-2 turbines described in Chapter 3) were instrumental in providing data to refine the technology required for the following generations of large-scale HAWTs. Currently, commercial machines in this size range are under development in Europe (see Table 3-2, but these are still considered to be in the pre-production phase. That is, research and development are not yet complete. To be commercially viable, additional cost reductions and/or performance improvements must be made. However, performance results obtained thus far have been encouraging [*e.g.* IEA 1992], and work continues on refining current designs and manufacturing methods to meet the cost and reliability goals.

Large-scale wind turbines, with rotor diameters larger than 45 m and/or power ratings of 1,000 kW or more, offer advantages that include

-- The ability to extract more wind energy per unit of land area when topography consists of one or more ridges and the wind blows predominantly from one direction.
-- Improved aerodynamic performance, because of higher *Reynolds numbers* associated with larger blade chord dimensions.
-- Lower sensitivity of larger blades to dirt, rain, and insects, because of larger blade thickness dimensions.
-- Potential economies of scale for some components, such as control system cost per unit of installed power.

While medium- and large-scale HAWTs share many of the same design considerations, some of these may be more critical for multi-megawatt machines and must be carefully addressed in the design process. These include

-- handling, storing, and transporting components in the shop and to the site;
-- availability of cranes and limitations on lift weights and heights;
-- dependence on aerodynamic control of speed and power;
-- provisions for personnel access and safety, including access inside the rotor;
-- good exterior condition with minimum maintenance;
-- siting to avoid electromagnetic interference;
-- quality control to high standards for steel weldments, castings, and forgings;

Only two large-scale HAWTs are currently operating in the U.S. These are the 3.2-MW *Boeing Mod-5B* in the Hawaiian Islands (Figs. 2-1 and 4-5) and the 4.0-MW *Hamilton Standard/KKRV WTS-4* in Wyoming (Fig. 4-4). As mentioned previously, these are one-of-a-kind prototypes that are now privately owned and producing energy for sale to their local utilities. Operating experience of the Mod-5B machine over a period of 55 months, including production and maintenance data, is summarized in [Spera and Miller 1992].

Commercial Wind Power Stations on Utility Grids

Most commercial wind turbines in the U.S. are installed in clusters connected by a common power line to a utility grid (Figs. 4-1 to 4-5). These installations are called *wind power stations* and have also been referred to as *wind parks*, *wind plants*, and *wind farms*. By the end of 1992, there were about 16,000 commercial wind turbines in service in California wind power stations. Because of the proximity of the individual machines to one another and the central way they are managed, such installations should be thought of as single entities, much as fossil-fuel or hydroelectric plants with multiple turbogenerators.

Turbines in a wind power station are generally sited in areas that have high *avoided cost of energy* (power purchase rate), high *annual average wind speed* (more than 6 m/s), a reasonable match of higher wind speeds (diurnal and annual) with periods of *peak power demand*, access to utility transmission lines, and easy access by vehicle. In addition, it is helpful if other economic incentives exist, so that the project will produce a rate of return sufficient to attract private capital investment. Wind power stations are usually located away from residences so that turbine noise, television interference, and visual impact do not present problems.

The physical arrangement of the turbines within the station depends upon the terrain, wind directions and speeds, and turbine size. In general, if a site is flat terrain, with winds predominantly from one direction, the turbines are spaced from 1.5 to 3.0 rotor-diameters in the cross-wind direction, in rows 8 to 10 rotor-diameters apart, as shown in Figure 4-16. The size of wind power stations varies widely. In the U.S., the average size has grown with the industry, reaching over 100 units (approx. 10 MW) during 1984 and almost 400 units (approx. 40 MW) by 1992. In Denmark, clusters are much smaller, averaging from 10 to 20 units.

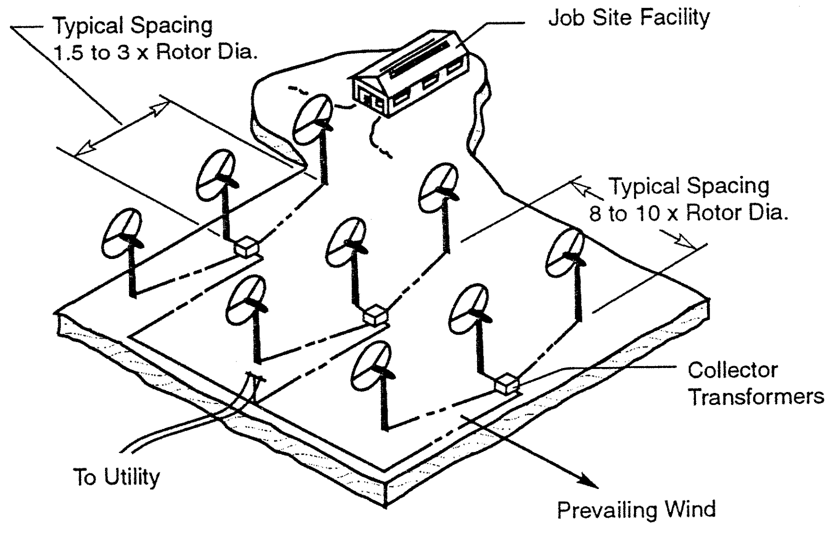


Figure 4-16. Typical arrangement of a wind power station on flat terrain.

Development of Wind Power Stations

Tax incentives and favorable power purchase rates in the late 1970s and early 1980s set the stage for an explosive growth in the sales of wind turbines to private owners. The economics of siting wind turbines near each other in wind power stations were more advantageous than installing many individual units, each with its own equipment for handling power and its own infrastructure for operations and maintenance. Prior to the 1980s, most wind energy development focused on the individual wind turbine. Little attention was paid to the design of clusters of machines and the impact of upwind turbines on other wind turbines operating nearby. Further, little was known regarding the logistics of operating large groups of machines.

Standard civil engineering practices and power handling devices were easily incorporated into the design of wind power stations. However, array effects (primarily wake effects) on wind turbine loads and energy production were not well understood. Machine siting began to focus on maximizing total energy generation while minimizing development expense. From today's perspective, this idea seems consistent with prior utility experience, since most conventional power plants are composed of several generating units. Prior to the 1980s, however, the concept seemed revolutionary. The fledgling wind industry was in the business of manufacturing turbines, not installing and operating thousands of machines.

The infrastructure of a wind power station in the U.S. is a highly-complex relationship among developers, investors, wind turbine manufacturers, utilities, insurers, and government entities (which must approve many aspects of the project.) From 1982 through 1984, more than 40 firms developed wind power stations in California. By the end of 1986, the ten largest wind turbine manufacturers installed over 80 percent of California's wind power capacity. The four largest of these (*U.S. Windpower, Micon, Fayette*, and *Vestas*) accounted for 55 percent. By 1987, however, only a half-dozen major companies remained. Despite expiration of tax credits in 1985, almost 60% of the total wind-power capacity in California was installed between 1986 and 1992, primarily by three developers.

Energy generated by wind power stations in California quadrupled from 1983 to 1984, tripled from 1984 to 1985, and quadrupled again from 1985 through 1991. In 1991, more than 95% of all California wind power capacity and energy output came from three areas: The Altamont Pass area (Fig. 4-1) accounted for 39%, the Tehachapi Pass area (Fig. 4-2) produced 38%, and the output from the San Gorgonio Pass area (Fig. 4-3) was 18% of the statewide total [CEC 1992]. Annual increases in generation moderated after 1986 because new turbines represented a smaller proportion of the total installed machines, and major gains in productivity through improved reliability had already been achieved.

Financial Elements Essential for Development

From a financial perspective, the key elements that determine the viability of wind power development are *cost*, *revenue*, and the desired *rate of return* on investment. Other factors may also be important (such as state or national policies), but these are often implemented through financial incentives (such as tax credits) or disincentives that are reflected in the overall financial equation. The *cost element* includes the price of the turbine, the cost of installation (including permits, site plans and drawings, insurance, and financing charges), the infrastructure needed to operate the station (*e.g.*, roads, transmission lines, power handling devices, and service buildings), and operation and maintenance costs. The infrastructure costs are significantly influenced by the terrain, difficulty of access and construction (whether the land is flat or mountainous), and proximity to the existing utility

grid. Operation and maintenance costs are determined by the station's size and the reliability of its equipment.

Revenue is determined by the wind resource, the turbine availability, turbine performance at individual sites throughout the station, and the rate paid by the utility for the energy generated. The desired *rate of return* is influenced by the investment community's perception of the *project risk*, the rate of return from competing investments of similar risk, the type of investment, investor needs, federal and state tax laws, and the political climate.

Wind Resource Assessment

To determine the feasibility of wind energy development in California, the California Energy Commission (CEC) began an extensive resource assessment program in 1977. The CEC classified as "excellent" a wind resource with an average annual wind speed greater than 6 m/s (at an elevation above ground of 10 m) and a wind power density greater than 300 W/m^2. A "good" resource was defined as one averaging from 4.9 to 6.3 m/s, with a density from 200 to 300 W/m^2. The CEC identified several areas of the state that looked promising, with the potential for over 7,000 MW of wind power stations in prime locations and an additional 6,400 MW in other areas. Some, but not all, of these locations have now been partially developed.

California development was concentrated in "excellent" areas, with some sites exhibiting average annual wind speeds above 9 m/s. However, developers underestimated the difficulty of characterizing the wind resource in hilly terrain for an entire wind power station from a few, widely-spaced anemometers. They also underestimated the decrease in wind speed within an array of turbines. As a result, they frequently overestimated the average wind speeds available for generating energy. In theory, the ideal resource assessment would include collecting wind speed, wind direction, and wind shear data for at least a two-year period at representative sites within an area where a wind power station might be installed. However, financial considerations usually make this impractical.

Typical wind resource studies have used long-term wind data from a nearby location, coupled with limited anemometer data on the site to be developed. Following the expiration of the tax credits in 1986, a greater emphasis on performance has resulted in improved turbine siting. By 1987, considerably more anemometers were used to define the local wind resource before turbines were installed. Despite improvements in micrositing technology and procedures, energy estimates for a new wind power station in hilly terrain may still be inaccurate by as much as ±15%.

During the tax credit period, sites with 6 m/s annual average wind speeds could be developed economically. After expiration of the tax credits, the average speed needed to make a project economically viable (even with favorable power purchase rates) increased to 8 m/s, which more than doubled the required energy content in the wind. This stimulated renewed interest in those prime wind sites that had already been partially developed.

In 1987 several operators were considering installing additional turbines on taller towers among the turbines already in service, to make better use of the leased land. This innovative concept, called *stepped arrays* or a *wind wall* allows power stations at prime wind sites to expand vertically. Siting new turbines among machines already in place also increases the accuracy of the operator's energy production estimates. The operator can use the actual production data from the installed turbines to anticipate the energy production from the new turbines, after accounting for the increased height of the towers and any additional array losses that may be incurred. The stepped array concept has not been studied enough to determine the net economic benefits.

Land Requirements

Existing wind power stations occupy from 60,000 to 120,000 m^2/MW, with 70,000 m^2/MW as a typical land requirement. Land costs are usually reflected in operating expenses. Land for wind power stations is generally leased to the developer or operator, although in some cases the developer may buy the site. Lease terms often include a one-time, advance payment of $200 to $2,000 per turbine site plus a lease fee based on a royalty or percentage of earnings. The royalty may be calculated on either gross or net earnings. Such fees have generally been 2% to 10% of gross revenue.

Wind power stations often are considered benign compared to conventional power plants with coal or nuclear fuel, but critics have raised concerns about visual pollution, noise, and other land-use impacts. Questions of aesthetic and noise impacts are comparable to the problems accompanying conventional energy facilities, but in other ways the land-use requirements for wind power stations are unique. Developers must place the turbines in geometric patterns to optimize the land use while minimizing the wake interference from upwind turbines on downwind machines. These patterns depend upon the terrain and the prevailing winds. In areas where the winds come from one direction, developers space the turbines in rows equidistant from one another. The rows are placed perpendicular to the prevailing wind. Where the winds come from several directions, turbines are spaced so as to maximize annual gross energy production, consistent with minimizing total land use.

Trends in Wind Turbine Size

The first wind power stations used relatively small wind turbines because that was the only size available in large quantities. The NASA/DOE program emphasized multimegawatt machines in the late 1970s and early 1980s, but these never became commercially available. Research on the small-scale systems then being produced by industry (with ratings from 1 to 40 kW) was begun in 1976. A series of prototype turbines, 5 to 25 m in diameter, was developed under the U.S. Federal Wind Energy Program from 1977 to 1981, and several were used in the first wind power stations. These systems included the *Enertech 44/40* and several derivatives of the experimental flex-hub rotor system developed at the *United Technologies Research Center.*

As the commercial wind energy industry began scaling up small-scale machines to the 100- to 200-kW power range, more government programs began emphasizing long-term research applicable to all machine sizes. The recent trend within the commercial sector has been to produce machines with ratings of 300 kW and more. The average capacity rating of wind turbines installed in California wind power stations has almost quadrupled since 1981 -- from 49 kW in that year to 191 in 1992. Over the same period, the maximum rating increased from 55 kW to 600 kW. Most manufacturers surveyed in 1987 believed that they would be producing machines rated at up to 600 kW by 1989-93. The trend to produce larger machines is a result of at least four factors:

- Wind turbine costs per kilowatt decrease as machine sizes increase from 100 kW to 200 kW. (Insufficient cost data are available for ratings larger than 200 kW).
- *Balance-of-station costs* per kilowatt (the price of the land and infrastructure) decrease as the turbine size increases (*e.g.* less wiring and land are required).
- Many good wind sites are comprised of ridges that enable the production of more energy per unit of land using larger wind turbines, because ridges frequently have only enough space for a single line of wind turbines.
- A segment of the O&M costs is dependent on the number of turbines, and therefore decreases with increasing turbine size.

Characteristics of Wind Power Station Output

On the Southern California Edison grid, it was found that the *peak power ratio* (station output divided by rated capacity) never exceeded 60% during an 18-month period, on a regional basis [Stock 1986]. This is illustrated in Figure 4-17. For smaller geographic areas, flat terrain, and uniform wind turbines, the peak power ratio could reach unity.

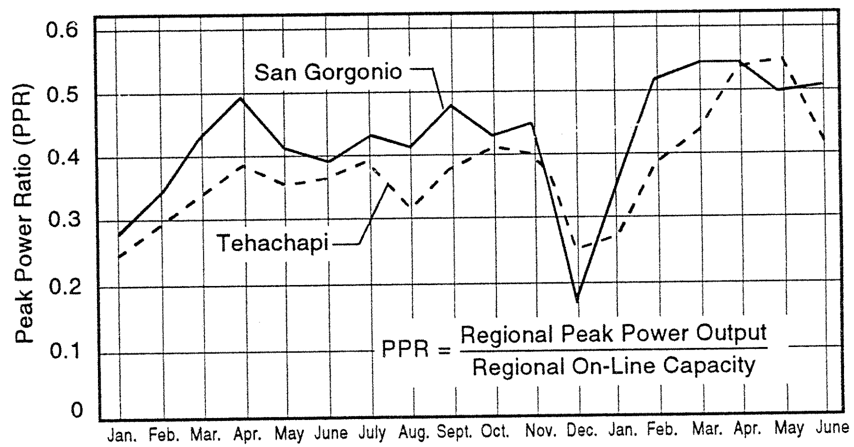


Figure 4-17. Regional peak power ratios for wind power stations in the Southern California Edison service area. [Stock 1986]

There are several factors that tend to *dampen fluctuations* in the output of a large wind power station. These include wind conditions, spatial diversity of winds over the station, and geographic separation of stations within a utility's service area. Figure 4-18 shows a typical combined output of wind power stations in two regions interconnected to the same grid [Stock 1986]. Output does vary on a one-minute average basis, but not as wildly as might be expected from wind variations during the same period of time.

Because of wind variability, wind power station output often does not coincide with changes in utility loads, as shown in Figure 4-19 for the Altamont Pass region in California. These data were taken in the month of June, which represents the peak season of wind power generation in the Altamont area. However, because of limited penetration, discrepancies in *load following* have not been a problem to date.

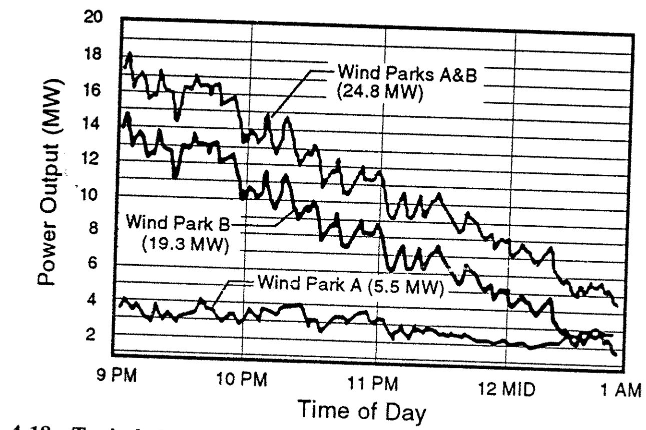


Figure 4-18. Typical short-term variations in wind power station output. Data are one-minute averages [Stock 1986].

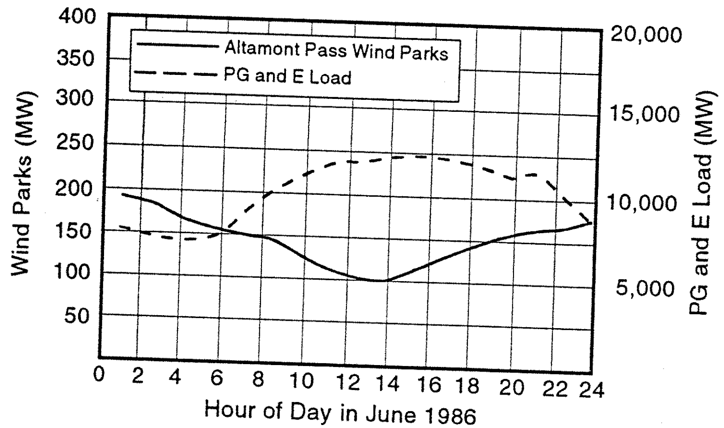


Figure 4-19. Comparison of hourly regional wind power station output and utility load. [Smith 1986]

Distributed Wind Turbines on Utility Grids

Distributed wind turbines are dispersed across a utility's service area, as opposed to turbines in wind power stations that are concentrated in one location. Distributed turbines generally serve residential or light commercial loads instead of generating bulk power for sale to a utility. Currently, there are 3,000 to 4,000 distributed wind turbines installed throughout the U.S. Many are no longer in service, however, and most of the machines still operating are small (10 kW or less). In total numbers, more small turbines have been installed in the U.S. than in Denmark, which has 70 to 80 percent of Europe's wind generating capacity, mostly in distributed applications. In 1987, wind turbines supplied 0.8% of Denmark's electricity consumption [Madsen May 1987]. About one-third (450 units) of the turbines installed in Denmark in 1987 were built by one firm, of which about 80% followed the nationwide pattern and were installed in single units.

U.S. Experience with Grid-Connected Distributed Turbines

The U.S. market for small-scale grid-connected wind turbines, designed to serve single-family homes and small businesses, was hampered from the start by several factors:

-- high cost of small machines;
-- lack of financing available to the buyer;
-- limited number of good wind sites;
-- poor wind energy conversion performance and reliability;
-- lack of distribution and service systems;
-- environmental impacts.

In the early 1970s, many small-turbine manufacturers in the U.S. identified a market for machines in the 1- to 5-kW range. They believed this size was ample to meet most of the electrical demand for homes without electric heat, throughout most of the country. Prior to the passage of the *Public Utility Regulatory Policies Act (PURPA)*, and in areas where power purchase rates were low, it was desirable to use as much electricity on-site as possible and to minimize the excess that was sold to the utility. Moreover, the new companies entering the wind turbine manufacturing business did not have the capital to build machines much larger than 5 kW. It was difficult to find individual buyers who could afford the cost of a larger turbine, and in the U.S. it was uncommon for two homeowners to cooperatively buy a wind turbine for their common benefit.

Another major impediment to U.S. wind turbine installations was the lack of sufficiently energetic winds in many areas that were otherwise attractive for wind power. Furthermore, wind resources seldom matched the electrical demand at small distributed applications, as shown by the graph in Figure 4-20. Interested buyers often found their sites had poor winds or were sheltered from high winds by buildings or trees. As a result, many companies produced turbines for local consumption that were installed by buyers in areas of low wind. Even when the turbines operated properly, their low energy production often reinforced the notion that wind energy was not cost-effective. The productivity problem was compounded by the erratic reliability of many early turbines.

These factors, and the difficulty in obtaining financing for this relatively new technology, limited the size of distributed machines available on the market. As a result, most small-scale U.S. turbines available during the period 1979-84 were more expensive per installed kilowatt than their larger counterparts in Denmark. The unit cost figures in Table 4-7 illustrate the economy of scale for rated powers below 200 kW. Perhaps the major

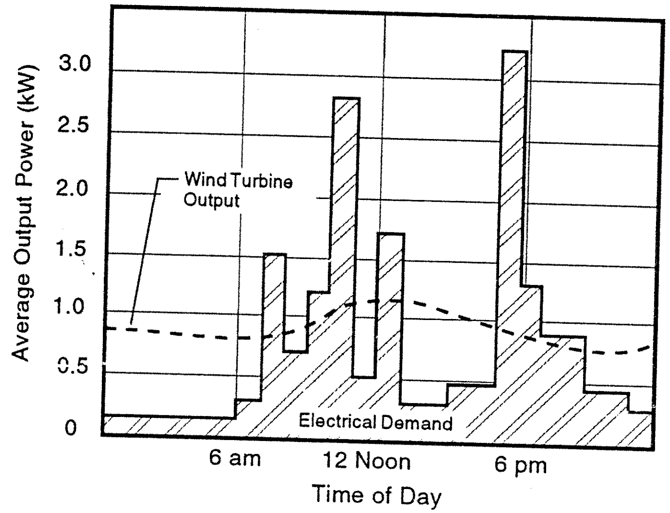


Figure 4-20. Typical mismatch between hourly residential power consumption in the U.S. and the output of a small-scale wind turbine.

deterrents to the successful deployment of large numbers of distributed systems in the U.S. were (a) the large distances between installations, and (b) the lack of an integrated maintenance system. This situation was reversed in Denmark, with its small land area and many local manufacturers, and led to more rapid deployment in that country.

Table 4-7. Comparative Costs of U.S. and Danish Wind Turbines: 1979-84

	Typical small-scale U.S. HAWTs			Typical medium-scale Danish HAWT
Rotor diameter	3 m	4 m	7 m	15 m
Rated power	1 kW	2 kW	10 kW	55 kW
Swept area	7 m²	13 m²	38 m²	177 m²
Cost	$6,000 to $8,000	$8,000 to $10,000	$18,000 to $25,000	$70,000 to $75,000
Cost per unit power	$6,000/kW to $8,000/kW	$4,000/kW to $5,000/kW	$1,800/kW to $2,500/kW	$1,270/kW to $1,360/kW
Cost per unit area	$850/m² to $1,130/m²	$640/m² to $800/m²	$470/m² to $650/m²	$400/m² to $420/m²

Danish Experience with Grid-Connected Distributed Turbines

The Danish wind industry, like its counterpart in the U.S., was first developed to serve a distributed market. Only years later did the industry begin to develop and sell turbines for wind power stations. For a variety of cultural and economic reasons the Danes were very successful in serving this distributed market. By 1993, about 3,500 wind turbines were operating in Denmark, mostly in distributed applications serving farms, homes, and small businesses. Although the total number of turbines in Denmark is only 22% of those in California, the average number per unit of land area is twice as much (one per 12 square kilometers in Denmark *vs.* one per 25 in California). The California turbines are generally concentrated in wind power stations, while the turbines in Denmark are generally dispersed.

The Danish Setting for Wind Energy

A nation of small cities, Denmark's population is distributed uniformly over the Jutland peninsula and the major islands of Zealand, Fyn, and Lolland. The uniform terrain is characterized by a flat, glaciated plain just above sea level with only a few hills and coastal dunes rising above the plain. Numerous inlets pierce the plain, creating a greatly indented coastline. There are 100 inhabited islands in Denmark. The indented coastline, the flat terrain, and the dominance of agriculture facilitate the installation of distributed wind turbines. Numerous bays and inlets provide an unobstructed fetch for winds sweeping across Denmark's open water. The flat terrain and the dominance of agriculture, with its dispersed housing and open fields, further contribute to a greater availability of good wind sites.

Like the Dutch to the southwest, the Danes have a long history of working with and using the wind, so the use of wind turbines seems more commonplace to them and less of a novelty. Another cultural characteristic in Denmark that is advantageous for the distributed-turbine market is the frequent use of *cooperative ventures*. Two or more homeowners or farmers will often buy a larger wind turbine together, taking advantage of the economy of scale and sharing the costs and benefits from production. Although there are no estimates of how many turbines have been installed in this way, cooperative ventures are significant not only as a means for obtaining a larger single turbine, but also because they are the model for acquiring multiple-unit installations.

There are many cases in Denmark where towns and villages have installed turbines to offset electricity consumption at municipal facilities (*e.g.*, sport stadiums, ferry terminals, and technical schools). About 50% of the projects using five or more turbines have been sponsored by municipal governments.

Development of the Danish Wind Turbine Industry

The early market for small wind turbines in Denmark developed like its counterpart in the U.S., along two lines: stand-alone systems to heat water and grid-connected systems. But later wind turbine development in Denmark took a different path that led to success in the distributed-system market. Influential factors were

-- the agricultural origin of turbine designs;
-- the well-established type of manufacturer;
-- the proximity of good sites to manufacturers;
-- the compact geographical size of the market served;
-- the development of a national certification program.

Most Danish turbine designs grew out of the agricultural sector, and design development was privately supported. Because of their agricultural roots, early Danish turbine designs were simple, rugged, and used well-understood technology. The Danes paid a price for their use of heavier construction methods in terms of higher initial costs, higher transportation costs, and higher installation costs, but these penalties were offset by higher reliability. Most of the firms entering the wind market were well-established, mid-sized companies. Their ample size, coupled with their willingness to fund design development, enabled Danish firms to build first-generation turbines that were fairly reliable in the low-turbulence wind environment common in Denmark. Problems in the field and the cost of the solutions were of limited magnitude, and their adequate financial resources permitted six leading Danish manufacturers of wind turbines to survive into the mid-1980s.

The distributed-turbine market in Denmark was aided by the close physical proximity of good sites to the machine manufacturers. For example, two of Denmark's largest wind power stations, the privately-owned 2.3-MW Tændpibe and the utility-owned 10-MW Velling Mærsk wind plants, are only a few kilometers from the *Vestas* factory where their turbines were built. Close proximity of site to manufacturing plant makes it much easier to move quickly through design iterations. Because of the small geographic area of Denmark, manufacturers were able to use in-house maintenance and repair teams to serve the entire country. Marketing was also beneficially affected. Because of the homogeneity of the market, the sales force of each manufacturer was able to call on customers directly, eliminating the need for an intermediate, cumbersome distribution system that relies on dealers who often have allegiance to more than one product.

Approval and Certification System

Denmark was the first to introduce design standards for wind turbines, and it did so through a *government certification* program. To qualify for federal tax credits and export loan guarantees, turbines have to be certified by the *Risø National Laboratory Station for Wind Turbines*. Risø personnel are aware that wind turbine design is complex and that manufacturers do not always fully understand the forces at work on the turbines. To address this problem, they originally set what they believed to be conservative design criteria for critical components. Later, Risø and the Danish industry learned that these criteria needed to be even more conservative. The result was Risø's imposition of design disciplines on the industry at an early stage. Although it may have delayed creative new designs and eliminated variety in turbine configurations, government certification plays an important role in ensuring that Danish turbines performed reliably once they are in the field.

In 1991 a new approval and certification system was introduced for the purpose of improving the overall quality of Danish wind turbines [Nielsen 1993]. It specifies very comprehensive requirements for documentation of all design criteria (*e.g.* load cases and loads), fatigue evaluation, safety levels, power curves, and noise emissions, plus quality procedures for manufacturing, transporting, installing, and subsequently servicing the turbine.

Status of Wind Energy Development in Denmark

At the end of 1992, the total number of grid-connected wind turbines in Denmark was 3,486 with a total rated capacity of 456 MW [Nielsen 1993]. Energy production from wind turbines in 1992 was 902,000 MWh, which was 3% of the national consumption. Private ownership accounts for 86% of the turbines, 76% of the installed power, and 79% of the energy production. The remainder comes from utility-owned wind turbines.

Wind Turbines on Isolated or Small Utility Grids

Applications on isolated or small grids are considered a new and growing market for wind turbines. Wind systems intended for isolated or small networks face problems uniquely determined by both the size of the network and the physical setting. There are a variety of application scenarios that can be classified as "isolated" or "small. For example,

-- large islands with large electrical loads (more than 10 MW);
-- large islands with small loads;
-- small islands;
-- isolated mainland communities;
-- mainland communities that are not isolated, but choose to generate their own electricity.

Large Islands

Some large islands use fossil-fuel power plants to feed a large electrical load through an extensive network (*e.g.*, Tasmania in Australia and Oahu in the Hawaiian Islands). Others are without thermal plants and instead use large and/or multiple diesel generators. On the Isle of Man in the Irish Sea, for example, the 45-MW average demand is met by three diesel engines. There are plans to replace these three diesels with one 75-MW conventional thermal plant and possibly ten 250-kW 25-m diameter wind turbines. Other large islands have relatively small loads of 5 MW or less. On Nantucket Island, off the coast of Massachusetts, the local utility began purchasing power in 1983 from a small wind power station located on the island. The station consisted of nine *Enertech HAWTs* with ratings from 25 to 40 kW. All have since been removed.

Small Islands

In 1979, a 200-kW Mod-0A experimental HAWT was interconnected with the utility on Block Island, off the coast of Rhode Island, and tested by NASA to identify problems with operating wind turbines in parallel with diesel units on a small grid (see Chapter 3). On nearby Cuttyhunk Island, peak electrical loads are about 500 kW during the summer tourist season. Examples in the British Isles of small islands with light loads are Lundy Island, Fair Isle, and the Scilly Isles. Electrical loads on islands near mainland population centers -- such as along the New England coast in the United States, near the British Isles, and in the Baltic and Aegean Seas -- reach their peaks during the spring and summer holidays.

Most small islands using small diesel stations are holiday resorts where commercial loads are highly seasonal [Oei 1986]. During the off season the load is mainly residential. In Greece, the ratio of on-season to off-season demand is 5:1 on the larger islands, and 15:1 on the smaller islands. Wind turbine installations in such areas are only economical if the peak wind season coincides with the peak demands.

Isolated Mainland Communities

Even in the developed world there are mainland communities isolated from regional electricity distribution systems. The first Mod-0A HAWT was interconnected with the diesel-fired, municipal utility in Clayton, New Mexico. In the developing world, where regional networks are rudimentary, such applications are much more common. Islands linked to mainland networks by undersea cables are similar to remote mainland communities, since it is advantageous to use wind turbines for local generation whenever possible, to offset purchases from the mainland.

Wind System Characteristics

Because the generation of electricity from the wind varies with wind speed, energy storage is needed in applications relying completely on wind turbines for power. In most small or isolated grids, however, wind generation is used as a fuel saver, in the form of diesel oil in storage tanks or water impounded behind a dam. Weather changes affect wind speed from hour to hour, and within these larger changes in wind speed there are random fluctuations from minute to minute. These fluctuations can create difficulties in using wind turbine output when a significant fraction of the electricity consumed is being generated by the wind power station.

The amount of time during which power must be stored is critical. For example, short-term variations in power, on the order of seconds or minutes, could be stored hydraulically in an accumulator which acts as a small-capacity, high-power buffer [Slack 1986]. It has yet to be demonstrated whether the costs of short-term storage are economical compared to better use of turbine generation (*e.g.*, less dumping of excess energy).

Penetration

The term *penetration* refers to the ratio of wind power to the utility's total power at any instant of time. If the amount of wind-generated power is small in relation to the total capacity of the utility, no *power curtailment* controls on the wind turbines (*i.e.* methods for reducing maximum power) are needed. Recent wind power station experience indicates that wind turbines can contribute between 10% and 15% of the grid power without upsetting *power quality*. Wind penetration in some areas of the Hawaiian Islands is already reaching this level during the night when demand for electricity is low. When wind power generation is a large fraction of the load, the control system of the turbines must play an active part in regulating power characteristics. This control can be achieved by reducing power, dumping energy, or storing excess energy.

The degree of penetration varies seasonally as a function of both wind and electrical demand. Wind turbines sized for modest penetration during peak summer loads will have a high penetration during the off season. This may entail dumping of excess power that might otherwise disturb grid stability, or it may require the use of a fully-controllable wind turbine. Wind system sizing and integration are more of a problem on small grids than on regional networks where power quality is negligibly affected by even large numbers of turbines.

Limitations on Diesel Fuel Savings

One factor that affects maximum wind penetration on diesel-powered grids is how much the output of the diesel generators can be reduced safely and economically. Diesel engines operate inefficiently at partial load, and their operating and maintenance costs may actually increase when they do not run at full capacity [Somerville 1986]. This inefficiency is caused by incomplete combustion, engine friction, windage, generator excitation current losses, and losses in auxiliary equipment. Therefore, fuel savings from reduced demand on a diesel generator are limited because of the machine's reduced performance under partial load.

Ideally, there should be a method to reduce partial-load costs, or to operate the grid with the diesel left in a standby mode to maximize fuel savings and economic benefit to the system. One option for a grid with a high peak-to-base load ratio is to use wind turbines to drive the engine, overcoming the no-load resistance [Oei 1986]. Doing so may entail frequent stop-start cycles of the engine or a sacrifice in power quality as wind speed varies. Avoiding these disadvantages once the diesel engine is taken out of immediate duty requires a wind system capable of either synchronous generation or short-term storage. The storage system need only act as a buffer between the generator and the load [Slack 1986]. A buffer capable of a few minutes' operation may be sufficient.

Two areas of technology development that could increase the amount of diesel fuel saved with wind turbines are *improved system models* [*e.g.*, Qi 1993] and *improved monitoring and control*. In the latter area, a PC-based system for remote control of three 110-kW wind turbines and a 100-kW diesel generator on the Hawaiian Island of Molokai has been developed that uses such technological advancements as *visualization software* and *synthesized sound* [Cousineau 1992]. This two-dimensional virtual reality permits an operator anywhere in the world to "see" and "hear" the power machinery, with the potential for reducing training time, errors, and maintenance response time. In this type of automatic supervisory controller, Diesel generator control and monitoring functions (*e.g.*, automatic and manual starting and stopping, and a view of the control panel) are integrated with the typical monitoring and data functions required to operate a modern wind power station.

Operating Wind Turbines on Small Grids

Grid Load Management

Load management is important in the successful integration of wind turbines into a small grid. Because power is expensive and often in short supply on small grids, users (unlike their counterparts on large grids) are accustomed to limiting their consumption to essential needs. Non-essential loads are either not met or delayed until the time of day when rates are lower. The effectiveness of wind power can be increased by regulating the grid load to reduce the degree of wind penetration. If nonessential loads are switched on as wind generation increases, the penetration will remain relatively constant, and it will be easier to maintain power quality. For example, the *dump circuit* illustrated in Figure 4-21 could direct excess wind power into a lower-priority heating load or dissipate it through a resistance load bank. With this load-management approach, fixed costs of operating the entire grid do not change, but fuel costs decrease as more wind energy becomes available.

Turbine Control

Variable-pitch turbines offer control advantages over fixed-pitch stall-regulated machines in a generating system designed to match power from fluctuating winds to the fluctuating demand of the electrical grid. The potential for greater control may allow higher penetration on small grids by variable-pitch turbines than by stall-regulated turbines. Pitch control regulate power coupled with a synchronous generator can regulate frequency as well as power, acting much like a conventional power plant.

Although there have been recent advancements in variable-speed constant-frequency generating systems, synchronous generation normally dictates that variable-pitch turbines hold the rotor speed constant. With asynchronous machines, such as induction generators driven by stall-regulated turbines, the output of the conventional generators on the grid must be sufficient at all times to provide reactive power.

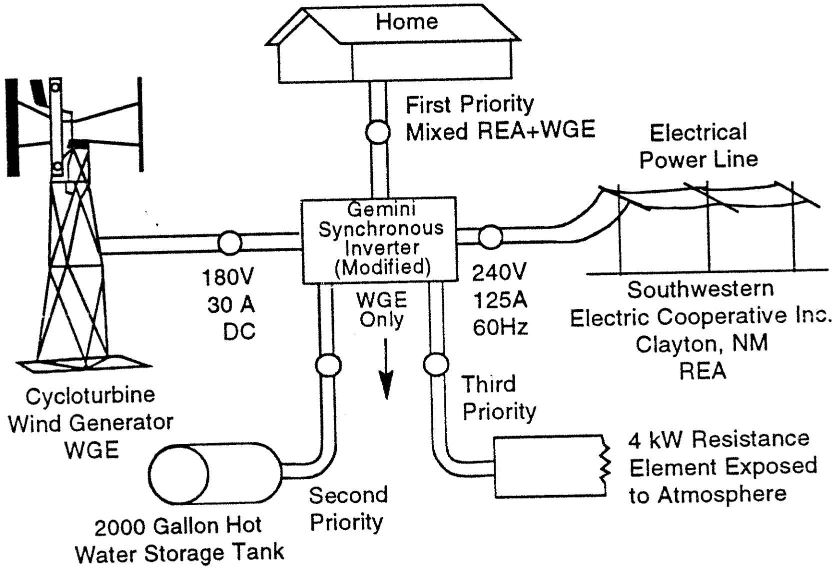


Figure 4-21. Schematic diagram of a dump circuit for switching excess wind power to non-essential loads on small grids.

Additions to the Capacity of Small Grids

Wind generation on small grid systems can not only save fuel but also reduce requirements for *new capacity* in certain situations. Wind turbines can benefit small systems by moving generation nearer to the load and by reducing *voltage drop* at the end of a long, weak line, particularly if the turbine drives a synchronous generator. For small grids, increasing demand may be met more economically in smaller increments by the addition of wind turbines rather than by expanding the conventional power plant [Madsen 1986]. Even where an island grid is linked by cable to the mainland network, installing wind turbines to serve growing demand may be preferable to laying another cable. In some off-peak cases, the island could become a net exporter of electricity to the mainland.

Another aspect of adding wind turbines to a small grid has been the stimulation of latent customer demand. For example, residents of Fair Isle gradually increased their consumption each year after a wind turbine was installed and more power was available than in the past. The additional power from the turbine altered the pattern of energy use.

Maintenance

On larger islands in the developed world, the servicing of small- and medium-scale wind turbines can generally be done by local maintenance personnel. But on smaller islands and on small grids in the developing world the machine suppliers must provide maintenance. Labor costs and transportation charges become significant, because of the extra time it takes to complete a task, the often difficult working conditions, and the fact that most workers, components, tools, and equipment must be shipped to and from the site.

Stand-Alone Wind Turbine Applications

As the name implies, wind energy systems intended for stand-alone applications are designed as the sole or principal source of mechanical or electrical energy, and are not connected in any way to an electrical distribution grid. The major tasks of stand-alone turbines are those that have been performed throughout the history of wind power: Pumping water and generating electricity for local consumption.

As shown in Figure 4-22, the electrical output from a stand-alone wind turbine can be DC for *battery charging*, DC or variable-frequency AC for *resistance heating*, or utility-grade AC to operate *lights* and *motors* directly. In practice, nearly all commercial wind generators for remote applications are designed for charging batteries. No wind system has been marketed successfully that is intended solely for heating, and few small-scale wind turbines have been designed for direct generation of utility-grade AC power.

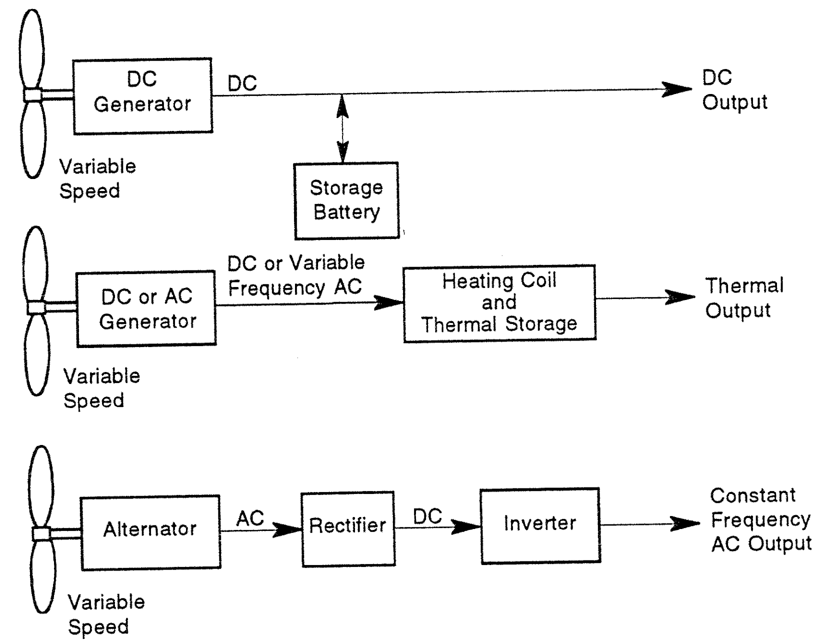


Figure 4-22. Output configurations for stand-alone wind turbine generators.

Water Pumping

Pumping water is an often-forgotten application of stand-alone wind systems. Water pumping conjures up images of an archaic technology, but wind power remains one of the most cost-effective ways to pump water in many areas of the world. The oil price shocks in the 1970s renewed interest in wind turbines that pump water.

In dry areas of the Great Plains (both in the U.S. and Canada), *American multibladed windmills* are still essential equipment for raising range cattle. Those working in the field of rural water supply estimate that there are from 500,000 to 1,000,000 multibladed windmills in use today, mostly in Argentina, the United States, Australia, and South Africa [Gaudiosi and Pirazzi 1987]. Researchers at *West Texas State University* estimate that in the Texas panhandle and adjoining areas of the Southwest, several thousands of windmills are still in use because the cost of extending a utility line to the range is prohibitive. The water-pumping windmill is also a symbol of Australia's outback and Argentina's pampas.

In mountain-ringed Central Europe, low average wind speeds have forced the government wind programs in Hungary and Czechoslovakia to concentrate on water pumping. Hungarian manufacturers have developed several indigenous windmill models patterned after the familiar American design for use on the Alfold, the Hungarian Great Plain. In the rural areas of developing countries, there is a need for low-cost methods of raising water for domestic and low-volume irrigation use. Assistance in meeting this need has been provided in the Caribbean by the *Brace Research Institute* of McGill University (Canada) and in Africa and Pakistan by the *Intermediate Technology Development Group* (U.K.). Between 1930 and 1960, about 10,000 water-pumping windmills were installed in Morocco, only to be replaced later by diesel- and kerosene-fueled motorized pumps [UN 1987]. Since the 1970s, Morocco has attempted to restore many of these windmills.

In comparison with the American multibladed machines, new windmills are more cost-effective because they use less material, are easier to install and maintain, and provide better performance. The United Nations estimates that these new turbines reduce water costs by a factor of four over the existing multibladed machines and are often competitive with other sources of domestic water provision [Gaudiosi and Pirazzi 1987]. Where irrigation is critical, there are regions where wind is an economical alternative even when average wind speeds are below 3.5 m/s. Sri Lanka has a program to replace some of its 50,000 diesel-driven water pumps with wind machines costing from $300 to $500 each, because the turbines are more cost-effective [UN 1987].

A water-pumping windmill for high-lift applications has been developed in China, patterned after the Australian *Southern Cross* windmill. The Chinese have ambitious plans to use this design on the 40,000 wells dotting the Inner Mongolian plains [Sexon 1987].

Stand-Alone Electricity Generation

Where remote electrical generation is desired, the role of wind turbines has changed in recent times. In the past, wind turbines were viewed as a sole source of electricity. Today, wind turbines are most often combined with other stand-alone generators which provide *backup generation* for the wind turbine during extended periods of low wind. These backup systems include engine-driven generators, photovoltaic cells, and fuel cells, but the wind turbine remains the principal source of power.

Residential and Agricultural Heating by Wind-Generated Electricity

Resistance heating, because of its insensitivity to the quality or frequency of electricity, allows the designer to tailor a relatively simple wind turbine for variable speed operation, which results in more efficient operation. Controls necessary for the generations of utility-grade power are eliminated, along with most power-conditioning electronics. Researchers in the U.S. and Ireland have experimented with the variable-voltage, variable-frequency output from wind-driven AC alternators and DC generators for producing heat with resistance elements. Several firms have tried to commercialize the concept, but without success.

One heating concept is the *wind furnace* developed at the *University of Massachusetts* and illustrated in Figure 4-23. Applications for such a system range from home heating to heating water for dairies. Although the wind furnace project succeeded in demonstrating that the water heating system worked, there have been no successful commercial ventures to date. In addition to the mechanical problems that beset these turbines, the economics were unattractive. The bulk of the expense in a small-scale wind system is not in the controls but in the turbine, tower, and installation. The savings from eliminating any power-conditioning controls and the improved rotor efficiency obtained from variable-speed operation do not reduce the cost of electricity sufficiently to compete with heating fuels.

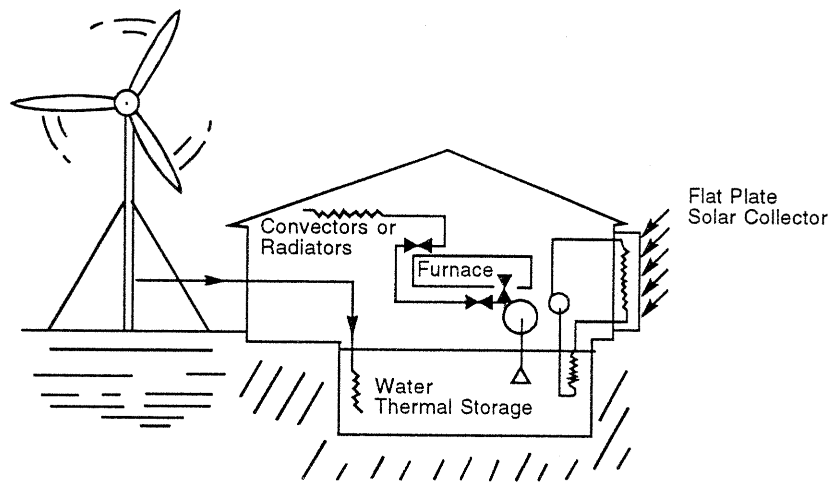


Figure 4-23. Schematic diagram of the "wind furnace" system for residential heating. [Cromack and Heronemus 1977]

As an alternative to resistance heating, *Cornell University* and several private manufacturers have attempted to market turbines for heating water mechanically, through friction. This system uses a *water churn* mounted on the tower centerline directly under the turbine and coupled to it through a right-angle drive, thereby eliminating generator and line costs and power losses. Thermal losses in the churn and pipes plus the power required for a circulating pump are major design considerations for this type of heating.

Stand-Alone Turbines for Remote Homesteads and Telecommunication Sites

The initial capital cost of a wind power system has been a major deterrent to homesteaders but less of a concern to operators of remote telecommunications equipment where reliable power is a necessity. The high cost of commercial wind turbines and the seemingly simple technology used in harnessing the wind have led many homesteaders to build their own machines. These home-built units have succeeded best in relatively benign environments found in the continental United States, England, and Ireland. But in harsher environments, the machines quickly succumb to various mechanical and electrical problems, with the homesteaders bearing the brunt of the repair duties. Nevertheless, some commercial products produced in the late 1970s have performed satisfactorily in harsh environments.

Because of the need for storing excess energy to compensate for extended periods of low winds, nearly all stand-alone wind systems are designed to charge batteries. However, few battery chargers today generate DC directly. Most drive alternators and rectify the AC output to DC. During the decline in oil prices in the 1980s, the market for small turbines used in remote applications in the developing world has been primarily for telecommunications, both commercial and military. Manufacturers who design products for the remote market have modified their turbines in response to customer needs, particularly their need for high reliability with little or no maintenance.

In the developing world, demand continues to grow for small wind systems of modest output. Approximately 30,000 small-scale wind turbines are operating in the province of Inner Mongolia, in the People's Republic of China [Sexon 1987]. At least half of the turbines are of Chinese design, with rotor diameters from 1.4 to 2 m and outputs ranging from 50 to 150 W. The 100-W version is the most popular. Herdsmen use these turbines to charge truck batteries which, with an *inverter*, run AC lights, televisions, radios, and (in some cases) washing machines and irons. The market in other parts of China is substantial. About 300 million people in China live without electricity, and some observers estimate that one-third of these live in areas with average wind speeds of 5 m/s or more.

Cathodic Protection

Cathodic protection prevents corrosion resulting from the effects of small electrical currents travelling through dissimilar ferrous metals. During the 1930s, cathodic protection of pipelines crossing remote parts of the U.S. was accomplished by using small wind turbines designed for charging batteries. Modern wind turbines designed for this market have rotors 0.5- to 2-m in diameter and generate from 50 to 500 WDC. By the mid-1980s, this small market had been captured by photovoltaic cells. Even the most maintenance-free turbines require considerably more service than the small solar panels needed for cathodic protection.

Wind-Assisted Irrigation and Drainage

As discussed earlier (see **Small Windmills Used for Water Pumping**) wind turbines that generate electricity can also be used to pump large volumes of water in stand-alone applications.

Wind Turbine Operation and Maintenance

Operation and maintenance (O&M) activities include all work necessary to *monitor and control power output* and keep the turbines *on-line* (available to generate electricity whenever the wind is within the operating range) through *scheduled* and *unscheduled maintenance*. These subjects will be discussed here primarily from the point of view of wind power stations composed of many turbines. Other O&M activities include contacts with government and utility personnel, and the public; general facility maintenance (*e.g.*, roads and buildings), and development and implementation of turbine improvements.

Performance Monitoring and Control Activities

Most modern wind power stations use a central control system from which the performance and operation of each wind turbine is continuously monitored. A central microprocessor is generally employed to store and display the operational status of all of the turbines within the station. The control systems in most modern wind turbines incorporate a means of measuring the cumulative and current day's energy production of the machine. In addition, some controllers contain software that acquires and records additional parameters related to performance, such as

-- wind speed and direction;
-- power output by each wind turbine and by the station;
-- wind turbine and station cumulative energy production;
-- actual energy production for each turbine and for the total station *vs.* expected production, based on measured wind speed and direction;
-- revenue earned, by each turbine and by the station.

Predicting and Assessing Energy Production

Figure 4-24 shows a flow chart for the most common method of predicting the *net annual energy production* from a wind power station. The level of uncertainty and the impact of errors on the final energy prediction are highest for the first step in the process (wind speed distribution) and decrease to the last step (miscellaneous losses).

Various *performance parameters* have been used to monitor and assess the net energy production from individual wind turbines and complete wind power stations. Two of these are *capacity factor* and *utilization factor*, which are defined as follows:

<u>Capacity Factor</u>: The ratio of actual net energy production to the product of the power rating times the calendar time interval of interest.

<u>Utilization Factor</u>: The ratio of actual net energy production to the product of the power rating times the cumulative time the wind was in the operating range.

Caution must be used when comparing the capacity factors of different turbines because wind regimes vary so much from site to site. Furthermore, there is no industry standard for rating wind turbines in relation to their rotor diameter. Because energy capture is primarily a function of rotor diameter, turbines with high *rated power densities* (rated power per unit of swept area) will have lower capacity factors than turbines with low rated power densities at the same site. Capacity factors for wind turbines vary widely. In 1992, for example, the average capacity factor for turbines in California wind power stations was

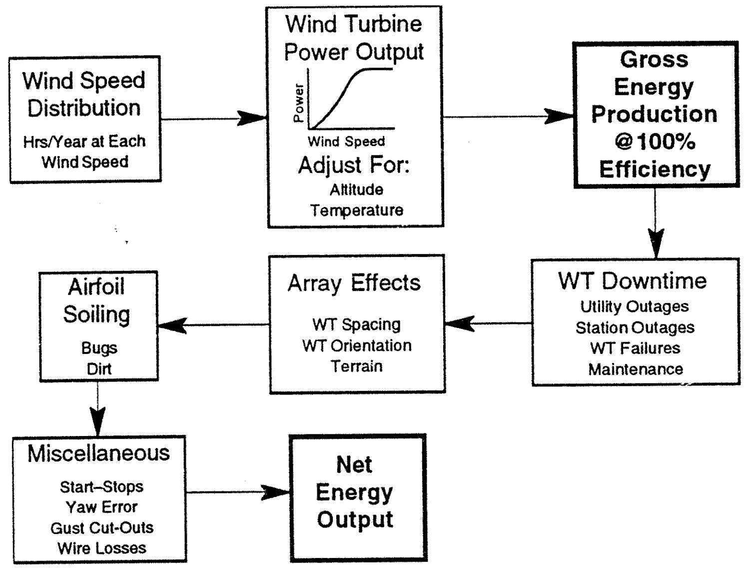


Figure 4-24. Flow chart for predicting net annual energy production from a wind power station.

18.5%, varying from a low of 2% to a high of 38% [Loyola 1993]. The large number of variables associated with capacity factors precludes any meaningful comparison among different turbines at different sites. However, capacity and utilization factors can be helpful in monitoring performance within a wind power station over time.

A performance parameter that is directly related to the purpose of wind power stations is *specific energy output*, expressed in terms of kilowatt-hours per unit of rotor swept area during a specified time period. Table 4-8 is an example of the use of this parameter by the California Energy Commission to determine the effect of turbine size on wind energy production in 1991 [CEC 1992]. Capacity factors are also included for comparison.

Table 4-8. Specific Energy Output of Wind Turbines in California during 1991, According to Size [CEC 1992]

Size range (kW)	Specific energy output ($kWh/m^2/y$)	Capacity factor
1 - 50	438	16%
51 - 100	670	19%
101 - 150	785	22%
151 - 200	833	22%
201 - 600 [1]	856	23%

[1] Plus one 750-kW turbine

Another form of the capacity factor is the ratio of annual energy output to rated power, expressed in the units "kWh/kW." The time period is understood to be one year unless otherwise stated. This parameter is also useful for monitoring wind turbine performance and/or comparing the performance of new or modified turbines with existing turbines, as long as the geographic areas are the same. As an example, Figure 4-25 uses this parameter to show the continuing improvement in energy productivity exhibited from 1983 to 1988 in California wind power stations [Gipe 1990]. The bars represent the annual energy output per unit of rated power.

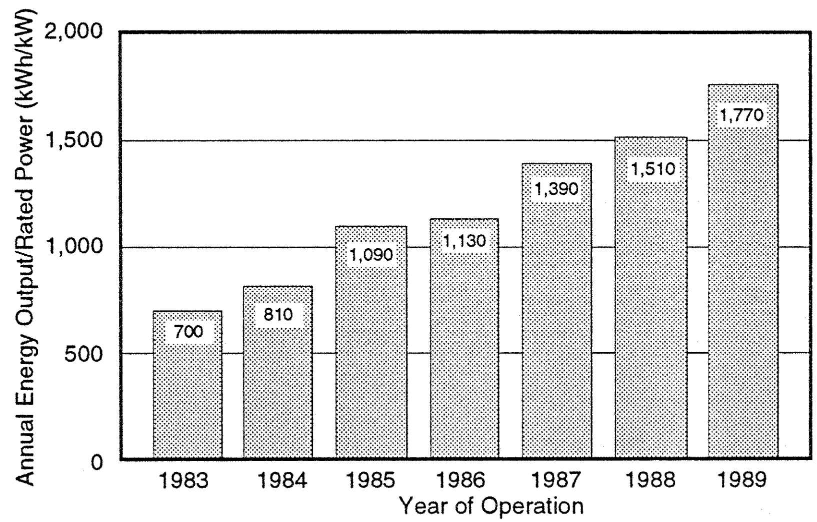


Figure 4-25. Energy productivity of wind power stations in California, from 1983 to 1988.

Actual vs Predicted Energy Production

According to the California Energy Commission, the wind energy industry in California generates about one-half of the electricity that it once predicted it would. One of the major reasons for this shortfall is that the wind resources were frequently overestimated by the wind power station developers (the first step in Fig. 4-24). In addition, other power losses were not adequately accounted for when the original energy projections were made. Figure 4-26 shows the magnitude of these losses based on extensive operating experience at California wind power stations.

Turbines installed in the late 1980s and early 1990s have met or nearly met their performance goals, as a result of

- -- characterizing the wind resource with more accuracy;
- -- more thorough accounting for losses within the wind power station;
- -- significant upgrading of turbines by the power station operators;
- -- more accuracy in prototype performance testing by manufacturers of new turbines.

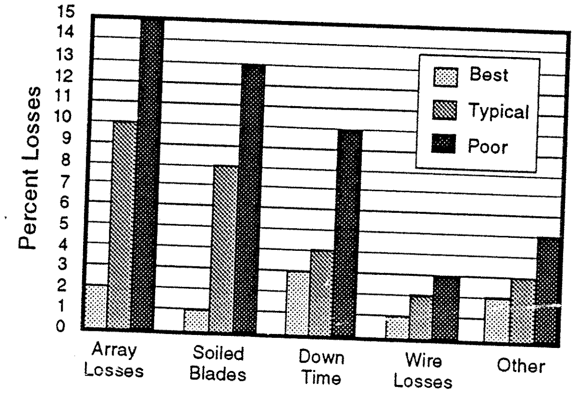


Figure 4-26. Estimates of energy losses in wind power stations that must be taken into account when predicting net annual energy production.

Wind Turbine Maintenance and On-Line Availability

Wind turbine reliability has shown a steady improvement since the early deployments of large numbers of machines in 1980-81. The *on-line availability* in wind power stations increased from 60 percent in 1981 to 97 percent in 1986 [Lynette 1985, 1986]. This improvement was the result of the many factors, including

-- better understanding of wind loads;
-- better design tools for conducting structural analyses;
-- better overall quality of engineering (a sign of maturity within the industry);
-- better siting of machines to avoid potentially destructive turbulence;
-- importation of Danish machines that incorporate conservative design features, such as active yaw control, lower rotor loads, and lower rotor speeds;
-- better logistics support, including more intensive preventive maintenance programs, more complete inventories of spare parts, and better diagnostic software.

However, the increased reliability exhibited by the newer wind turbines may still be insufficient to provide satisfactory long-term availability. The long-term fatigue resistance of most major structural and mechanical components has yet to be proven under operational conditions. Analysis of maintenance records indicates that wear and/or fatigue failures continue to occur in major components such as yaw drives and blades, even on conservatively designed Danish machines.

Danish O&M experience indicates that one full-time person can service wind turbines totaling 5 MW in capacity [Madsen April 1987]. This service requirement is considerably lower than that in the U.S., where total employment in California wind plants is about one full-time person per 1.5 MW of capacity. Because wind turbine maintenance generally involves climbing towers or the use of cranes and bucket lifts, most activities are carried out by a crew of two people for safety reasons.

Scheduled Maintenance Activities

Most maintenance activities are initiated by a central dispatch system and are performed during normal working hours, though a few maintenance activities are performed at night and on weekends. As a general practice, scheduled maintenance is performed during periods of low winds to limit revenue losses. Scheduled maintenance activities include lubrication, changing oil in sumps, washing blades, checking the torque on critical bolts, and checking the condition of brake pads and belts. These activities are generally performed at six-month intervals and require 8 to 15 labor hours annually for a typical wind turbine (65- to 150-kW rating). Long-term scheduled maintenance consists of painting, fiberglass blade touchups, and major component overhauls.

Unscheduled Maintenance Activities

Unscheduled maintenance includes the repair of failed wind turbine components and balance-of-plant equipment. Also included in this category is the resetting of controls on machines that have shut down as a result of overcurrents, blade tip-brake deployments, or other events that do not result in an automatic machine reset. Table 4-9 presents some statistical data on the distribution of unscheduled maintenance events and maintenance labor hours among the various turbine subsystems. These data were derived from a survey of five different turbine models operating in wind power stations in California.

Table 4-9. Distribution of Unscheduled Maintenance Among Wind Turbine Subsystems

	Percent of events	Percent of labor hours
Sensors	23%	12%
Electrical equipment	21%	10%
Yaw drives	17%	30%
Drive trains	12%	26%
Controls	10%	9%
Rotors	8%	4%
Other equipment	6%	5%
Towers	3%	4%

Typical Maintenance Problems and Corrective Actions

Tip Brakes

The problems which have occurred with tip brakes include premature deployment during normal operation and failure to deploy all tip brakes during an overspeed incident. Some tip brakes are reset manually, which results in increased downtime and labor costs. However, an automatic system may reset inappropriately, thereby risking possible serious damage to the turbine. The ideal tip brake would be selectively programmable for either manual or remote reset, depending on current operating conditions. Tip brake deployment mechanisms must be refined further in future wind turbine designs.

Soiled Blades

Most small- and medium-scale wind turbine blades are sensitive to soiling, which can cause turbine power to be substantially reduced. This is particularly true when bugs soil the blades. Soiled blades can decrease energy production by 8 to 13 percent, even if the blades are cleaned periodically. Corrective actions have included more frequent washing and the use of silicon-based solutions to decrease bug accumulation and make washing easier. The long-term solution is to employ airfoil shapes for which lift is not sensitive to the increases in roughness associated with soiling.

Mechanical Brakes

Some manufacturers are still experiencing problems with premature wear-out of mechanical brake pads, usually as a result of selecting brakes with ratings too low for the size of the turbine rotor. This is less of a problem among mature wind turbines.

Power Train Couplings

Mature wind turbines are no longer having problems with couplings in the power train. However, coupling failures continue to be a problem in the newer, larger wind turbines, possibly as a result of inadequate design.

Gearboxes

Fatigue problems have occurred in the gearboxes of several wind turbine designs, and remedial actions are being implemented. Unexpectedly high cyclic and peak loads appear to be the cause of the problems.

Towers

Cracks in the joints of truss towers have been a problem, while shell towers have not experienced fatigue problems to date. More information has been gathered regarding the ability of towers to withstand earthquake shocks. Few problems were encountered in local wind power stations following an earthquake that had its epicenter in the San Gorgonio Pass area and measured 5.9 on the *Richter Scale.*

Yaw Drives

Operators of wind turbines that employ active yaw drives continue to experience problems with cracked transmission mounts, broken pinion shafts and gears, broken worm gears, and rough yawing operation. Two types of yaw systems have experienced minimal yaw drive problems: One employs an upwind rotor with a positive coning angle, which passively tracks the wind once initially aligned; and the other is an active yaw drive that employs sliding yaw brake shoes.

Generators

Problems with generators have been primarily associated with moisture in the windings. Corrective actions have included installation of generator heaters, increased insulation around the windings, and the use of drip-proof generators.

Sliprings and Droop Cables

Problems of material degradation, contamination, ring-to-ring short circuits, and leakage from moisture have occurred in wind turbine sliprings. Although some manufacturers have redesigned their sliprings, most new turbine designs eliminate sliprings and employ droop cables. These allow from 5 to 25 rotations of the nacelle before they have to be unwound. Droop cables are unwound either manually or automatically (if the turbine has an active

yaw drive). Most problems associated with twisted droop cables on passive yaw turbines have been solved by the use of a *pop-out connector* on the lower end of the cable.

Operation and Maintenance Costs

In 1987, the *Electric Power Research Institute* (EPRI) estimated O&M costs to be 0.8 to 1.2 cents per kWh (in 1987 dollars, not levelized). Assuming a capacity factor of 0.25, the annual O&M costs for a 50-kW system would range from $900 to $1,300, and from $3,200 to $4,800 for a 200-kW system. O&M costs for small-scale machines are higher per kilowatt-hour than for medium-scale turbines, because many of the same activities have to be performed on each of the smaller units. Thus, there are economies of scale that can be realized in O&M costs. However, there is insufficient commercial operating experience to draw any conclusions regarding the relationship of O&M costs to machine size for turbines rated at 300 to 600 kW. According to EPRI estimates, O&M expenditures are distributed approximately as follows:

Labor	44%
Parts	35%
Operations	12%
Equipment	5%
Facilities	4%

Based on wind power station experience up to 1988, annual O&M costs can be assumed to be 3 percent of the initial cost of the wind turbine. It should be noted, however, that this percentage is for a "mature" turbine, whose design defects have already been corrected. It does not provide for special inspections, product improvements, or other retrofit activities.

Operation and Maintenance Trends

Operators of wind power stations have begun to incorporate computer-controlled wind turbine monitoring systems that provide maintenance personnel with the current status of all machines within the station. Many of these systems are beginning to include diagnostic information for each turbine that is out of service. *Tuning* each wind turbine to its particular site is becoming more common. This process involves changes in the configuration of the turbine or its controls in order to maximize energy production once the wind characteristics at its local site are understood. Techniques used include the following:

-- resetting the blade pitch (on fixed-pitch machines);
-- putting *blade extenders* between the blade root and the hub, in order to increase rotor diameter;
-- using *vortex generators* on the blades;
-- extending the tower height at a site where there is a positive wind shear;
-- changing the cut-in and cut-out wind speeds and/or their associated time delays;
-- relocating turbines to sites with higher winds.

Newly-designed turbines also incorporate features to reduce maintenance costs, such as

-- quicker access to component parts that require regularly scheduled maintenance;
-- automated lubrication and blade washing;
-- warning alarms for brake pad wear.

Social and Business Environments Leading to Wind Power Development

Development of wind energy in the world did not take place in an economic or political vacuum. Changes in the international price of oil spurred interest in wind technology, and future changes in the price of oil and other competing energy sources will determine its economic viability in the future. A number of non-economic factors will also influence the ability of wind power to compete with other energy sources. Foreign and domestic political considerations, international trade policies, and local and regional concerns are all expected to impact the future development of wind energy.

Global Changes in Energy Costs

The initial growth of the wind energy industry occurred in response to market and regulatory forces resulting from the 1973 Arab oil embargo, that drastically increased the price of crude oil, as shown in Figure 4-27. Oil prices increased again following the Iranian revolution, reaching more than $40 per barrel by 1980. Prices for other energy fuels also increased. However, the effects of conservation, a slowdown in the world's economies, and the development of alternative energy sources began to curb the world's appetite for oil. By the early 1980s, world demand began to soften as more non-Middle Eastern supplies entered the market, putting downward pressure on prices. The Persian Gulf accounted for 45 percent of the open-market oil supply in 1975 when cartel control of world prices reached its peak, but by 1985 this had dropped to 23 percent.

In 1986, Saudi Arabia attempted to regain price control of world oil supplies by flooding the market, forcing oil prices to drop to $10 to $20 per barrel. The Saudi action had negative repercussions not only throughout the international oil industry (forcing the closure of wells and refineries worldwide) but also in other energy industries that offset oil consumption, such as wind.

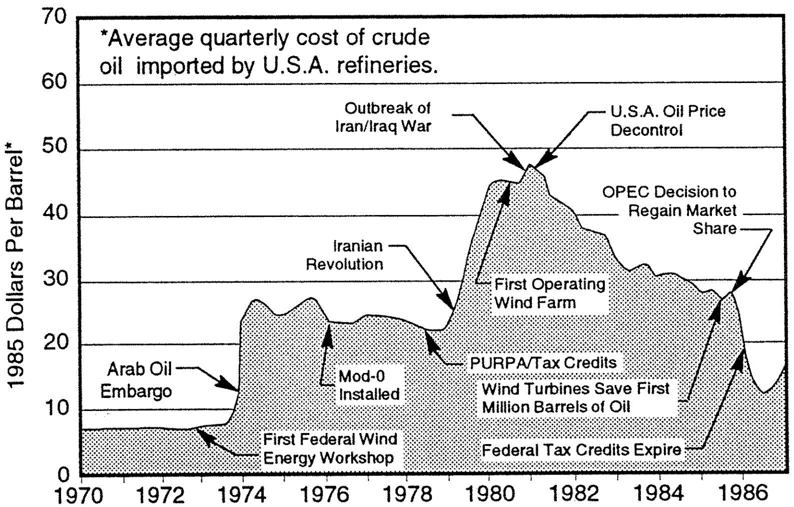


Figure 4-27. History of crude oil prices and milestones in wind energy development.

Some experts believe that the conditions that led to the saturation of the world oil market in the mid-1980s may change in the mid-1990s, after the impact of the war in the Gulf has been absorbed. Many observers expect that Persian Gulf producers will regain their lost market share and force prices upward during the 1990s, when production will have peaked on Alaska's North Slope, in the North Sea, and at other major oil fields. However, past experience has proven that future oil prices cannot be predicted reliably, and this situation is expected to continue for the next several decades.

Although social and political considerations will have some effect, the worldwide prices of oil and natural gas will remain the dominant factors in the future of wind energy. The recent emergence of the global warming issue could change this picture, if nations move to decrease fossil-fuel burning. Therefore, the future rate of development of wind energy resources in the world remains uncertain, although the outlook is promising.

Federal and State Incentives in the U.S.

Nations responded to the sharp price increases and economic disruption of the early 1970s by instituting programs for reducing oil consumption and developing substitute or alternative sources of energy. In the U.S., federal tax credits of up to 15 percent spurred the domestic wind industry. Several states, including California, followed the federal example and created state tax incentives to increase the development of alternate energy sources of all types, including wind.

In 1978, the U.S. Congress passed the *Public Utility Regulatory Policies Act (PURPA)*, which required every utility to buy electricity from independent producers at its *avoided cost*. Avoided cost is the cost per kilowatt-hour that the utility would have to pay for additional energy and capacity if it were to build new facilities. Although implementation of the new statute was delayed until the early 1980s, PURPA immediately established both a market and a pricing system for wind-generated power.

The California "Wind Rush"

Even with PURPA, many utilities objected to negotiating power sales contracts with independent energy producers. These objections dissipated just before the end of 1979 in California, when the California Public Utilities Commission fined the *Pacific Gas & Electric Company* $15 million for not considering conservation and alternative energy in its future generation plans. Major utilities in California began to actively support PURPA by giving more consideration to independent suppliers of renewable energy.

The following year, in 1980, California's governor organized a conference to attract financial interest in commercial wind power development, particularly in mountain passes where state-funded studies had identified "excellent" wind resources. In 1981 independent energy producers installed the first commercial wind power stations in the Tehachapi Mountains, northeast of Los Angeles, and in the Altamont Pass, east of San Francisco. Since then, development continued to be concentrated in California because of several advantages, including the following:

- excellent wind resources;
- abundant low-cost land with few land-use conflicts;
- favorable power purchase rates (avoided costs), since a large percentage of the state's electricity is generated by gas- and oil-fired plants;
- strong state regulatory support for developing alternative sources of energy;
- liberal investment climate, receptive to new ideas like commercialized wind power;
- abundance of wealth, second only to New York in the U.S.

The number of wind power stations in California grew rapidly during the 1980s. By 1989, California wind turbines constituted almost 80 percent of the commercial wind power in the world, as shown by the data in Table 4-10 [Gipe 1990]. Approximately 4,000 small-scale turbines had been installed elsewhere in the U.S., including New Hampshire and Hawaii.

Figure 4-28 illustrates the growth of wind power in California during the 1980s and the early '90s. From 1982 to 1983, wind generating capacity in California tripled. In 1984, it doubled again. By the end of 1992, over 1,650 MW of capacity had been installed in California wind power stations.

Table 4-11. Worldwide Distribution of Wind Power in 1989 [Gipe 1990]

California		78.0%
Altamont Pass	34.3%	
Tehachapi Pass	25.0%	
San Gorgonio Pass	18.7%	
Denmark		15.6%
Netherlands		1.6%
Hawaii		1.1%
Others		3.7%
Total:		100.0%

Between 1981 and 1985, the major source of financing for California's wind industry was private individuals who invested in *limited partnerships*. By the end of 1987, about $2.4 billion had been invested in California wind power stations.

The Post-Tax Credit Wind Industry in the U.S.

The federal energy tax credits expired at the end of 1985 and were not renewed. The 10 percent federal investment tax credit, which could be applied to most equipment investments (whether wind turbines or industrial machinery) was repealed by the 1986 tax reform act. California's state tax credit decreased in 1986 from 25 to 15 percent and expired by July 1987. Following expiration of these tax credits, new turbine orders fell in 1986 and

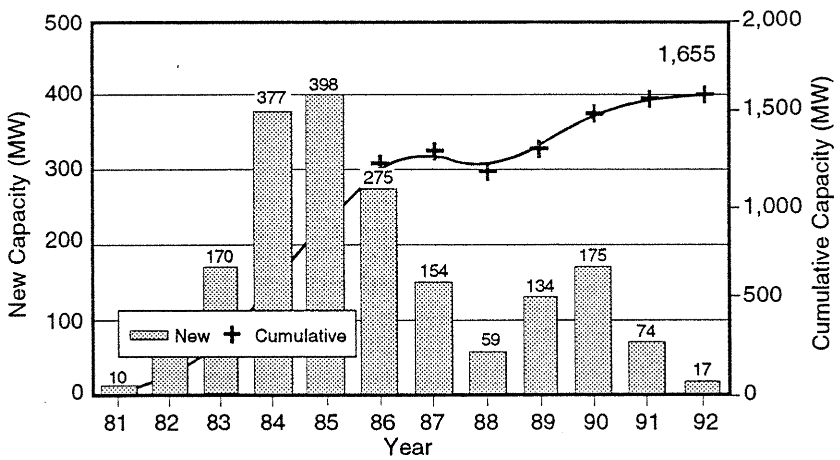


Figure 4-28. Growth of wind power installations in California: 1981 to 1992. [Gipe 1990]

1987. However, the existing California stock of more than 16,000 turbines assured a substantial business in wind turbine operations and maintenance. At one time, as many as 200 to 300 firms professed interest in building wind turbines. By late 1986, however, less than a dozen major manufacturers, worldwide, were still building commercial wind turbines. This small fraternity shrank even further in 1987, as several major manufacturers faltered or went into bankruptcy.

With the expiration of the U.S. tax credits, investment sources shifted away from limited partnerships. During 1986 and 1987, about half of the new wind turbines installed in California were financed through institutions such as banks, pension funds, and bond holders. These investments often took the form of a *sale-leaseback*, where the wind power station was sold to an institution which then leased it back to the wind station operator. After 1987, all new installations have been financed by institutional investors.

The European Wind Energy Industry

European and some Middle Eastern countries also instituted financial incentives to develop alternate energy sources. Although most of these programs were associated with tax credits, other incentives were employed, such as partial government subsidies of early projects.

Denmark

Although Denmark does not have a comprehensive law equivalent to PURPA to encourage competitive sources of electric power, individuals are permitted to connect wind turbines to the utility grid and sell their excess electricity to the utility. Alternatively, they can use this excess generation to offset their consumption, whether or not the wind turbines are installed at the owner's residence or business.

Flexible tax incentives and utility power purchase provisions, among other factors, encouraged the growth of a powerful wind turbine manufacturing industry in Denmark. Total production reached over 200 MW per year, more than three-fourths of which went to California during 1984 and 1985. The Danish industry has the largest market share for dispersed wind turbine applications in the world.

In the early 1980s the Danish krone was low in relation to the U.S. dollar, which provided a competitive advantage for sales in the U.S. But the Danes were not immune to the reduced world market for wind turbines. The expiration of the U.S. tax credits made wind power stations in this country more expensive to potential investors, and developers needed significant cost reductions to make new projects economically viable. Concurrently, the Danish krone rose in value almost 40 percent against the dollar in the mid-1980s, making Danish exports more expensive. By 1987 only a few Danish manufacturers had escaped hardship or bankruptcy. Nevertheless, Denmark is still the world's leading producer of commercial wind turbines.

Other European Countries

Businesses in European countries other than Denmark were slower to exploit the market for commercial wind turbines. Notable exceptions were *WindMaster/HMZ BV* in Belgium and *Bouma Windenergie BV* in Holland. Research activities in most European countries began in earnest by the early 1980s and accelerated after the Chernobyl nuclear accident in 1986, when 19 countries and territories had installed medium-scale turbines. The Netherlands, Greece, Spain, Germany, the United Kingdom, Sweden, Finland, Iceland, and

Italy all have active research and development programs aimed at eventual commercial applications (see Table 3-1).

Factors Accelerating Wind Technology Development

Energy technologies normally take 15 to 30 years to move from the research, development, and demonstration stage to commercial units. The time required depends any outside incentives designed to shorten the process, as well as the complexity of the technology and the market to be served. For example, because of federal involvement nuclear power reached the commercial stage in half the time it took for heat pumps to do the same (15 years versus 30 years). With government incentives, a promising market, and achievable technical goals, wind turbine development took much less time. Work began in the mid-70s, and by the early 1980s the industry had grown to the commercial stage.

Wind Turbine Costs

The costs of commercial wind turbines used in wind power stations have declined dramatically since 1980, as shown by the trend in *turnkey system costs* (costs to investors) in Figure 4-29. The major reasons for these large reductions in cost are

-- increased competition which forced manufacturers to reduce profit margins;
-- quantity discounts for component parts offered to manufacturers;
-- increases in turbine size resulting in economies of scale.;
-- improvements in manufacturing and installation techniques.

In 1986, Pacific Gas & Electric [Smith 1986] estimated that a wind power station could be built for $1,050/kW, operated at a capacity factor of 27 percent, and maintained for $0.01/kWh. At a *fixed charge rate* of 10 percent, a 30-year life, and constant (real) dollars, such a wind power plant could generate electricity for $0.054/kWh.

By 1987, wind turbine costs (turnkey costs less the *balance-of-station costs*) had declined to approximately $700 to $900 per kW. Further reductions are anticipated as wind turbine designs are refined. Although costs appear to be stabilizing from 1987 to 1990, this effect is actually caused by two opposing factors: (1) Wind turbine costs per installed kilowatt decreased by about 30%, and (2) the dollar weakened by approximately 35% during the same period.

Danish turbines have become more cost-effective as energy production has increased and installed cost has decreased, per unit of swept area. During 1987, a 55-kW turbine could be installed in Denmark for about $390/m^2$ and a 75-kW model for $370/m^2$. Reduced cost coupled with better performance made the 75-kW turbine 21 percent more cost-effective.

Figure 4-30 shows the *cost of energy (COE)* as a function of *capacity factor* for various turnkey station costs. If the price to the utility is in the range of $0.05/kW to $0.06/kW and a typical capacity factor is 0.25, turnkey station costs will have to be limited to approximately $700/kW to $900/kW, to provide a fair rate of return for the station owners. Because the *balance-of-station* costs are approximately $250 per kW, turbines will have to be produced for less than $600/kW and/or energy productivity will have to be increased. This appears to be achievable in light of the recent cost reductions realized within the industry and the development of more-efficient rotor blades.

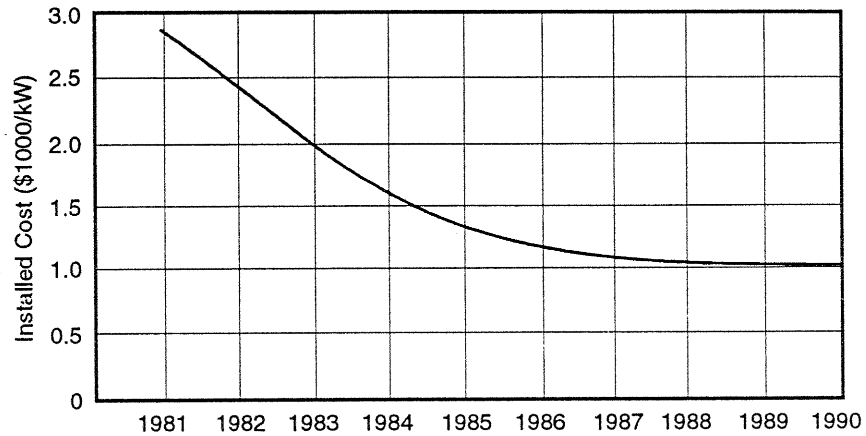


Figure 4-29. Trend of turnkey costs for wind power stations during the 1980s.

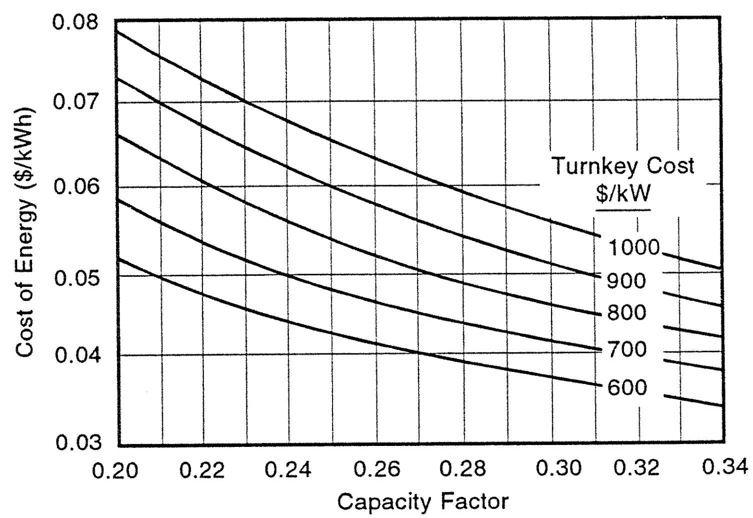


Figure 4-30. Effect of capacity factor and turnkey cost on the cost of energy. Interest rate is assumed to be 12% and O&M costs are $0.01/kWh.

Wind Power Station Costs Compared with Other Alternatives

The Office of Technology Assessment of the U.S. Congress has estimated that the typical wind power station in the 1990s will cost from $900/kW to $1,200/kW [OTA 1985]. Current research by the *National Renewable Energy Laboratory* (formerly the Solar Energy Research Institute) and private companies indicates that additional reductions of 10% to 15% are achievable. In contrast, nuclear power plants being completed in the United States during the mid-1980s ranged in cost from $3,000/kW to over $5,000/kW of capacity. However, because wind power stations are primarily *fuel savers*, with little *capacity credit* (*i.e.*, utilities cannot depend upon wind power to produce energy when needed) a direct kilowatt-for-kilowatt comparison is not equitable. Nevertheless, this fourfold cost advantage per unit of installed power compared to nuclear plants and the absence of dangerous wastes may make wind power become attractive to many utilities.

Both nuclear and wind turbine generation eliminate *air pollution* that otherwise would be caused by conventional power plants, a health and economic benefit often not accounted for quantitatively in the cost of energy. Most wind power stations in California during the 1980s offset generation from conventional plants fired with natural gas. Wind generation reduced emissions of nitrogen oxides, sulfur oxides, and carbon monoxide that otherwise would have been released. A study performed at *Brookhaven National Laboratory* on the benefits of nuclear power in offsetting air pollution found that gas-fired plants caused 150 deaths per gigawatt-year of generation, coal plants 220 deaths, oil 140 deaths, and wood 57 deaths [Hamilton 1984]. Based on these findings, wind power stations will have saved about 200 lives during their first decade of operation. This invaluable benefit is difficult to quantify.

Wind power cannot currently compete with large hydroelectric power plants, which generate electricity for $0.02/kWh to $0.05/kWh and represent firm capacity. However, most sites for large hydroelectric dams have already been exploited, so little new capacity is available.

Wind energy proponents have often argued that wind power stations would generate electricity inexpensively once they were amortized. This assumption was based on the absence of fuel costs at wind power stations. By 1986, enough operating experience with wind turbines had been gained to determine their operation and maintenance costs relative to those for conventional power plants. As shown in Table 4-13, the cost of operating and maintaining wind plants was approximately one cent per kilowatt-hour in 1985 [Lynette 1985]. This is about half the cost to operate, maintain, and fuel a coal-fired or nuclear plant, and about one-fourth the cost to do the same for an oil- or gas-fired plant.

Table 4-12.
Comparative O&M and Fuel Costs for Different Power Sources
(cents/kWh)

Source	1984	1985
Wind[1]	2.0	1.0
Coal	2.2	2.3
Nuclear	1.8	1.9
Gas	4.3	4.2
Oil	5.5	5.3
Other	4.8	4.5

[1] [Lynette 1985]; remainder of data from Utility Data Institute, Washington, DC.

Modularity

The *modularity* of wind power plants has contributed significantly to the industry's rapid growth. Modularity is a powerful argument for further industry expansion because it offers substantial cost savings to developers. An individual wind turbine costs a fraction of a conventional power plant. Independent energy producers, or the utilities themselves, can install as many as they need and at the time they need them. Modularity has driven wind turbine technology at a faster pace than conventional energy sources because wind technology has a much shorter lead time between research and application. Modularity and short lead time have resulted in quick adoption of technological refinements.

In an era of uncertain growth in demand for electricity, modularity offers utility planners not only flexibility but also cost savings. When growth is uncertain, the addition of a large central station may commit too much of the utility's financial resources for too long a period of time. The utility runs the risk that some of the added capacity may stand idle once completed. The utility must then absorb the financing costs until the plant enters the rate base plus any plant costs not contributing to useful capacity, as determined by regulators. Instead of spending a decade of time and committing large amounts of capital to the construction of one conventional power plant, developers can start bringing wind power stations on line in a year, adding as much capacity as the demand requires.

One modeling study indicated that the *cash flow benefits* of small, short lead-time generating plants could be considerable, in the short term [OTA 1985]. Another study [Sutherland and Drake 1984] was more specific. It found that utilities could afford to pay as much as four times more in construction costs for 5-year lead-time plants than for 15-year lead-time plants. For example, if a conventional plant costs $1,000/kW, a utility could afford up to $4,000/kW for a plant with only a 5-year lead time. Thus, even where new wind power capacity is more expensive per unit than conventional base load plants, the benefits of modularity make wind energy financially attractive.

Wind Energy Business Outlook and Future Trends

Since the passage of PURPA in 1978, the U.S. electric utility industry has seen increasing competition from independent energy producers. By the late 1980s, nearly 10% of California's electricity was generated by non-utility sources, and much of the state's new generation was built by independent energy producers. Structural changes in the electric utility industry also played a major role in enabling independent energy producers to gain a foothold. Major financial burdens from large power plants during a period of high interest rates brought several utilities to the brink of bankruptcy during the 1980s. High energy prices slowed growth in electricity consumption, and regulatory agencies were under pressure to protect rate payers from the cost of expensive new facilities. Independent energy producers offered both the utilities and their regulators lower-cost, lower-risk alternatives to building these large new plants.

Changes in the Regulatory Environment

Because electric utilities are monopolies, *regulatory changes* affecting them also have wide-reaching consequences for the wind industry. If, for example, regulatory agencies dictate that utilities must hold an auction for the next increment of generation, and that the lowest bid must be used to build the capacity, wind generation will often (if not always) lose to *cogeneration* because cogeneration receives *firm capacity credits*.

Unregulated Subsidiaries

Under PURPA, utilities are prohibited from owning a controlling interest (more than 50%) in a so-called *qualifying facility (QF)*, such as a wind power station. This prohibition was designed to encourage competition and eliminate self-dealing (*e.g.*, offering more favorable treatment to the utility subsidiary than to independent producers). For several years after its passage, this provision caused little concern to the utilities. But by the mid-1980s, as the independent producers became increasingly successful, this prohibition frustrated utilities who sought to diversify into unregulated subsidiaries that would build, own, and operate renewable energy plants.

Participation in an unregulated subsidiary permits the utility to act much like a independent energy producer, raising capital based on the utility's balance sheet, building plants, and selling energy in an unregulated environment. Several U.S. utilities have established subsidiaries that finance and invest in cogeneration and other small power plants. Although this development could be used to construct wind power stations, only one utility, the *Hawaiian Electric Company*, had done so by 1988. Since that time, a number of utilities have established unregulated subsidiaries for wind power development.

Least-Cost Planning and Fixed-Price Contracts

Another change that may prove detrimental to the wind energy industry is the regulatory emphasis on *least-cost planning*. Under this type of regulation, a new generation source of electricity can be added only if it has been found to be the least costly, regardless of who the developer is. Bidding by independent energy producers to sell least-cost electricity pits wind generation against cogeneration and other fossil-fuel plants. Bidding, however, works fairly when long-term costs are used in preference to short-term costs.

In 1983-84, the California Public Utilities Commission proposed fixed-price contracts between independent energy producers and utilities in order to encourage renewable energy technologies and diversify the mix of generating methods. In spite of the low oil prices during the late 1980s, the unused fixed-price contracts (agreements that were signed but where no wind power stations were yet installed) assured that the wind energy industry in California would continue to grow. By 1993-94, the fixed-price portion of these contracts expires.

Utility Concerns

The utility industry's initial reluctance to interconnect with wind turbines was predicated on its lack of control over the power produced. Institutional issues, such as opening a regulated monopoly's market to competitors, provided the backdrop against which the technical questions (like safety and power quality) were raised. Utilities have asserted that widespread use of distributed wind turbines by utility customers would erode the total sales upon which the distribution system itself was based. Self-generation threatened the equal distribution of the costs for providing and maintaining the transmission system. But the limited use of wind turbines at residential or commercial sites appears to have put this concern to rest.

Utilities have expressed concern that wind power stations would consume considerable *volt-ampere reactance units (VARs)*, since the bulk of wind turbines worldwide use induction generators that require an external source of VARs. Although each turbine is installed with its own *capacitors for power-factor correction*, this capacitance is fixed and does not vary with the amount of power generated as the VAR demand does. By mid-1987, additional VAR support to wind power stations was being provided by utilities as part of their normal customer load support. On "stiff" local grids in California, such as those in Altamont Pass and San Gorgonio Pass, VAR supply has not been a problem. But in Tehachapi, where wind power stations draw VARs from a switching center 32 km away, VAR support is more of a concern.

A concern of the utilities is that, because of wind variability, wind power generation often does not coincide with utility demand (Fig. 4-17) and this could pose a *dispatch* problem if grid penetrations were to become large. But wind power stations are no different than other renewable technologies, such as run-of-the-river hydro plants, where energy output is a function of flow. A portion of a wind power station's output could be made dispatchable, so that it could be called upon as needed to follow the utility load. However, independent energy producers argue that providing a dispatch capability is, in reality, like holding generating power in *reserve*, and they should receive compensation in a fashion similar to the way the utility's own reserve capacity is compensated. If this concept were incorporated into power pricing, wind power stations with some means of *short-term storage* could receive higher rates for generation held in reserve.

Grid Transmission Capacity Limits

Transmission capacity may be one of the limiting factors on future development of the wind energy resource. Transportation routes to the market determine whether any resource can be used economically. Because areas of energetic winds are seldom near population (and, therefore, electrical load) centers, the location of transmission lines becomes critical. In the PG&E service area near San Francisco, independent energy producers are quickly exhausting the available grid power transmission capacity. As non-utility generation continues to grow, state regulators are examining whether rationing of the available transmission capacity is needed. At present, a portion of the utilities' transmission capacity is reserved for competing technologies, with priority given on a first-come, first-served basis. This process has yet to affect wind industry growth in California, but it has the potential to do so in the long run.

A secondary limit on transmission capability exists within the wind power station itself. Each station has its own power lines located within station property (Fig. 4-16). Pad-mounted *collector transformers* receive the energy output from several turbines (or a single large-scale turbine) and increase the voltage for delivery to a *central substation*. From the substation, the power is delivered to the utility's overhead lines at 66,000 volts or 115,000 volts, depending upon the local transmission voltage. All elements of the station's internal grid are potential limitations on installed capacity and require economic justification before they can be increased in size.

Wheeling Wind-Generated Power

Other areas of the continental U.S. have energetic winds (*e.g.*, the Great Plains). However, they do not provide the same combination of factors that launched development in California. For example, the Great Plains are served by low-cost, coal-fired plants and federally-subsidized hydroelectric power. Thus, the *avoided costs* in these areas are extremely low. The challenge for the industry is to tap the wind resources of the Great Plains and *wheel* the power (*i.e.*, transport it over the lines of several adjacent utilities) to distant cities that have higher avoided costs. During the late 1970s, wheeling privately-produced electricity from wind turbines was not considered practical. But wheeling is now nearing reality for cogeneration facilities in several areas of the country. Wheeling of wind-generated power may not be far behind.

References

CEC, 1992, *Results from the Wind Project Performance Reporting System: 1991 Annual Report*, Sacramento, California: California Energy Commission.

Clark, R. N., V. Nelson, R. E. Barieau, and E. Gilmore, 1981, "Wind Turbines for Irrigation Pumping," *Journal of Energy*, Vol. 5, No. 2: pg. 104-108.

Clark, R. N., and W. E. Pinkerton, 1988, "Operating Electric Motors with Autonomous Wind Power," *Proceedings, Windpower '88 Conference,* Washington, DC: American Wind Energy Association, pp. 313-323.

Clark, R. N., and K. E. Mulh, 1992, "Water Pumping for Livestock," *Proceedings, Windpower '92 Conference*, Washington, DC: American Wind Energy Association, pp. 284-290.

Cousineau, K. L., 1992, "Remote Control and Operations of a Hawaiian Wind Diesel Plant from the Mainland," *Proceedings, Windpower '92 Conference, Washington, DC: American Wind Energy Association, pp. 250-257.*

Cromack, D. E., and W. E. Heronemus, 1977, "Wind Power for Space Heating," *Proceedings, Third Biennial Conference and Workshop on Wind Energy Conversion Systems*, Vol. 1, Washington, DC: JBF Scientific Corporation, pp. 185-196.

Gaudiosi, G., and L. Pirazzi, 1987, "Wind Pumping Applications Meeting in Rome," *BWEA Windirections*, Vol. VI, No. 4, London: British Wind Energy Association, pp. 15-16.

Gipe, P., 1990, "Wind Energy Comes of Age," Tehachapi, California: Paul Gipe & Associates.

Gipe, P., 1993, *Wind Power for Home and Business*, Post Mills, Vermont: Chelsea Green Publishing Company.

Hamilton, L. D., 1984, *Health and Environmental Risks of Energy Systems*, International Atomic Energy Agency Paper IAEA-SMM-273/51, Upton, New York: Brookhaven National Laboratory, p. 37.

Herrera, J. I., T. W. Reddoch, and J. S. Lawler, 1985, *Experimental Investigation of a Variable Speed Constant Frequency Electric Generating System from a Utility Perspective*, NASA CR-174950, DOE/NASA/4105-1, Cleveland, Ohio: NASA Lewis Research Center.

Hurley, B., 1986, "Wind Energy for Land Drainage in Ireland," *Proceedings, 1986 BWEA Wind Energy Conversion Conference*, London: British Wind Energy Association.

IEA, 1992, *IEA Wind Energy Annual Report 1992*, Stockholm, Sweden: NUTEK

Jaras, T. F., 1987, *Wind Energy 1987: Wind Turbine Shipments and Applications*, Great Falls, Virginia: Stadia, Inc.

Johnson, W. R., and W. R. Young, 1985, "Status of the DOI SVU Wind Turbine Project," *Proceedings, Wind Power '85 Conference*, SERI/CP-217-2902, Washington, DC: American Wind Energy Association, pp. 604-609.

Loyola, J., 1993, *Wind Project Performance: 1992 Summary,* Sacramento, California: California Energy Commission.

Lynette, R., January 1985, *Wind Power Stations: 1984 Experience Assessment*, Interim Report for EPRI Project 1996-2, Palo Alto, California: Electric Power Research Institute.

Lynette, R., June 1986, *Wind Power Stations: 1985 Performance and Reliability*, Report for EPRI Project 1996-2, Palo Alto, California: Electric Power Research Institute.

Madsen, B., October 1986, "The Time is Ripe for A Design Breakthrough," *Windpower Monthly*, Vol. 2, No. 10, Knebel, Denmark: p. 25.

Madsen, B., April 1987, "Analysis of a Success," *Windpower Monthly*, Vol. 3, No. 4, Knebel, Denmark: p. 4.

Madsen, B., May 1987, "Danes Spread the Word," *Windpower Monthly*, Vol. 3, No. 5, Knebel, Denmark: p.4.

Moroz, E. M., 1993, "A Critical Review of "Water Pumping for Livestock" Presented at Windpower '92," *Proceedings, Windpower '93 Conference*, Washington, DC: American Wind Energy Association, pp. 551-558.

Nielsen, P., 1993, "Development of Wind Energy in Denmark," *Proceedings, Windpower '93 Conference*, Washington, DC: American Wind Energy Association, pp. 401-410.

Oei, T. D., 1986, "Estimation of the Fuel Savings by Wind Energy Integration into Small Diesel Power Grids," *Proceedings, 1986 BWEA Wind Energy Conversion Conference*, London: British Wind Energy Association.

OTA, February 1985, *New Electric Power Technologies: Problems and Prospects for the 1990s*, Washington, D.C.: U.S. Congress Office of Technology Assessment.

PG&E and U. S. Windpower, Inc., 1986 and 1988, *Altamont Pass Windfarms*, L. Pettibone, designer, unpublished brochure, San Francisco: Pacific Gas and Electric Company.

Qi, G., 1993, "Mathematic Programming Models for Economic Design and Assessment of Wind/Diesel Systems," *Proceedings, Windpower '93 Conference*, Washington, DC: American Wind Energy Association, pp. 501-507.

SCE and U. S. Windpower, Inc., 1986a, *San Gorgonio Wind Parks*, unpublished brochure, L. Pettibone, designer, Rosemead, California: Southern California Edison Company.

SCE and U. S. Windpower, Inc., 1986b, *Tehachapi Wind Parks*, unpublished brochure, L. Pettibone, designer, Rosemead, California: Southern California Edison Company.

Sexon, B. A., 1987, "Wind Energy in Mongolia," *BWEA Windirections*, Vol. VI, No. 4., London: British Wind Energy Association, pp. 26-27.

Slack, G., and P. Musgrove, 1986, "Longterm Performance Modelling of a Wind/Diesel System with Hydraulic Accumulator Storage," *Proceedings, 1986 Wind Energy Conversion Conference*, London: British Wind Energy Association.

Smith, D., 1986, "Wind Energy at PG&E's Department of Engineering Research," *Proceedings, Fifth ASME Wind Energy Symposium*, New York: American Society of Mechanical Engineers.

Somerville, W. M., 1986, "Applied Wind Generation in Small Isolated Electricity Systems." *Proceedings, 1986 BWEA Wind Energy Conversion Conference*, London: British Wind Energy Association.

Spera, D. A., and M. Miller, 1992, "Performance of the 3.2-MW Mod-5B Horizontal-Axis Wind Turbine During 55 Months of Commercial Service in Hawaii," *Proceedings, Windpower '92 Conference*, Washington, DC: American Wind Energy Association, pp. 231-238.

Stock, J., February 1986, "Wind Power Generation: One Utility's Perspective," *Proceedings, Fifth ASME Wind Energy Symposium*, New York: American Society of Mechanical Engineers.

Strategies Unlimited, 1987, *Status of Commercial Wind Power: 1986 Survey Report for EPRI Research Project 1590-9*, Palo Alto, California: Electric Power Research Institute.

Suehiro, D., and M. Miller, 1988, "HEI's Wind Farm Control Experience," *Proceedings, Windpower '88 Conference*, Washington, DC: American Wind Energy Association, pp. 260-269.

Sutherland, R. J., and R. H. Drake, 1984, *The Future Market for Electric Generating Capacity: A Summary of Findings*, Los Alamos, New Mexico: Los Alamos National Laboratory.

UN, 1987, "Wind Energy Resources and Developing Countries," UN Institute for Training and Research, *BWEA Windirections*, Vol VI, No. 4, London: British Wind Energy Association, pp. 25-26.

5

Aerodynamic Behavior of Wind Turbines

Robert E. Wilson, Ph.D.
Professor of Mechanical Engineering
Oregon State University
Corvallis, Oregon

Introduction

Designing wind turbines to achieve satisfactory levels of performance and durability starts with knowledge of the aerodynamic forces acting at the critical interface between wind and machine. This chapter concentrates on the basic principles of the aerodynamic behavior of conventional horizontal- and vertical-axis wind turbines (HAWTs and VAWTs). Aerodynamic theories are discussed, starting from the *actuator disk model* of a HAWT, extending through the *Glauert optimum actuator disk model,* to the *strip theory* which is the current mainstay of HAWT aerodynamic design and analysis. Various corrections, including *thrust coefficient modifications*, *tip-loss models*, and *gap corrections*, are developed. Comparisons are made between test data, strip theory, and *free vortex* calculations to evaluate the accuracy of strip theory.

HAWT operational and design features are presented, including the *teetered rotor*, *yawing* and *yaw stability*, *blade-* and *tip-pitch controls*, *ailerons*, *transient aerodynamics*, and *vortex generators*. *Power outputs* and *aerodynamic loads* of medium- and large-scale HAWTs are presented and compared with theory. The aerodynamic behavior of VAWTs is examined in a parallel fashion, starting with an analysis of limiting VAWT performance and then proceeding to a development of the *streamtube theory*. Comparisons are made between power output predictions and test results for a medium-scale research VAWT. The effects on VAWT performance of *rotor solidity*, *blade number*, *rotor shape*, and *Reynolds Number* are presented, along with a discussion of starting and stopping. Test data are used to demonstrate the shape of rotor power curves and the effects of *vortex generators*.

Translating Aerodynamic Devices

Perhaps the simplest type of wind power device is one that moves in a straight line under the action of the wind, like the iceboat shown in Figure 5-1. Historically, these wind-driven *translating devices* have been used for propulsion rather than power extraction. However, examination of translating *lift-* and *drag-driven* devices can be illuminating for the aerodynamic analysis of rotary machines, since a rotating blade element can be considered as instantaneously translating.

Figure 5-1. An iceboat traveling at a speed of 27 m/s. *(Courtesy of Gougeon Brothers, Inc., Bay City, MI)*

Drag Translator

First, consider a device driven only by drag forces. Figure 5-2 illustrates the action of an elementary drag device in which the power extracted is the product of the drag force and the translation velocity. Drag results from the *relative velocity* between the wind and the device, so that

$$P = D\,l\,v = C_D\,p_d\,A_p\,v = \left[0.5\,\rho\,(U - v)^2\right] C_D\,c\,l\,v \tag{5-1}$$

where

P = power extracted (W)
D = drag force per unit length of device (N/m)
l = length (spanwise) dimension of device (m)
v = translation velocity (m/s)
C_D = *drag coefficient*; function of device geometry
p_d = *dynamic pressure* = $0.5\rho V_r^2$ (N/m^2)
ρ = *air density* (kg/m^3)
V_r = relative velocity (m/s)
A_p = projected area of device (m^2)
c = width (chordwise) dimension of device (m)
U = steady free-stream wind velocity (m/s)

Thus, the velocity of the device must always be less than the wind velocity. The *power coefficient* of a wind power device is defined as the ratio of the power extracted to the wind power over an area equal to the projected area of the device, or

$$C_P = \frac{P}{0.5\,\rho\,U^3 A_p} = \frac{v}{U}\left(1 - \frac{v}{U}\right)^2 C_D \tag{5-2a}$$

where C_P = power coefficient

The power coefficient for a drag-driven device is a maximum when $v/U = 1/3$. Thus,

$$C_{P,\max} = (4/27)\,C_{D,\max} \tag{5-2b}$$

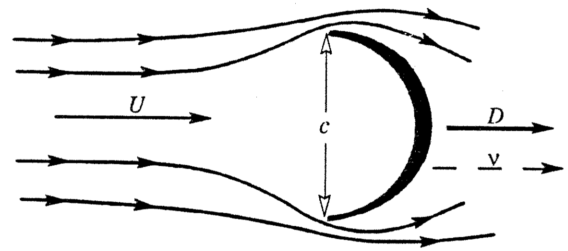


Figure 5-2. Translating drag device.

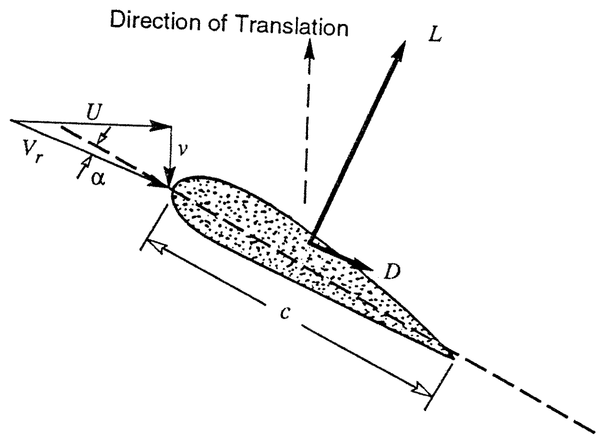


Figure 5-3. Translating airfoil with lift and drag forces acting.

Lifting Translator

By contrast, the lifting translator does much better. Figure 5-3 illustrates an airfoil that is translating at right angles to the wind direction and is subject to both lift and drag forces. This *lifting surface* sees a relative velocity that is the vector sum of the free-stream wind velocity and the wind speed induced by translation. The angle from the direction of the relative velocity to the *chord line* of the airfoil is termed the *angle of attack*. Lift and drag forces are perpendicular and parallel, respectively, to the relative wind and are given by

$$L = 0.5\,\rho\,V_r^2\,C_L\,c$$
$$D = 0.5\,\rho\,V_r^2\,C_D\,c \qquad (5\text{-}3)$$

where

L = aerodynamic lift force per unit length of airfoil (N/m)
D = aerodynamic drag force per unit length of airfoil (N/m)
C_L, C_D = lift and drag coefficients, respectively; functions of airfoil shape and α
α = angle of attack

Analysis of the airfoil as a *free body* yields the power extracted as

$$P = 0.5\rho U^3 A_p \frac{v}{U}\left(C_L - C_D\frac{v}{U}\right)\sqrt{1+\left(\frac{v}{U}\right)^2} \qquad (5\text{-}4)$$

At maximum power $v/U \doteq (2/3)C_L / C_D$ (*i.e.* 2/3 the *lift-to-drag ratio*). Therefore, the maximum power coefficient for an airfoil translating at right angles to the wind is given by

$$C_{P,\max} \doteq (2/9)\,C_L\,(C_L/C_D)\sqrt{1+(4/9)(C_L/C_D)^2} \qquad (5\text{-}5)$$

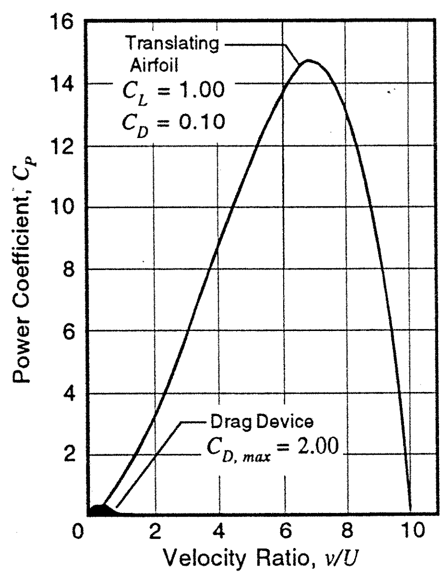


Figure 5-4. Comparison of typical power coefficients of a translating airfoil and a translating drag device. The airfoil is moving at right angles to the wind direction.

Figure 5-4 is a sample comparison of lift and drag as mechanisms to extract power from the wind which readily shows the advantages of using lifting surfaces. Equations (5-2) and (5-4) are used to construct the curves in this figure. The aerodynamic properties are C_L = 1.0 and C_D = 0.10 for the airfoil, and $C_{D,max}$ = 2.0 for the drag-driven device. The airfoil has a maximum power coefficient of 15.0, compared with 0.3 for the drag device. Thus, lift devices can quite readily produce 50 times the power per unit of projected area than that produced by drag devices. Moreover, operating a lifting device at velocities well in excess of the wind velocity is easily achieved by rotating machines. It is further noted that the maximum power coefficient of any rotary machine using drag is also less than $(4/27)C_{D,max}$, based on projected area of the drag elements.

With the superiority of the lifting translator established, the concept of placing lifting surfaces on a rotating machine to form a turbine is seen to be an obvious method of converting wind energy to useful work.

Performance Parameters

The *power performance* of a wind turbine can be expressed in dimensionless form in two ways. First, for a fixed wind speed, the *power coefficient, C_P*, and the *tip-speed ratio, λ*, are used. The power coefficient is defined in Equation (5-2), in which A_p is now the projected area of the *moving* rotor (called the *swept area*) and the tip-speed ratio is

$$\lambda = (v/U)_{\max} = R\Omega/U \qquad (5\text{-}6)$$

where

λ = tip-speed ratio
R = maximum rotor radius (m)
Ω = rotor speed (rad/s)

The power in the Equation (5-2) can be either the rotor output, in which case we have the *rotor power coefficient, $C_{P,r}$*, or the system output power, in which case we have the *system power coefficient, $C_{P,s}$*. The difference between these two outputs is the power-train and electrical equipment losses.

The second dimensionless form for expressing performance is for a fixed rotor angular speed, in which the *advance ratio, J*, and a *rotor speed power coefficient, K_P* are used. These parameters are defined by

$$J = (U/v)_{\min} = \frac{U}{R\Omega} = \frac{1}{\lambda} \qquad (5\text{-}7a)$$

$$K_P = \frac{P}{0.5\rho R^3\Omega^3 A} = \frac{C_P}{\lambda^3} \qquad (5\text{-}7b)$$

As before, K_P can be given for the rotor or for the entire system.

Figures 5-5 and 5-6 illustrate $C_{P,r}$ as a function of λ and $K_{P,r}$ as a function of J for a typical HAWT operating at fixed pitch. Operating points A, B, C, and D are shown in both figures. The left-hand side of Figure 5-5 (ABC) is controlled by *blade stall*. Local *angles of attack* (angles between the relative wind and the blade *chord line*) are relatively large as point A is approached. Changes in blade *pitch angle* have a great effect on power output along segment ABC. The right-hand side of Figure 5-5 (CD) is controlled by drag, particularly *skin friction*, because the angles of attack are small as point D is approached. The plot of K_P versus J is a dimensionless plot of *power vs. wind speed*, or a *power curve*,